Deep-sea sponge grounds

Reservoirs of biodiversity

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Regional Seas

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Preface

Long overlooked, deep-water sponge grounds are now emerging as a key component of deep-sea ecosystems, creating complex habitats hosting many other species. They are an important refuge in the deep ocean and they are also reservoirs of great species diversity, including commercially important fish. Playing a similar role to that of cold-water coral reefs with which they often co-occur, sponge grounds are even more ecologically and geographically diverse, consisting of many individual species and occurring in many places around the world.

The rapid development of sophisticated technology has provided opportunities to observe and study deep-water sponges in a way that has never been previously possible. This report highlights what is currently known about deep-water sponge grounds in terms of their distribution, biology, ecology and present-day uses in biotechnology and drug discovery, and introduces case studies of particular deep-water sponge habitats from around the world.

Worrying findings are presented on the impacts of human activities, in particular bottom trawling used by commercial fisheries, and gaps in knowledge are also brought to our attention. We do not yet know the full global distribution of deep-water sponges, or fully understand their biological processes and ecological roles. Furthermore, there is limited scientific understanding of the ramifications of climate change and ocean acidification on the health and continued function of these important and fragile deep-water habitats.

This report highlights the need to minimize the risk of damage to deep-sea sponge grounds through appropriate conservation and careful management, and presents further evidence of the need to improve awareness and understanding to ensure that future generations have the opportunity to explore, study and benefit from these vulnerable deep-water habitats. I therefore welcome the recommendations made by the authors. As a result of their work, deep-water sponge grounds – for so long out of sight – will no longer be out of mind.

Chris Elliott
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Acknowledgements

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Executive summary

Until recently, deep-water sponge grounds have remained Cinderellas of the deep seas, largely overlooked and poorly understood. However, it is now clear that these sponges create habitats, support high biodiversity, provide refuge for fish, and are a storehouse of novel chemical compounds, some of which show promise for pharmaceutical drug development.

International concern is now focused on the vulnerability of deep-water sponge grounds. Sponges are slow-growing and long-lived, and therefore slow to recover from perturbations, including physical damage. The impacts of climate change on sponges are largely unknown, but bottom trawling is currently considered to be the most pervasive and damaging deep-water human activity. This has been recognized in a number of international arenas.

This report outlines what is known about deep-water sponge grounds in terms of their distribution, biology, ecology and present-day uses in biotechnology and drug discovery. It also reviews the policy environment within which deep-water sponges can be conserved, discusses options for future policy development, and concludes with a series of recommendations focusing upon:

- Under UN General Assembly Resolution 61/105:
  ❑ formally identifying sponges as a vulnerable marine ecosystem;
  ❑ adopting precautionary management of sponges, including refinement of sponge bycatch thresholds for fishing vessels;
- Under the Convention on Biological Diversity's 2012 target for marine protected areas:
  ❑ ensuring the representation of sponges in marine protected area networks;
  ❑ supporting broad international engagement in the scientific research needed to:
  – map and predict sponge distribution globally,
  – understand sponge ecology, particularly the role of secondary metabolites;
- Enhancing monitoring through the use of vessel monitoring and fishery observer approaches;
- Developing regional monitoring programmes with full stakeholder involvement;
- Ensuring effective science-policy interactions to promote better management of sponge grounds and other vulnerable deep-water ecosystems.

Sponge grounds form structurally complex habitats supporting locally rich biodiversity. They have provided society with a range of ecosystem goods and services for thousands of years, dating back to the times of Homer and Aristotle. For generations, some local communities have relied on shallow-water bath sponge fisheries as a source of income. More recently – since the 1970s – a growing and significant biotechnological industry has developed, which extracts potential drugs from marine organisms. As a group, sponges produce a particularly diverse array of secondary metabolites – compounds that have powerful metabolic effects on other species, comparable to the antibiotics produced by bacteria. A number of drugs have now been discovered from sponges and taken through clinical trials. Understanding secondary metabolites in sponges and their role in sponge biology has tremendous potential for future drug discovery. For example, whereas up to 10,000 compounds may have to be synthesized in the laboratory for a single drug to pass through clinical trials, only around 200 secondary metabolites are typically screened to produce a successful new drug. However, despite their inherent and biotechnological value, we risk irreversibly damaging deep-water sponge grounds before we have been able to study their ecology and explore their wider potential for providing ecosystem goods and services.

As with all deep-water ecosystems, sponge grounds remain poorly mapped and understood. Current knowledge of the global distribution of sponges is biased to those areas of the world with a history of deep-sea surveys, although recent technological advances now allow three-dimensional seabed surveys and remotely operated vehicles to map and explore the deep sea as never before. Where scientific studies have been carried out, the scale and significance of deep-water sponge grounds have been unexpectedly high.

Deep-water sponge grounds often occur as distinct bands where local environmental conditions are suitable for their growth. In the Northeast Atlantic, such bands of '*Holtenia* grounds' formed by the glass sponge *Pheronema* were first

Deep-sea sponge grounds
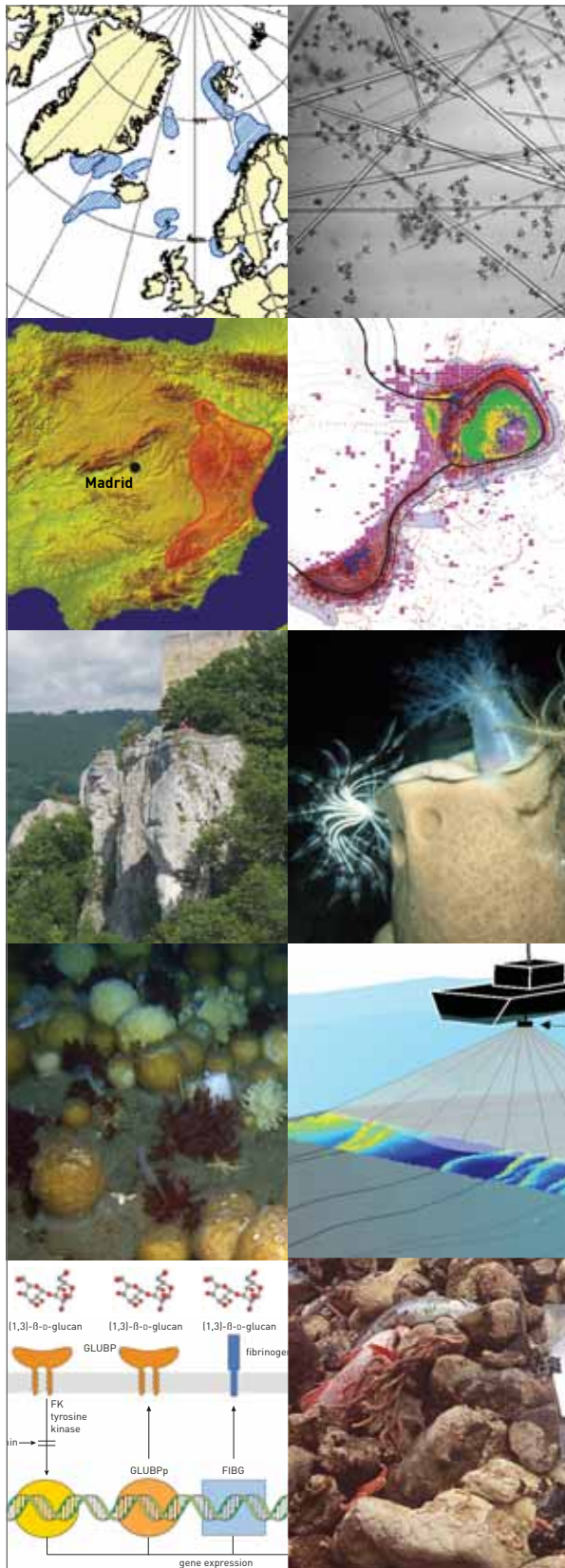
discovered in the 19th century. Sponge grounds are typically found in truly oceanic waters with suitable hard substrate on which to settle and local water currents to supply food particles from the surface ocean. There are thought to be more than 500 sponge species in the well-developed 'sponge kingdom' on the deep continental shelf of Antarctica. However, a global map of sponges does not exist and the recent discovery of giant glass sponge reefs off western Canada – a throwback to Jurassic times – shows that more mapping is a priority for future work.

Sponges are long-lived and slow-growing. For example, today's Canadian sponge reefs are up to 9,000 years old, with individual sponges reaching ages of more than 100 years. They are also fragile structures that are easily damaged by physical perturbations. As scientific surveys record deep-water sponge distribution and discover new sponge habitats, many also bring back clear evidence that they have been damaged by bottom trawling. Bottom trawling of sponge grounds physically injures, dislodges and captures sponges. If returned to the sea after having been caught, they rarely survive. Seabed sediments disturbed by the passage of a trawl also clog the complex filtering apparatus that sponges use to catch their food. Similar concerns have been raised over the deep-sea disposal of cuttings from oil and gas drilling and the localized seabed impact associated with cable and pipeline laying and seabed mining. There is almost no scientific understanding of the impacts of climate change and ocean acidification on deep-water sponge grounds.

To date, management and conservation of deep-water sponges is widely considered to be inadequate and uncoordinated. However, there are various existing frame-works which can be used to rectify this. Perhaps the most notable is the adoption in December 2006 by the United Nations General Assembly (UNGA) of Resolution 61/105. This resolution calls upon states and regional fishery management organizations to ensure that vulnerable marine ecosystems do not suffer significant adverse environmental impacts from bottom trawling. International guidelines on the identification of such vulnerable areas were published by the Food and Agriculture Organization of the United Nations (FAO) in 2009. Following these guide-lines, deep-water sponge grounds meet the criteria of being vulnerable marine ecosystems on a number of levels:

- they are limited to discrete areas with suitable environmental conditions;
- they support high biodiversity of other species;
- they are fragile and unlikely to recover from trawl damage;

■ they are slow-growing, long-lived and form structurally complex habitats.

However, while UNGA Resolution 61/105 provides a mechanism for states and regional fisheries organizations to prevent damage from bottom trawling, the effectiveness of this is currently limited by a number of factors. For example:

■ there remains uncertainty over the formal definition of a vulnerable marine ecosystem;
■ current guidelines on the level of sponge bycatch needed to require a fishing vessel to move on to a different area can be as much as 800 kg; there is growing consensus that this limit is too high;
■ guidelines do not currently consider the rate of bycatch, which is important given the highly variable geographic distribution of sponges;
■ upon encountering a vulnerable marine ecosystem, vessels are required to move on 2-5 nautical miles, which may not be far enough to reduce the spread of trawl impact to nearby habitats.

The conservation of sponge grounds may also be achieved through the Convention on Biological Diversity (CBD), in two ways. The first is the target to establish a global, representative network of marine protected areas by 2012, adopted by the Parties to the Convention in 2006, which should include representation of sponges. Secondly, deep-water sponge grounds meet several of the criteria adopted by the CBD in 2008 to identify ecologically and biologically sensitive areas of the open ocean and deep seas (including areas beyond national jurisdiction). These criteria are being used to support countries' identification of areas in need of improved management or protective measures, including marine protected areas, but the process is still in its infancy.

While there are currently no known marine protected areas that have been created explicitly to protect deep-water sponges, there are some examples of successful sponge conservation at the regional level, particularly the establishment in 2009 of several fishery closures by the Northwest Atlantic Fisheries Organization (NAFO) in response to UNGA Resolution 61/105, to protect sponge grounds off Atlantic Canada. Furthermore, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and the New Zealand government have adopted far more precautionary move-on rules than those currently provided in UNGA Resolution 61/105. Such precautionary measures may be more effective, especially in the case of New Zealand where these rules are combined with a representative network of closed areas.

These examples of successful deep-sea sponge management and conservation are encouraging, but there is much more to do. There is a clear need to bring the research community together to focus efforts on understanding deep-water sponge grounds and to provide the funding and infrastructure needed for this work. Given the expense and technically challenging nature of such research, strong collaborations and international partnerships should play an important role, including transfer of expertise and infrastructure from developed to less developed nations. Efforts to improve fishery observer coverage and gather information on sponge ground distribution from fishers should be increased.

Finally, and perhaps most importantly, there is a great need to improve awareness and understanding of deep-water sponge grounds. Without this, future generations may be denied the opportunity to explore, study and benefit from these important and fragile architects of the deep sea.

1. Introduction

Over the last decade there has been a resurgence of both scientific and public interest in sponge grounds, with increasing recognition of their importance to the biodiversity and functioning of marine ecosystems. Scientific research has revealed new insights into how deep-water sponges provide habitat for many species and influence biodiversity (Klitgaard 1995). Uncertainties over the current ecological state of sponge grounds, coupled with significant gaps in our knowledge of their global distribution, have also caused great concern among regional, national and international agencies. This has largely been in response to the threats posed by deep-water bottom trawling. Large habitat-forming deep-water sponges are particularly slow-growing, and these long-lived creatures could take many decades – probably several human generations – to recover, if at all (Klitgaard 1995).

The wider availability of deep-sea survey and sampling technologies, including remotely operated and autonomous underwater vehicles, is now allowing the first detailed observations of deep-water sponges in their natural habitats. The widespread perception that sponges are 'simple' and 'primitive' in their functioning is being overturned as the complexity of their biology and ecology is revealed. Many different kinds of deep-water sponge

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BOX 1.1: DEFINITION OF SPONGES

The Phylum Porifera (Grant 1836): 'Sessile metazoans with a differentiated inhalant and exhalant aquiferous system with external pores, in which a single layer of flagellated cells (choanocytes) pump a unidirectional water current through the body, containing a highly mobile population of cells capable of differentiating into other cell types (totipotency) and conferring a plasticity to growth form, and with siliceous or calcitic spicules present in many species.' (From Hooper *et al.* 2002.)

BOX 1.2: DEFINITION OF 'SPONGE GROUNDS'

Aggregations of large sponges that develop under certain geological, hydrological and biological conditions to form structural habitat. Sponge-dominated habitats have variously been called sponge beds, sponge fields, sponge accumulations, sponge grounds, sponge associations, sponge mass occurrences, ostur and sponge reefs. These terms are ambiguous, although the last three are to some degree defined in the literature. In this report we will adopt the term 'sponge ground' and refine this broad term with reference to the sponge species dominating in body size and abundance, and also often by the accumulation of its skeletal remains on the seabed.

Figure 1.2: Illustration of the biological structure and skeleton of some glass sponges (Hexactinellida). *E. Haeckel, Kunstformen der Natur 1904.*

grounds have been explored, mostly at high latitudes, including glass (hexactinellid) sponge reefs off the coast of British Columbia, western Canada. Carbon dating techniques have revealed that these reefs have been growing for up to 9,000 years and geological records show that these sponges have existed for many millions of years, making them true living fossils (Conway *et al.* 1991).

The sponges (Porifera) form one of the most ancient animal groups on the planet, with a fossil record reaching back to the Cambrian, 580 million years ago. The sponge body is multicellular, comprising several cell types with different functions. Sponges have no true tissues or organs, but are considerably more differentiated than single-celled organisms (protozoans). Despite their relatively simple structure the group is highly diverse, comprising around 8,000 present-day (or extant) species, an estimated 7,000 undescribed species and hundreds of fossil species (Hooper *et al.* 2002).

Apart from 150 freshwater species, sponges are a marine group and are found in all the oceans and at all depths, including at depths greater than 8,000 m. The number of species described to date is highest in tropical shelf areas, decreasing toward polar regions and with greater depth on the continental slope. Most species live on hard substrata like rock, gravel and coral reefs. A small number are soft-bottom dwellers, and have special arrangements to keep them above the muddy surface, such as a stalk, a basal tuft or a fringe along the lower edge of the body.

Sponges are highly effective filter feeders, both in terms of the size spectrum of particles they can catch and the volume of water they can filter. Their filtering system is a complicated interior arrangement of canal-like structures – the unique hallmark of this group. Different subgroups of sponges have evolved their aquiferous canal system in different ways, the most surprising being a reduction of the filtering capacity in favour of a carnivorous mode of life (Brusca and Brusca 2003).

This report summarizes the recent growth in understanding of deep-sea sponge habitats to brief policy decision makers, environmental stakeholders and the public about the central issues and our existing state of knowledge. It presents key concepts, current thinking and approaches for management and conservation as well as providing recommendations for appropriate measures that can be taken to protect the most vulnerable deep-water sponge habitats.

2. Research

Most of the 20th-century information gathered on deep-sea sponges is centred in the Atlantic Ocean, but even here datasets are sporadic and infrequent. However, they provide valuable information about the richness of sponge life in bathyal waters (200-2,000 m depth) and build on pioneering historic oceanographic expeditions. In the 19th century the ships HMS *Porcupine*, *Lightning* and *Challenger* used dredging techniques to collect deep-sea samples, with the *Challenger* expedition (1872-76) providing particularly detailed records of sponges. The samples collected during the cruises of HMS *Porcupine* are described extensively by Carter in his reports of 1874 and 1876. These cruises marked the birth of oceanography as a science and were fundamental in showing that animal life could persist at depths greater than 600 m.

Other cruises sampling deep-sea life at around the same time as HMS *Challenger* included, amongst others, the Norwegian cruises of Michael Sars, which also reported marine life at great depths. Amongst the many different sponges hauled from the deep during these Norwegian expeditions, *Cladorhiza* must have been one of the most startling in appearance. To modern eyes, this sponge resembles a 'space-age microwave antenna'; in the 19th century they were observed to be 'sponges with a long stem ending in ramifying roots, sunk deeply in the mud. They act as a bush-like seafloor cover lying over extensive tracts of the sea bottom' (Alexander Agassiz in Heezen and Hollister 1971).

TECHNOLOGY

The vision of building a diving vessel that could go to the greatest depths of the ocean was first initiated by pioneers like Auguste Piccard. A so-called bathyscaph, FNRS-3, built for underwater exploration was supported by the French navy. In February 1954, FNRS-3 reached 4,049 m in the mid-Atlantic, although it had no gear with which to collect samples. The year before, US-Italian bathyscaph *Trieste* reached the near-deepest spot in the Mediterranean, achieving 3,167 m, and in January 1960 off the coast of Guam it sealed a record of 10,916 m. But despite these exciting advances, the bathyscaph was still cumbersome and difficult to operate in remote areas far from its home base.

After the success of *Trieste,* the USA created an even more advanced submersible named *Alvin*. The submersible had a remote-control arm with a claw for sampling and a propeller for horizontal propulsion. By the 1970s, improvements in deep-sea engineering meant that higher strength steel and titanium pressure hulls permitted *Alvin* to reach depths of more than 3,000 m. Geological mapping in the Gulf of Maine off the northeast coast of North America and the discovery of deep-sea hydrothermal vents was a piece of groundbreaking research that *Alvin's* high manoeuvrability and strength enabled it to achieve. Since then, many innovations have followed, particularly in the use of remotely operated vehicles or ROVs. Indeed, the most recent vehicle to visit the greatest depths of the ocean was the *Nereus* hybrid ROV from Woods Hole Oceanographic Institution (USA), which dived to 10,902 m in May 2009. Equipped with sophisticated cameras and sampling devices, *Nereus* and vehicles like it illustrate the potential we now have to explore and understand the deep sea and its ecology as never before.

Carrying out deep-sea research requires rigorous planning combined with technical expertise. Recent advances in deep-sea sonar and submersible technologies have been hugely significant in developing a greater understanding of deep-water sponge fields. However, before these technologies emerged, historical data from fishermen's charts provided the foundation for what was known about deep-water sponge grounds and coral banks that lasted for more than 100 years.

The discovery of areas with high abundances of sponges dates back nearly 150 years. At that time investigations were made with early dredges and trawls, and only occasionally reached depths of more than 1,000 m. The early records most often came from localities widely scattered on a long-distance expedition route, and therefore precise positioning is rarely available. With better mapping of near-coast and slope areas and the establishment of national sea territories, there followed an interest in regional investigations typically based on a grid of sampling stations. A need for better knowledge of local resources arose when fishery limits were established and, over time, extended to greater distances offshore to reach present-day limits at 200 nautical miles (or in some cases 400 nm). Many nations now run regular multidisciplinary or bottom trawl fish sampling

Figure 2.1: Distribution of *Geodia* and *Stryphnus* sponge grounds in the Northeast Atlantic. *Ole Secher Tendal.*

Figure 2.2: Survey-trawl coverage between 2005 and 2008 in the Canadian exclusive economic zone (EEZ) (red line). Different trawl types were used down to depths of 1,450 m and different colours refer to different surveying institutions. *ICES 2009.*
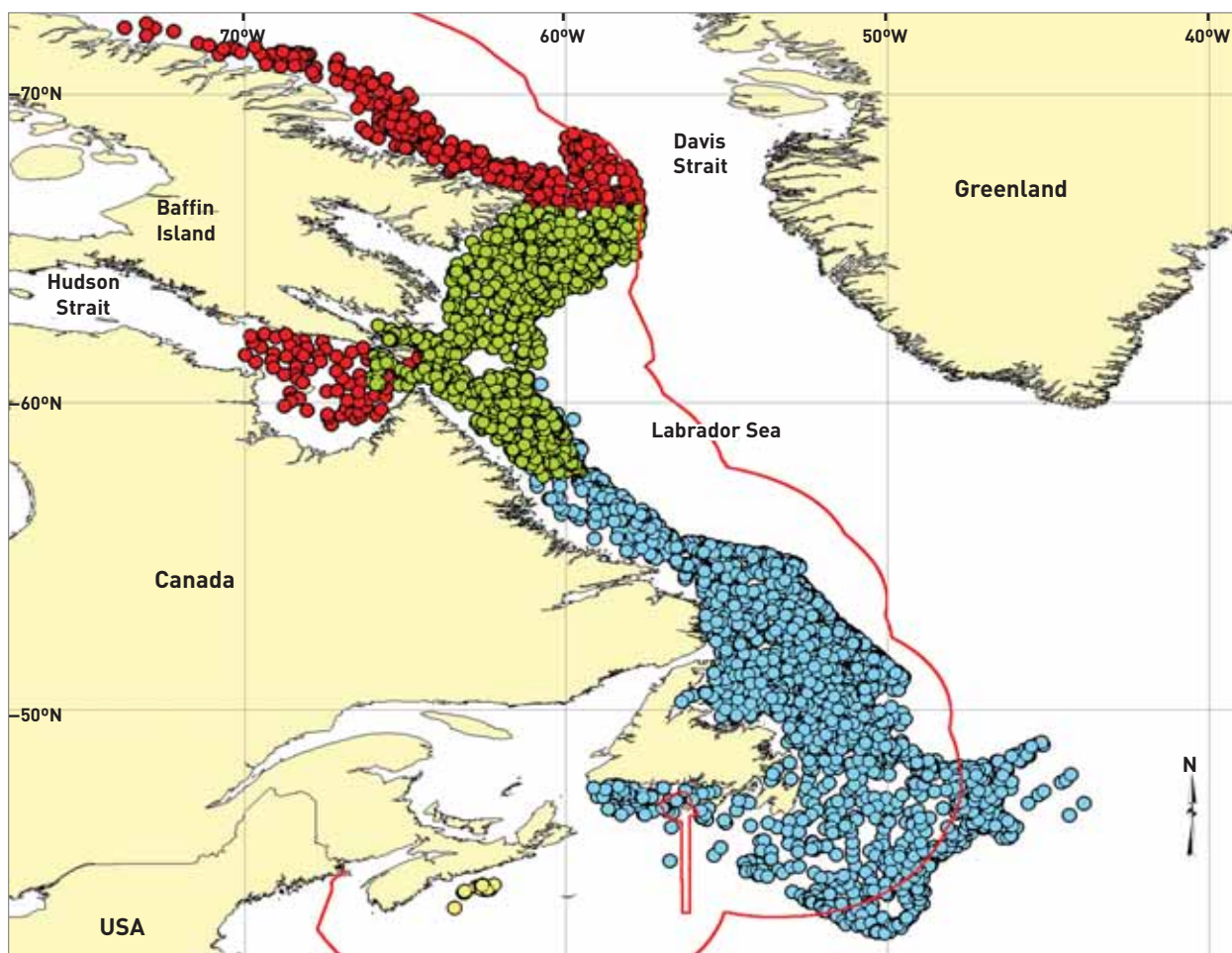
surveys in their fishery areas along annually repeated transects. These surveys may also record bycatch information including data on sponges, corals and echinoderms, amongst others. Examples of recent mapping based on trawling efforts are shown in Figures 2.1 and 2.2.

The recent BIOFAR programme (on marine benthic fauna of the Faroe Islands) provided important insights into the Northeast Atlantic. The region's deep-water sponge ground or 'ostur' distribution is defined in two arc-shaped bands related to the flow paths of the Norwegian Atlantic Current and the Irminger Current (Klitgaard and Tendal 2004). The bands are not continuous but instead form a series of patches influenced by local topography. The majority of sponge grounds are found on the shelf plateau near the shelf break, as well as along slopes and ridges.

Fishing records alongside scientific research cruises using classical sampling approaches (e.g. dredging, trawling, grabbing, box coring) have led to our present-day understanding of sponge distribution and biodiversity. Scandinavian studies

(Klitgaard and Tendal 2004) have integrated otherwise fragmentary information to address key issues of taxonomy, biology and observed distributional patterns. With a substantial collection of evidence in support of their key role in deep-sea ecosystems, it is now important that additional research is undertaken so that the vulnerability of sponges to both global climate change and human activity can be assessed and their potential recovery explored.

Sampling datasets for deep-sea sponges are still relatively scarce and are restricted in their geographical locations. Most of the available data are from the Atlantic and North Pacific, with very few records from other parts of the world's ocean, notable exceptions being the Southwest Pacific (New Caledonia), eastern Australia and New Zealand (Schlacher *et al.* 2007). In contrast, because their skeletal remains can form distinctive reef structures, data on cold-water corals are more abundant, although again large areas of the global ocean remain very poorly known. Cold-water coral reefs can be identified with multibeam echosounder surveys and then surveyed visually using deep-sea camera systems, manned submersibles or remotely operated vehicles. This has allowed cold-water coral habitats to be observed *in situ* so that not only can they be mapped and samples be taken, but ecological roles and biological processes can be studied (Roberts *et al.* 2009b).

REMOTE SENSING

The first permanent photograph was an image made in 1825, and within just 15 years people began experimenting with remote sensing by tethering cameras to balloons to help map local topography. In the 1960s the first images of planet Earth were taken from space, helping to crystallize our view of Earth as a discrete system and promoting environmental movements around the world.

In the marine environment light travels only short distances whereas sound waves resonate over great distances. Thus marine remote sensing usually relies on acoustic techniques which grew out of military sonar applications in the Second World War (see Fosså *et al.* 2005).

MAPPING AND ACOUSTICS

Acoustic mapping has become an efficient method to map and survey the seabed and the habitats that form upon it. Although the use of acoustic mapping is limited for deep-water sponge grounds because they tend to absorb sound waves, certain forms of sponges, such as the hexactinellid 'glass' sponge reefs off the coast of Canada, have been successfully surveyed using this approach. Techniques used include side-scan sonar, seismic profiling and bathymetric surveys derived from multibeam echosounders.

The first of these, side-scan sonar, can map a large area of seabed relatively quickly and at certain frequencies sonograms can depict characteristics in the uppermost deposits of the seafloor. The sonar 'towfish' is typically towed behind the vessel, and transducers in the towfish transmit soundwaves from each side and receive the reflected signals. An image is produced as an echogram and, typically, where higher sound frequencies are used, a higher mapping resolution will be obtained. However, using this system is not without its challenges, and there is a trade-off between the area mapped in a given time and the resolution of the seabed features within the defined area (Kenny *et al.* 2003). This means that side-scan sonar is often used in conjunction with other, wide-area mapping methods and is frequently used to help identify particular objects on the seafloor.

Seismic profiling uses low- and intermediate-frequency sound pulses of approximately 10 herz to several kilohertz emitted from a system operated by survey vessels. The sound pulses penetrate the seabed and are reflected from interfaces of different densities or acoustic impendence. These reflections or echoes are received by hydrophones that are either towed by or mounted in the hull of the vessel. Seismic data and profiling of the sub-seafloor generates broad-scale information in two-dimensional form about the geological setting surrounding deep-water sponge grounds that would be unavailable through other systems of remote sensing. However, this technique does not provide detailed local habitat mapping information and cannot confirm the definite existence of sponge grounds or cold-water coral reefs, or estimate their horizontal extent.

Multibeam echosounders use a wide range of frequencies, often employing more than a hundred beams transmitted at different angles from the same transducer unit. They create

Figure 2.3: Diagram showing how a multibeam echosounder sonar would operate from a scientific research vessel. *C. Wienberg/MARUM, Germany.*
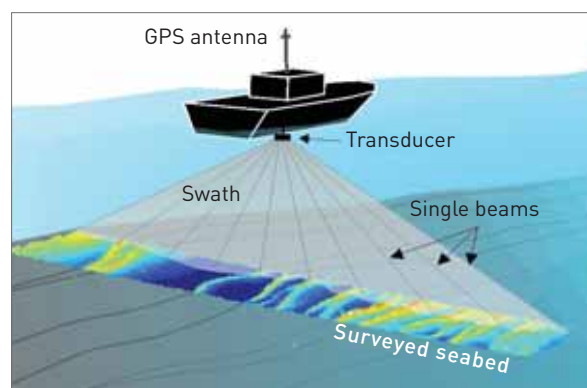
a fan which travels perpendicular to the direction of the survey vessel, and the angle of this fan (the swath angle), along with the water depth, determines the width of the corridor mapped (Figure 2.3). This process produces shaded-relief topographic maps which are very valuable in helping to identify marine habitats and the wider topographic context in which they are found.

The strength of the reflected echoes from multibeam echosoundings can also be extracted and used to create 'backscatter' maps of the seabed that contain information on sediment types (Kenny *et al.* 2003). Echo strength depends on the hardness, roughness and homogeneity of the seabed. The combination of shaded-relief bathymetry and backscatter maps, together with slope analysis, can help to understand relict and current processes including erosion and deposition. Recent advances have made it possible to display the acoustic survey data collected in real-time whilst at sea by using software packages, such as Olex (Ocean DTM), which allow for the immediate identification of potentially important seabed terrain for deep-water sponges. (It is important to note that as yet it has not proved possible to detect deep-water sponge grounds using purely acoustic methods, apart from the large sponge reefs off the west coast of Canada, see Case study 1.)

SUBMERSIBLES

The use of *in situ* techniques such as remotely operated vehicles (ROVs) and submersibles allows detailed understanding of small areas of seabed. Therefore these tools are most effective when used alongside wide-area habitat maps based on acoustic datasets, such as multibeam bathymetry and backscatter data. This may, for example, allow observations made during submersible surveys to

Figure 2.4: A Johnson-Sea-Link manned research submersible in action. *Florida Atlantic University/HBOI.*
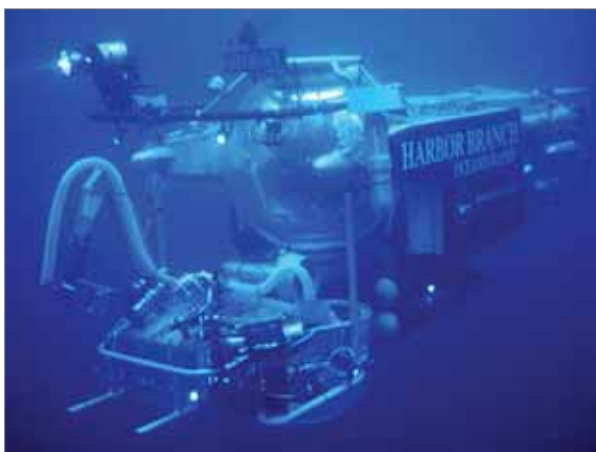
be extrapolated beyond the limited track covered by the visual survey.

The first manned research submersibles appeared in the 1960s as part of scientific and technological advancements catalysed during the two World Wars. They allowed scientists to observe and survey deep-sea animals in their natural habitat on the seabed for longer periods of time than ever before. They also allowed inhospitable environments such as mid-ocean ridge and vent communities to be explored. In 1964, the submersible *Alvin* was used to investigate cold-water coral mounds on the Blake Plateau off South Carolina (USA). On the other side of the Atlantic, another manned submersible, *Pisces III,* was used to examine *Lophelia pertusa* coral colonies growing on Rockall Bank off the west coast of Scotland (Roberts *et al.* 2009b). Use of submersibles for surveying deep-water sponge grounds is relatively rare, although there has been a resurgence of interest in recent years. For example, the vast hexactinellid sponge reef complexes off the west coast of Canada have been surveyed using submersibles, revealing siliceous sponge reefs that were previously thought to be extinct. Their discovery enabled a greater understanding of fossil taxa and the process of sponge reef building. Direct observation from submersibles also revealed that these sponge reefs had been damaged over the past decade by bottom trawling (Krautter *et al.* 2001).

A survey of bioherms on the Pourtalès Terrace off the south coast of Florida used Johnson-Sea-Link (JSL) manned submersibles to explore the high diversity of Porifera, where 66 different taxa were identified. This method allowed benthic population densities and microhabitat associations of the individual species to be studied (Reed *et al.* 2005). The JSL manned submersibles, which have been used for biomedical sponge research since 1984 by the Harbor Branch Oceanographic Institution group in Florida, USA, provide platforms that enable researchers to go deeper, stay longer and visit unusual sites (e.g., steep walls, rocky bottoms and vent communities) that cannot be accessed using conventional methods. Sampling from these submersibles has allowed researchers to be more precise and selective in sampling than conventional deep-sea collection methods would allow. Some submersible systems now have the ability to maintain samples at ambient conditions of high pressure and low temperature. These vehicles go to increasingly greater depths, stay for longer periods of time and collect significant amounts of environmental data. With steadily decreasing funding for ship operations, manned submersibles have now reached a critical juncture between cost and logistical requirements. This has created a shift towards building a new generation of smaller, more sophisticated

submersibles that can be deployed from smaller research vessels (Adkins *et al.* 2006).

The advantage of manned submersibles is the degree to which the benthic environment may be examined in a 'natural sense' by a human observer, where the flat video monitors and lack of wide-angle vision opportunities associated with ROVs limit the perspectives of scientists. Of the few who have dived in manned research submersibles, almost all report the unique value of having personally visited the environments they have often spent a lifetime studying from the surface.

REMOTELY OPERATED VEHICLES (ROVs)

ROVs have developed since the 1970s, largely to serve the needs of industrial applications such as the offshore oil industry. They come in a diverse array of shapes and sizes and are normally designed for specific tasks. For scientific applications the trend has been towards vehicles with greater capacities for detailed visual survey, experimental manipulation and equipment deployment at increasing depths.

ROVs rely on a combination of visualization, propulsion, manipulation, sonar and navigation to produce high-quality data for sampling, mapping and ground-truthing (Orange *et al.* 2002). Increasingly, acoustic tools such as sector scanning sonars and multibeam systems are being mounted directly onto ROVs. Often as costly as manned submersibles and requiring considerable technical expertise, ROVs are useful for high-resolution imagery and investigation for the characterization of habitats and for observing processes *in situ*. They have been instrumental in giving researchers a deeper understanding of habitats which are otherwise both hard to reach and difficult to observe. The success of ROVs often depends on the quality of their support systems, such as precise underwater navigation and positioning techniques. Alongside ROVs, autonomous underwater vehicles (AUVs) and hybrid vehicles which can both act in tethered ROV and untethered AUV modes are becoming increasingly important in deep-sea survey and sampling.

Figure 2.5: The *Victor* remotely operated vehicle from the French marine research institution Ifremer. *J.M. Roberts.*

The importance of surveying and sampling deep-water sponge grounds using habitat mapping approaches linked to ROV surveys lies in their reduced impacts on the habitat being explored, unlike historic destructive sampling using deep-sea trawls and dredges. Finally, it is also important to note that sponge species can rarely be identified from visual information alone and that samples, such as those that can be taken and stored by ROV, are needed for microscopic examination.

3. Biology

Sponges are among the most ancient animal groups on Earth, with a fossil record reaching back to the Cambrian over 580 million years ago. Reef-building sponges were most widespread during the Late Jurassic, when siliceous sponges formed a vast sponge reef belt more than 7,000 km in length on the northern shelf of the Tethys Sea and the adjacent North Atlantic basins.

Four sponge classes are presently recognized, the extant Demospongiae, Hexactinellida and Calcarea, and the extinct Archaeocyatha, all dating back at least to the Early Cambrian (Hooper *et al.* 2002). More than 8,000 valid extant species have been formally described (van Soest *et al.* 2008: www.marinespecies.org/porifera), and it is predicted that another 7,000 species have yet to be discovered (Hooper *et al.* 2002). In addition, there are several hundred fossil species which need to be described or redescribed and then classified. Thus, despite great efforts from many sponge specialists reviewed in *Systema Porifera: A Guide to the Classification of Sponges* (Hooper *et al.* 2002), the classification of sponges at higher taxonomic levels, the phylo-genetic relationships between the classes and the relations to other Metazoa remain the subject of lively debate (Boury-Esnault 2006).

ANATOMY

The body form of a sponge is related to the interior arrangement of the aquiferous system (Figure 3.1), the skeletal configuration, the age of the individual and influences from the wider environment (e.g. water currents, food supply and substratum). For some sponges, especially at generic level, their shape is characteristic (meaning that it is shared by a number of species in that genus). Shapes can be difficult to define, and are described using simple, broadly applicable terminology, such as 'thinly encrusting', 'thickly encrusting', 'lumpy', 'globular', 'urn-shaped', 'funnel-shaped', 'fan-shaped', 'branching', etc.

A unique characteristic shared by all adult sponges is the interior aquiferous system of canals and flagellated chambers through which water is pumped. This water supplies food and oxygen and removes waste and reproductive elements. The walls of the aquiferous system form the internal cellular layer of the sponge body, consisting of cells called endopinacocytes lining the incurrent and excurrent canals. There are also choanocytes (flagellated cells which maintain water currents and extract food) lining larger or smaller chambers (choanoderm). The outer surface

Figure 3.1: Diagram illustrating patterns of seawater flow through three different sponge body structures: asconoid (a simple vase or tube shape); syconoid (with a pleated body wall); and leuconoid (with a network of chambers). *J. Berman, University of Wellington, New Zealand.*
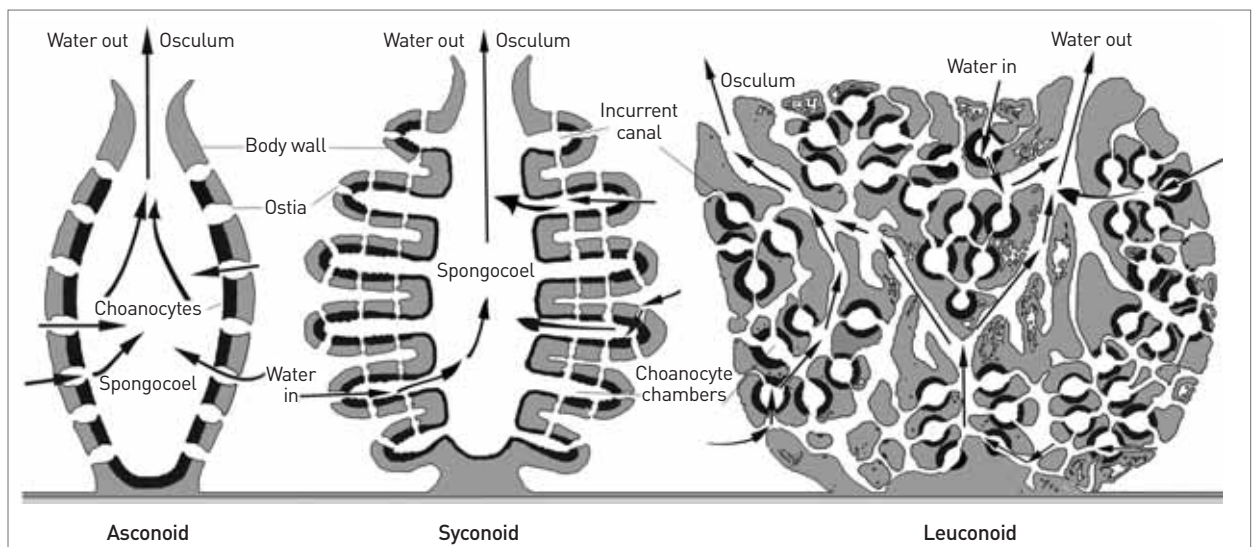
Figure 3.2: A few sponges are carnivorous. They have a reduced canal system and are able to catch small prey (typically crustaceans) on protruding spicules. These species can be numerous in certain places and some are often found in or near sponge grounds. This image shows the carnivorous sponge *Cladorhiza gelida* (about 40 cm high) colonized by a prominent crinoid (feather star). In the background is another carnivorous sponge, *Chondrocladia gigantea*. The photograph was taken in the Faroe-Shetland Channel in October 2009 at about 1,000 m depth. *D. Jones, The Serpent Project (www.serpentproject.com).*

of a sponge is formed by a layer of thin, epithelia-like cells, the pinacoderm. While the Demospongiae and Calcarea have discrete individual cells, the Hexactinellida have their pinaco- and choanoderm composed by syncytia, large cell-like structures containing many nuclei. These layers are considered to be particular to the sponge body plan and differ from the entoderm and ectoderm of other multicellular animals.

Between the aquiferous system and the outer pinacoderm surface is a more or less well developed gelatinous layer, the mesohyl, with functionally different cell types and skeletal elements. The skeletal elements are produced by some of the cells and differentiated into protein fibres (spongin), collagen fibres and mineral 'needles' called spicules. The skeleton supports the canal system and the soft parts of the sponge, and forms many variations with respect to both its form and the amount and arrangement of organic and inorganic elements. Finally, although sponges are multicellular, they do not possess true tissues and organs (this means that sponges do not have a muscular or nervous system).

Most sponge cells are mobile and some show totipotency, meaning that the individual sponge cell has the potential to transform itself into another cell type and play another role. Archaeocytes are large amoeboid totipotent cells regulating the relative number of cell types in the sponge. Choanocytes have a rounded cell body with a long flagellum (tail) and a filtering device around the base of the flagellum. Amoebocytes perform different functions in connection with digestion, storing food reserves, waste discharge and reproduction. Collencytes secrete collagene and perform a similar function to connective tissue cells. After catching particles from the filtered water current, the amoebocytes wander within the sponge body digesting the food, delivering nutrients to other cells (notably egg cells) and discharging waste into the excurrent canals. Some amoebocytes receive the particles caught by the choanocytes and digest them. Finally, sclerocytes produce the mineral spicules that are so important to sponge skeletal structure.

Figure 3.3: A *Geodia barretti* sponge. *P. Mortensen, Institute of Marine Research & MAREANO project (www.mareano.no).*

Figure 3.4: A habitat-forming sponge ground off the coast of Norway. *P. Mortensen, Institute of Marine Research & MAREANO project (www.mareano.no).*

Figure 3.5: Sponge filtration shown by allowing giant barrel sponges (*Xestospongia muta*) in the Florida Keys to take up a fluorescent dye. This dye can be seen leaving the sponge in a strong water current from the sponge oscula. *C. Martens and P. Gibson, University of North Carolina at Chapel Hill.*

The choanocytes, which in most sponges are concentrated in spherical, oval or finger-shaped chambers in the canal walls, pump water through the canal system. The water enters the sponge through many small surface pores (ostia) and is led through fine canals to the flagellar chambers. From here it flows through successively larger canals to a few large openings in the sponge surface (oscula), where it leaves the sponge. In effect, the water is taken in slowly close to the sponge surface, and leaves the sponge under some pressure, avoiding any recirculation (Figure 3.5).

SPICULES
Other than a few exceptions without a skeleton, the vast majority of species of the classes Demospongiae and Hexactinellida form spicules of silica (SiO_2) to support the soft body parts formed by the mesohyl, canal system and cells. Sponges of the third class, Calcarea, produce calcium carbonate ($CaCO_3$) spicules. In most demosponges the

silicious spicule skeleton of the mesohyl is combined with spongin, a fibrous collagenous substance, allowing the formation of a great variety of skeletal structures and body forms in the group. Spicules and their role in skeletal configuration are the main taxonomic characteristics used to identify sponge species and have been the subject of much descriptive research (Figure 3.6).

Silicon uptake is an important process for sponges, both in relation to the general growth of individuals and to ensure that they can generate a sufficient density of spicules. It seems to be an energy-demanding process, since starving sponges and those in reproductive phases produce fewer spicules than under normal conditions (Frølich and Barthel 1997). The retention of silica by sponges can be so significant that it alters local geochemical conditions: spicules from dead sponges become incorporated in seabed sediment and influence both the composition and structure of the sedimentary record (Maldonado *et al.* 2005), and the distribution of other animals as well (Bett and Rice 1992). As some hexactinellid sponges lay down more silica per unit biomass than many demosponges, they are probably most common in silica-rich environments such as the deep sea, Antarctica and regions of local upwelling (Barthel 1995; Uriz *et al.* 2003).

CHEMICAL ECOLOGY
As sessile animals, sponges cannot move to avoid predators or other organisms competing for space, and this dual pressure of predator defence and spatial competition has been a critical evolutionary driver. Sponges have developed a bewildering array of secondary metabolites (Thoms and Schupp 2008), making them one of the most prolific sources of secondary metabolites in the ocean, and accounting for 50 per cent of natural products found in marine invertebrates (McClintock and Baker 2001).

Sponge chemical defences vary both temporally and spatially. Until very recently, it was generally believed that the potency of chemical defence in sponges and other marine invertebrates was higher in the tropics than at temperate latitudes (Hay 1996). However, new research found a similar potency of chemical defence in sponges from a tropical latitude in the Indo-Pacific (Guam) and a temperate latitude in the Mediterranean (Spain) (Beccero *et al.* 2003). Thus, contrary to conventional wisdom, the potency of chemical defence in sponges was equal at both tropical and temperate latitudes (Thoms and Schupp 2008).

Secondary metabolites from deep-sea sponges include compounds such as triterpene glycosides that play a wide range of roles not only in defending the sponges from

predation and spatial competition, but also in supporting symbiotic fauna. It has been suggested that some of these chemical metabolites may be 'evolutionary baggage' with no specific role, but this probably accounts for only a small proportion of the compounds that sponges produce (Wang 2006).

Sponges are sophisticated in using their chemical processes, and are selective in their filtering of trace nutrients, metals, sediment and detritus in order to metabolize the most useful ingredients for their survival. For example, a system of cell coordination in sponge tissues facilitates the incorporation of foreign material such as quartz (in sand grains), used in the production of collagen (Cerrano *et al.* 2007).

Medical researchers conducted immune-system studies by using antibodies against the enzyme lysozyme to identify how sponges use it. What transpired was that the sponge targeted it towards potentially harmful extracellular bacteria while protecting the bacteria that are symbionts and use the sponge as a host (Thoms and Schupp 2008). These reactions were studied using immunofluorescence, and revealed how sponges distinguish finely between different bacterial organisms. The chemical ecology of sponges is of special interest in medical studies of tissue metabolism and evolutionary biology and has become a valuable source of chemical compounds for the pharmaceutical industry.

Other studies have also shown how the chemical reactions and compound conversions observed in sponges can both give a deeper understanding of sponge biology and be used in medical and other applications. For example, chemical secretions from sponges in the Caribbean were found to contain antifungal activity (limiting fungal attack in the field) that could help overcome problems of resistance to conventional fungicides in the paper industry and to treat common fungal infections in skin, hair and nails (Gaspar *et al.* 2004). Further, the process of spicule formation in which amorphous silica is synthesized by the enzyme silicatein has helped establish that the process begins intracellularly and is completed extracellularly, closing a contentious debate (Schröder *et al.* 2007). This latter study has also outlined key

Figure 3.6: Example of sponge spicules from *Paratimea* sp. viewed through the microscope. This image shows long spicules (up to 2 mm in length) along with smaller star-shaped microscleres known as asters. *B. Picton, National Museums Northern Ireland.*
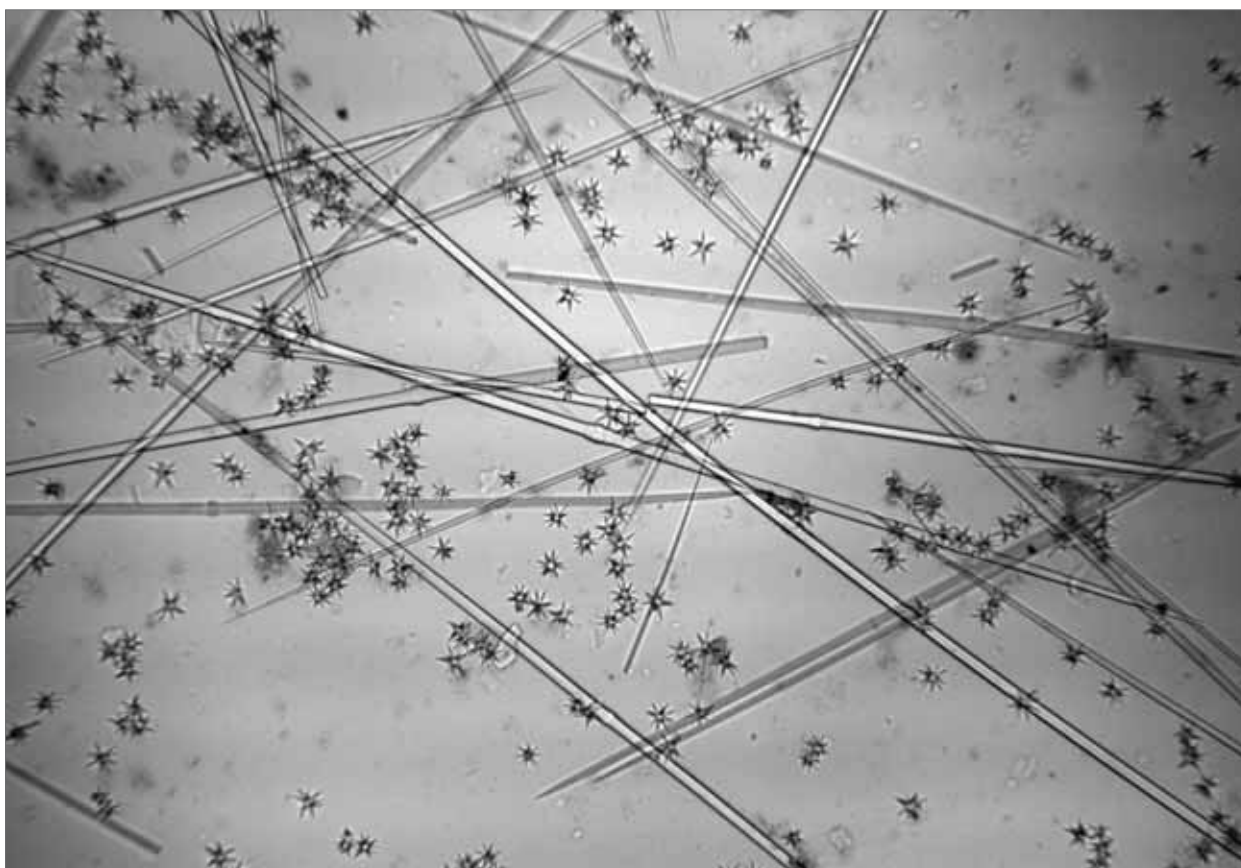
enzymes that could be synthesized in the laboratory and used for the surface modification of biomaterials and the encapsulation of biomolecules, amongst other applications.

Although pharmaceutical companies have been successful in discovering biologically active compounds, our understanding of their wider ecological significance is in its infancy. Major uncertainties remain; for example, are these compounds synthesized by the sponges themselves, by microorganisms associated with the sponges or by an interaction between the two?

Recent leaps in knowledge about deep-sea sponges in the midst of a revival of interest has fostered emerging taxonomic and geographic trends in chemical ecology and its applications, as well as in the biology of these ubiquitous metazoans as a whole. Integrative research has certainly helped to consolidate current knowledge, and it is clear that further exploration of the biology, chemistry and ecology of sponges can only move this research field forward.

GROWTH, SIZE AND LONGEVITY

Throughout their lifecycles, sponges undergo growth, shrinking, division and fusion, and have extraordinary regenerative capabilities. These are in part responses and strategies to deal with substratum competition and the environment surrounding them (Garrabou and Zarbala 2001). In the 1980s it was observed that growth patterns in sponges were irregular over time, and that rates of tissue regeneration were far more rapid than undisturbed growth rates (Ayling 1983; Hoppe 1988). In a more recent and detailed study in British Columbia, Canada, the average growth rate for temperate deep-water hexactinellid sponges was found to be 1.98 cm per year. In contrast, the rates of tissue regeneration were up to 20 times higher (Leys and Lauzon 1998). However efficient, regeneration is dependent on many intrinsic and extrinsic factors, and requires significant resource investment by the sponge, which consequently compromises sponge growth, reproduction and defensive capacities (Henry and Hart 2005).

Individual sponge growth rates are variable due to the organism's ability to change its characteristics in response to its environment (phenotypic plasticity), so body size is not a reliable indicator of age. Thus, age is determined by carbon and strontium isotopic dating in both living and fossil sponge specimens (Xiao et al. 2005). The extraordinary longevity of some sponges has been demonstrated, with some sponges hundreds of years old (Leys and Lauzon 1998). Therefore the capacity for sponges to provide ecosystem services such as habitat formation, nutrient cycling, trophic structuring and energy exchange must be stated in terms of long ecological

timescales. The implication of these findings is that damage to or death of these often long-lived creatures will take, at a minimum, several human generations to regenerate to their current standing, making damage irreversible over several human generations.

REPRODUCTION

Most sponge species are hermaphrodites or, more rarely, egg and sperm cells are produced by separate individuals (dioecious). Patterns of sexual reproduction vary from one group to another, but in general they are poorly known. Egg cells originate from transformed archaeocytes or choanocytes. Sperm is formed from single choanocytes or whole choanocyte chambers lowered from the canals into the mesohyl. Ripe spermatozoa are released from the mesohyl into the excurrent canals and carried out with the water through the osculae. Thus the spermatozoa must be transported to other sponges within reach by local water currents before the spermatozoa die (Spetland et al. 2007). Eggs are either embedded in slimy strings and released into the surroundings where they are fertilized by the sperm, or retained in the mesohyl and fertilized internally. However, during internal fertilization, which is by far the most common, spermatozoa enter the sponge with the incurrent water and are caught by choanocytes, which lose their flagellae and collars, migrate into the mesohyl and transport the spermatozoa to the egg cells.

Most sponge species are viviparous, with larval development occurring in the maternal mesohyl. Cleavage of the egg is total (the whole egg divides, rather than forming a separate yolk and embryo), but with great variation in developmental pattern between sponge groups. Division and differentiation of cells is appreciable and leads in the majority of cases to a solid, large parenchymella larva that settles a few days after leaving the sponge (Fell 1974; Ruppert et al. 2004). In oviparous sponges and some viviparous species, cleavage of the fertilized egg is also total, with all cells of the embryo of about the same size, and leads to a small coeloblastula larva. Cells develop and differentiate during the short free-swimming stage (one to three days), after which the larva attaches to the substratum and develops into a juvenile sponge.

Many sponge species also reproduce asexually, producing genetically identical but somatically distinct individuals (clones). Clonal reproduction can be induced intrinsically, but probably of more interest for conservation and protection measures is the effect of anthropogenic influences on sponge cloning. The use of mobile fishing gear is particularly destructive to sponges, which can snap or fragment upright and encrusting sponges. Demographically, this increases

the number of individuals (providing they survive) in that population, but reduces both the average sponge size and genetic diversity, making the sponges more susceptible to disease or inbreeding.

Overall, the variety of reproductive methods in sponges is so vast and complex that the strategies of particular species and groups are only just emerging. The ability to be sexual or asexual, viviparous or oviparous and to have gametes of both sexes gives sponges some of the most plastic strategies for reproduction. Studies to date mostly concentrate on a particular element of the reproductive process for a specific species (e.g. Ereskovsky 2000; Lanna *et al.* 2007; Gonobobleva 2007). However, two recent studies have examined reproductive processes more clearly. From a strategic point of view, it is possible to identify some of the reproductive challenges that deep-water sponges face as distinguishable from those of sponges in shallow–water habitats.

In the first of these studies, Maldonado and Uriz (1999) drew attention to the strategic role of deep-water sponge reproduction. They recognized that the fragmented habitats characteristic of the deep sea often produce apparently discrete, spatially separated animal populations. They suggested that for sessile species including sponges, it is important that they have the capacity to disperse and colonize new areas. As sponge larvae are only dispersed over short distances it is not clear how this is achieved, although ocean currents clearly play an important role. It is also possible that sponge fragments (clones) may be transported by ocean currents to settle and colonize new areas. A final surprising finding from this study was the high genetic variability within a sponge population, indicating contributions from both asexual and sexual reproduction.

In the second study, Spetland *et al.* (2007) examined the dense communities of *Geodia barretti* (Bowerbank, 1858) found in many Scandinavian fjords. This species undergoes gametogenesis in annual cycles. As a dioecious and oviparous sponge, *G. barretti* has either spermatic cysts or oocytes that are clustered within its mesohyl. The annual reproductive season is triggered by phytoplankton blooms in the fjords and gametes are released in early summer at the end of these blooms. This event is therefore synchronous with peaks in organic matter sedimentation that occur as a result of the blooms, with each population exhibiting a ʼspawning phaseʼ with gametes being released simultaneously. More research on the reproductive cycles of sponges of the Order Astrophorida, such as *G. barretti,* are necessary to understand population dynamics and the potential for periodicity in the chemical ecology of astrophorids.

For most deep-water sponge species that experience seasonality in food supply, reproduction may be seasonal and occur during the summer months (January to March in the southern hemisphere). A rise in water temperature and/or primary production are key triggers for egg production (oogenesis), which runs through a multi-stage process of development, from oocytes, a mixture of zygotes and larvae, to a larva-dominated spawning ground (Lanna *et al.* 2007). In the deep sea, large habitat-forming sponges are likely to be ʼK-strategistsʼ, with long lifespans and low reproduction rates and reproductive efforts, coupled with adaptation to a specialized ecological niche (Ereskovsky 2000). Further, a case study of *Pheronema carpenteri* population dynamics off the coast of Morocco by Barthel *et al.* (1996) indicated that shifts in age can occur across a bathymetric range so that the sponge grounds appear to be ʼwanderingʼ. Spicule mats, which form when an individual sponge dies and its skeleton disintegrates, were found below a maximum abundance band of smaller and younger individuals higher along the slope. This was taken to show that the population of *P. carpenteri* had effectively relocated or ʼwanderedʼ to a slightly shallower depth. More studies are needed to examine whether other sponge grounds show similar capacities. Encouraging more investigation into how particular deep-water sponge species reproduce will help to define their ecological niches and therefore predict their likely distribution on both regional and global scales.

DISEASE

The study of sponge disease first began when epidemics that periodically affected commercial sponge populations were discovered. For example, early reports in the mid-1880s of diseased sponges in British Honduras received much attention and speculation about the mechanisms governing the spread of the disease, such as transmission by water currents (Smith 1941). Later, after observations of sponge disease in the Indian Ocean and eastern Gulf of Mexico, fungal infection was also cited as a possible source (Lauckner 1980).

In the 20th century, surveys of deep-water ʼwildʼ sponge populations have revealed other possible causes of disease. Rützler (1988) investigated diseased specimens of the mangrove species *Geodia papyracea*, which had difficulty balancing the number of cyanobacterial symbionts within its tissues. This imbalance was caused by the rapid multiplication of cyanobacteria at a rate faster than the sponge archaeocytes could remove the excess. This caused destruction of the sponge host tissue, which may have involved the secretion of toxic substances from the cyanobacteria. The response of *G. papyracea* to this disease paralleled that observed in other species, i.e. producing a spongin

barrier of collagen consistency and sloughing off tissue that had decayed.

Evaluating the role of disease in sponge population dynamics has proved difficult since sponge skeletons disintegrate into spicule mats after death. Smith (1941) observed diseased sponges of medium size disintegrate within just three weeks. However, studies of sponge community dynamics and the influence of disease amongst coral reefs in Florida and the Caribbean are now giving a better understanding of these processes in shallow, tropical ecosystems (Wulff 2007). These studies build on earlier work, which suggested that keratose sponge genera such as *Spongia* and *Hippospongia* are especially vulnerable to pathogen infection in warmer waters because they evolved in cooler, deeper seas (Vicente 1989).

It also seems that climate change may alter the vulnerability of sponge grounds to disease. Periodic episodes of mass sponge mortality related to higher water temperatures have been recorded in the northwest Mediterranean and in Scandinavian fjords. In the latter case, large-scale necrosis linked to local seawater warming has recently been observed in populations of *Geodia barretti* (T. Lundälv, pers. comm. 2009). The last major event in the northwest Mediterranean occurred in July 1999. A general warming of 2-3ºC at the sea surface was observed, with this warming reaching a depth of 40 m (Perez *et al.* 2000). The first sign of mortality was the appearance of a white bacterial veil on the sponge epidermis. This was followed by rot occurring underneath the layer of bacteria and sponge death within just two days. For commercial sponge species

(*Spongia* and *Hippospongia*), the combined action of intense harvesting and temperature-induced disease has taken a number of populations to the brink of extinction (Pronzato 1999).

The symbiosis between sponges and the communities of bacteria that surround them are limited by environmental thresholds. If these factors change, environmental community shifts in bacteria can cause pathogenic outbreaks harmful to the sponge. The temperature thresholds for these bacterial symbioses have been studied in the warm-water sponges *Spongia* and *Hippospongia*, occurring at temperatures between 27 and 33ºC (Gaino *et al.* 1992). Between temperatures of 27 and 31ºC no change in sponge health or bacterial community composition was detected. But sponges exposed to temperatures of 33ºC lost their bacterial symbionts within 24 hours and showed cellular necrosis after three days (Webster *et al.* 2008). A dramatic shift in bacterial community composition was observed between 31 and 33ºC. The heat shock protein hsp70 found in *Geodia cydonium* is also a useful biomarker in following these biological responses to physical stress (Koziol *et al.* 1997). The breakdown of symbioses and stress in sponges occurred at very similar temperatures to those reported during tropical coral bleaching events.

Other than the initial reports of *Geodia* necrosis from Scandinavian fjords, very little is understood about the vulnerability of deep-water sponge grounds to temperature change, but it is imperative that this research be prioritized given the threats posed by global climate change and the effects of ocean acidification.

4. Biodiversity

Recent research in the Northeast Atlantic has shown how diverse deep-water sponge assemblages can be. On the Rockall Bank west of Scotland and Porcupine Bank west of Ireland, van Soest *et al.* (2007) recorded between 105 and 122 sponge species in just three localities. In this study, both depth (500-900 m) and the presence of live cold-water corals were found to be primary influences on sponge species composition and spatial variation. A biodiversity census from the Mingulay cold-water coral reef complex, west of Scotland, reported 100 sponge species in a very localized area (Roberts *et al.* 2009a). Thus it is becoming clear that, alongside the diversity of associated fauna found with deep-water sponge grounds, there is an appreciable biodiversity of deep-water sponges, notably among thinly encrusting species associated with cold-water coral habitats.

Other trophic groups including fish, molluscs, crustaceans and echinoderms all graze sponges, often non-fatally (Taylor *et al.* 2007). A survey of hexactinellid sponges on the Weddell Sea shelf in Antarctica greatly influenced future research by illustrating the importance of substratum texture and composition (Barthel 1992). Species-poor associations appeared to be linked with muddy, soft-bottom seabeds, whereas species-rich associations were linked with more solid sponge spicule mats and bryozoan debris. From these observations another more revealing finding was made. One hexactinellid sponge, *Rosella racovitzae,* was present on both softer bryozoan debris and hard spicule mats, with markedly different population structures characterizing each one. The bryozoan mats supported small, young specimens whereas the spicule mats were home to older, more established specimens. This suggests that these Antarctic sponges colonize the bryozoan debris and alter the quality of the substratum by depositing spicules which then develop into spicule mats. The biomass volume, shelter and probably also food supply all increase with the presence of spicule mats, and sponge communities – including these hexactinellid sponges – then become a major biological structuring agent providing habitat in the Antarctic deep sea.

Figure 4.1: A sponge ground of *Geodia* sponges found around Norway. *H.T. Rapp, University of Bergen.*

Deep-sea sponge grounds

ASSOCIATED FAUNA

Many sponges have microbial associations and some host specific assemblages of microbes. The microbial associates occur throughout the sponge, both inter- and intracellularly, and can constitute up to 40 per cent of the sponge's volume (Osinga *et al.* 2001). A distinction can be made between epibionts, which are organisms living on the surface of the sponge, and endosymbionts which live in the sponge mesohyl.

These microbes come from each of the following major groups: archaea, bacteria, cyanobacteria, microalgae, heterotrophic eukaryotes and fungi. As well as playing roles in sponge nutrition and carbon fixing, these microorganisms are also thought to play an important part in sponge metabolism through the production of other compounds (known as secondary metabolites), which provide the sponge host with protection against predation and spatial competition.

In the shallow-water tropics, studies have revealed that a substantial increase in bacterial biomass can be found surrounding sponges, which also helps to support diverse assemblages of symbionts. In some cases, deep-water sponge grounds can also be important centres of chemosynthetic activity (Hentschel *et al.* 2002). In addition, sponges are known as sinks for dissolved organic carbon in tropical coral-reef habitats where they play an important role in coral reef energy budgets (De Goeij and Van Duyl, 2007). The mutual symbiosis between sponges and their associated microbes is therefore also likely to be of crucial importance in the deep sea. The expected sponge diversity of 15,000 species probably holds an even larger number of undiscovered microorganisms that are only found in sponges, and may significantly increase currently known microbial biodiversity. For instance, a new bacterial Phylum, the Poribacteria, has been discovered with members at present only known to occur in sponges (Fieseler *et al.* 2004).

As well as forming intricate symbioses with a variety of microbial organisms, deep-water sponge grounds are emerging as significant centres of invertebrate species diversity. In the Northeast Atlantic, over 242 epi- and infaunal species (living on and in seabed sediments) were reported with deep-water sponges from around the Faroe Islands, 115 of which were related to sponges for the first time (Klitgaard 1995). This study also demonstrated that community composition was often specific to a particular species of sponge. For instance, the habitat-forming sponge *Geodia cydonium* has an internal structure that particularly favours certain endosymbionts and polychaetes.

Sponge morphology is thought to play an important role in the composition of associated fauna, although more research is needed to examine this in detail. In her 1995 study, Klitgaard only found one predator, the chiton mollusc *Hanleya nagelfar*, and this low predator diversity was explained by the inhospitable texture of the sponges, or by an artefactual failure to sample predators adequately. However, the production of secondary metabolites may also help to protect sponges from predation (Clavico *et al.* 2006) and explain the rarity of sponge predators observed.

Close associations between sponges and crustaceans have also been documented. Klitgaard (1991), working in the North Atlantic, observed the isopod *Caecognathia abyssorum* living in a hollowed-out crevice in sponges, where it creates a territorial harem. Off Kamchatka, Russia, young-of-the-year red king crabs *Paralithodes camtschaticus* were associated with sponges, bryozoans and hydroids (Tsalkina 1969). Further, laboratory experiments found that recently moulted red king crab glaucothoe larval stages preferred to settle on complex substratum (hydroids, bryozoans, algae and plastic mesh) rather than sand (Stevens and Kittaka 1998; Stevens 2003).

Fish often use the structural habitat that sponge grounds provide for shelter and reproduction and to forage for food. The intricate architecture of sponge grounds also provides important nursery grounds for juvenile fish in their early stages of growth (Auster 2005). Rockfish (or 'redfish') of the genus *Sebastes* are particularly prevalent in sponge grounds, living in and between sponges. Other groundfish including cod and ling are often found in trawl catches along with sponges, demonstrating in their abundance the importance of sponge-formed habitat for commercial species of fish (Hixon *et al.* 1991). There is also some evidence that, over time, removal of the sponge grounds by trawling changes composition of the fish fauna (Sainsbury 1988 in Klitgaard and Tendal 2004). Thus, it seems that sponge grounds are a crucial refuge and habitat for fish, although little ecological work has been carried out to understand the exact nature of this habitat use in the deep sea and studies to date are limited to tropical waters (e.g. McCormick 1994; Cleary and de Voogd 2007).

The scarcity of complex structural habitat in the deep sea means that sponges play a crucial role by enhancing the number and complexity of microhabitats and, ultimately, biodiversity in the deep sea. Deep-water sponges form a network of habitat 'patches' in deep-sea settings around the world, but our understanding of the roles these play in sustaining deep-water biodiversity and the ecological connectivity of these habitats remains at best descriptive.

5. Threats

The major threats to sponges are deep-water bottom trawling and fishing with other gears that touch the seabed. By the late 1980s, the intensive use and exploitation of resources in marine coastal regions had severely depleted stocks of commercial fish, especially the more common continental shelf species such as cod. As a result, fishing effort has shifted, targeting the deep sea in an attempt to maintain fish catches (Roberts 2002). Other activities have been directed at valuable biological, mineral and hydrocarbon resources; this exploration developed markets for deep-water fish such as the roundnose grenadier (*Coryphaenoides rupestris*). The result has been an increase in both vessel capacity and the spatial scale of fishing operations, which has raised international concern over the sustainability of fish stocks in both shallow and deep waters. Sponge grounds provide refuge, local food webs and nursery grounds for fish in the deep sea where structural habitat can be scarce, and photographic surveys carried out over the last decade have revealed widespread damage caused by commercial fishing (Hernkind *et al.* 1997; Roberts *et al.* 2000; Ryer *et al.* 2004).

Sponges are often slow-growing with long lifespans, and consequently their recovery and regeneration after damage or disturbance may take decades (Jones 1992). In recent years, collaborative initiatives advocating caution over deep-sea fishing and calls for the protection of the deep-sea habitats on which these fish depend have received considerable attention. Consortia such as the Deep-Sea Conservation Coalition (DSCC) and the IUCN World Conservation Congress supported the United Nations General Assembly (UNGA) resolutions on sustainable fisheries of 2006 (61/105) and 2009 (64/72), which called upon Member States to close bottom fishing in areas where 'vulnerable marine ecosystems' are likely to occur, including cold-water coral areas, deep-water sponge grounds and seamount habitats.

Observed threats to sponge grounds are:
- commercial bottom trawling and other mobile fishing gear;
- hydrocarbon exploration and exploitation;
- cable and pipeline placement.

Potential threats include:
- deep sea mining;
- altered geochemistry of the ocean;
- carbon dioxide sequestration.

COMMERCIAL TRAWLING AND OTHER FISHING GEAR

The deep seas that extend beyond the exclusive economic zones (EEZ) of national boundaries have operated on open-access policies which, combined with generous subsidies, have led to the overexploitation of fisheries using bottom

Figure 5.1: Photographs illustrating a trawl mark through an area of seabed previously abundant with sponges: (a) shows an untrawled area with an intact stalked deep-sea glass sponge (*Hyalonema*); (b) shows linear marks from a trawl and the broken stalk of a glass sponge. *Roberts* et al. *2000/Springer publishing.*
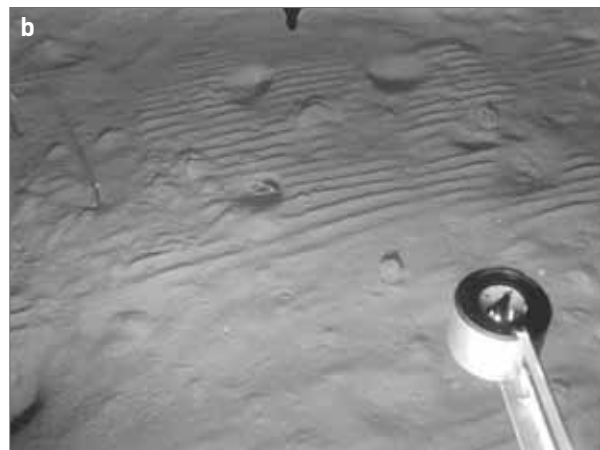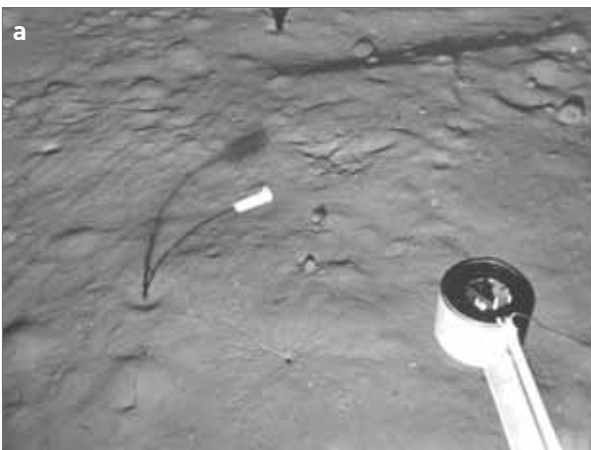
trawls and dredges. There is a general consensus that fishing is the single most influential anthropogenic impact on continental shelves worldwide (Auster and Langton 1999; Norse and Watling 1999; Halpern *et al.* 2008), and the expansion of the deep-sea fishing industry has consolidated this opinion in recent years. There is also growing acknowledgement that the collapse of fish stocks is only one consequence and arguably a symptom of wider impacts caused by bottom trawling.

The complex three-dimensional structure of sessile animals such as sponges, bryozoans and cold-water corals is broken up into rubble with the passage of a trawl, which eliminates habitat for commercially important fish (Wassenberg *et al.* 2002). It has been reported that some species of sponge appear to be so fragile that they even disintegrate on contact with a pressure wave induced by trawl gear (UNGA 2006 paragraph 53). Rare hexactinellid sponge reefs off the coast of British Columbia, Canada, where extensive trawl damage has been observed, exhibited a low presence of usually abundant rockfish for which sponge debris could no longer be used as a nurturing habitat (Conway 2007). Rockfish were therefore less abundant on trawl-damaged hexactinellid sponge reefs than on intact sponge reefs.

A second, more indirect way that suspension-feeding sponges are affected by trawling is through smothering. Bottom fishing re-suspends large quantities of seafloor sediments that could smother sponges. While this is not easily observed or measured, remote-sensing images illustrate the kilometre-long plumes of re-suspended sediment generated by trawling vessels in shallow waters (Amos 2008), and point to the spatiotemporal scales at which this activity could impact sponge grounds. A third, rarely considered, threat is that fishing gear can inflict sub-lethal injury on sponges, which are left to regenerate from their partial mortality. However, injured sponges have fewer energetic and cellular resources to grow, reproduce, and defend themselves against predators and disease (Henry and Hart 2005).

Mobile fishing gear that contacts the seabed, particularly **trawling**, is the fishing apparatus that poses the greatest threat to deep-water sponge grounds. Bottom trawls consist of bag-shaped nets towed behind a vessel. Deep-water trawls are held open by vanes (or 'doors') made of wood or steel which can weigh up to 1 tonne (Jones 1992), and trawl nets can be as large as 55 m across and 12 m high. Chains and cables with heavy discs or rollers may also be mounted along the bottom of the net so that rough seabed does not obstruct the passage of the fishing equipment or damage

the nets. This gear inflicts significant damage and mortality on many animals living on the seabed, the extent of which depends on the weight of the gear on the seabed, the nature of bottom sediments, the towing speed at which the equipment is dragged and the tidal and current strength, and the species themselves (Jones 1992).

The impacts of trawling on cold-water coral reefs have been well documented and, although deep-water sponge grounds have yet to be given the same attention, it is reasonable to assume that the extent and degree of damage is similar. On an average 15-day trip in the Rockall Trough in the Northeast Atlantic, one trawling vessel covers an area of approximately 33 km^2 of seabed (Hall-Spencer *et al.* 2002). Fishermen usually attempt to avoid extensive sponge grounds as these obstruct and damage trawling gear, representing a rather time-consuming nuisance in cleaning and re-deploying nets that are full of massive quantities of sponges. Nevertheless, given the rich abundance and diversity of fish that these sponge grounds harbour, the edges of the grounds often receive direct, physically devastating damage, which has been supported by visual observations. Recording the impact of bottom trawling requires regular and consistent monitoring of sponge grounds and fisheries bycatch if meaningful observations and measurements are to be obtained.

The first records of deep-sea trawl marks on the seabed to the west of Scotland were made in the late 1980s (Roberts *et al.* 2000). Sponge and coral bycatch in the Aleutian Islands, which contain some of the most pristine cold-water coral and sponge habitats on Earth, is 12 times the rate observed in the wider Gulf of Alaska or Bering Sea. From 1990 to 2002, US federal data from fishery observers recorded approximately 2 million kg of mostly sponge bycatch from the Aleutian Islands. This figure is a cause for much concern and must be considered in appropriate conservation measures (Shester and Ayers 2005; Heifetz *et al.* 2009). In 2005 and 2006, the US National Oceanographic and Atmospheric Administration (NOAA) froze the footprint for bottom trawling in the Aleutian Islands and the Bering Sea respectively as precautionary measures to protect sensitive essential fish habitat. Regularly updated reports on this can be found at www.fakr.noaa.gov.

Dredges are another form of fishing gear, similar to bottom trawling, used typically to catch clams, scallops and oysters. They remove all sediments, rocks and organisms in their path, vastly reducing habitat complexity and function, with a large bycatch of non-target marine fauna including sponges. Communities living in the wake of the sediment-laden plumes created by dredging activities are often smothered.

The anchors and weights of **demersal longlines** and **gillnets** also cause damage to the fauna on the seabed, and result in potentially substantial bycatch with the hooks set close to the bottom. Mechanical longline sets can extend to a length of 50 km or more; deep-water gillnets, trammel nets and combinations are deployed in sets of 300-1,000 nets x 50 m (15-50 km length) – on average 20 km in the monkfish fishery, for example. Each vessel in this fishery, which takes place on the upper slope, uses approximately 5,000-8,000 nets, a total length of 250-400 km. The relative rate of loss of bottom-set gillnets increases with depth, reaching 15 per cent of nets set in the Greenland halibut fishery at 700 m depth (Hareide *et al.* 2005). Due to their non-biodegradable material, such nets continue to catch fish for very long periods, and can, when moved by currents, also destroy or trap other fauna such as corals or sponges.

HYDROCARBON EXPLORATION AND EXPLOITATION

The wealth of oil reserves in the Gulf of Mexico attracted some of the first hydrocarbon production in the deep sea in 1979 (French *et al.* 2006, in Davies *et al.* 2007). Diminishing conventional terrestrial and shallow-water oil reserves, com-

bined with rising extraction costs and intense consumer demand, have increased pressure for new stores of oil and gas to be found. The Brazilian oil company Petrobras is now working at depths of over 2,000 m, and newly discovered oil reserves in water depths greater than 1,000 m off the coast of West Africa suggest than hydrocarbon production in the deep sea will continue to grow (Polunin 2008).

The release of drilling muds and cuttings from hydrocarbon exploration and production are important benthic impacts and threats to sessile suspension-feeding fauna and benthic habitat structure. Drilling muds can contain refined lubricant oils and other synthetic components which are used to facilitate the drilling process (Bett 2001). Drill cuttings and muds are separated on the platform where the cuttings, often contaminated with muds, may be discarded back into the marine environment where they can accumulate on the seabed (Polunin 2008). In the North Sea, up to 1.5 million tonnes of drill cuttings have

Figure 5.2: Sponge bycatch from a trawl taken during a BIOFAR expedition. *Ole Secher Tendal.*

been left to accumulate on the seafloor over the last 30 years (UKOOA 2002).

There are no published studies to date focusing on the impacts of hydrocarbon exploration and production on sponge grounds, yet there is some evidence that sponge grounds are not immune to drilling activity. In the Faroe-Shetland Channel of the Northeast Atlantic, the effects of active drilling platforms on epibenthic megafauna such as sponges have been observed. Depressed abundances can be found within 50 m of the drill-spoil source due to the effects of smothering, and some level of impact can occur at distances up to 100 m depending on the current regime and nature of the drilling activity (Jones *et al.* 2007).

Smothering involves the mantling of existing communities with layers of fine sediment, which reduces rates of re-colonization and larval settlement. The majority of oil and gas fields are located on the upper slope, which normally supports a high diversity of deep-water fauna, often within a unique oceanographic regime (Thiel 2001). Oil exploration is thus occurring in areas of great vulnerability and importance to benthic biodiversity. It may reduce substratum availability by smothering suitable sites with fine sediment, so homogenizing habitat and reducing species diversity. As sponges often disintegrate when killed or physically damaged by direct impact, regular monitoring and recording is urgently needed to detect environmental effects.

Under European and US legislation, environmental impact assessments must be carried out by oil companies intending to exploit a deep-water oil or gas field before starting any operation (Colman *et al.* 2005). Much survey work carried out in the Northeast Atlantic, including off the west coast of Scotland and around the Faroe Islands, has been financed by the oil industry and this has led to the discovery, accurate location and mapping of new sponge grounds and cold-water coral habitats, helping to identify areas that need to be avoided by industrial activity. Careful regulation has reduced the risk of damage to sponge grounds through environmental impact assessments. However, this regulatory framework needs to be established on an international scale, together with measures for enforcement, so that the industry works towards high standards of monitoring for the deep-sea environment worldwide. Quantification of the impacts of oil-well drilling and oil spills on sponge grounds and the fauna they support is required so that the severity and persistence of impacts can be known and managed.

CABLE AND PIPELINE PLACEMENT

Telecommunication and electrical cables and oil and gas pipelines have also been installed in increasingly deeper seas since the 1980s. These are now frequently buried within the seabed to minimize elements of geological stress such as corrosion, instability and accidental damage by trawling to depths of up to 1,500 m. Sponges would most likely be damaged or destroyed if a cable or pipeline corridor crossed sponge grounds, and the area of impact during installation may cover a larger footprint than the pipeline or cable itself. Sediment is also likely to be re-suspended during construction and could smother nearby sponge grounds, although further studies are required to understand and model this potential impact. Guidance and consultation with engineering firms are needed to increase awareness of the potential impacts to deep-water sponge grounds and other vulnerable deep-water habitats. It is important to note that tele-communications cables cover a smaller footprint than pipelines and carry no associated risk of pollution leakage (see Carter *et al.* 2009 for a detailed report on submarine tele-communications cables).

WASTE DISPOSAL AND DUMPING

Historically, increasing levels of global waste and sewage production have placed ever greater pressure on solutions for their final disposal. Dumping waste into the open ocean has been viewed as a viable political option for several decades (Rieley *et al.* 1997; Thiel 2001). In 2006, however, the London Convention on the prevention of pollution by dumping wastes at sea was enforced by the International Maritime Organization, so that dumping is now largely prohibited except for selected materials on an approved list. The limited extent of research into the impacts of sewage disposal on deep-sea ecosystems has made this issue controversial, and has already initiated an intergovernmental conference in the last decade sponsored by the United Nations.

MINING OF GEOLOGICAL RESOURCES

Manganese and iron nodules on the seabed were first discovered during the *Challenger* expedition in 1872, and a century later the potential for their development into poly-metallic ore was studied. From the mid-1980s, a series of large-scale environmental impact assessments of poly-metallic nodule mining in the Pacific Ocean called DISCOL (later ATESEPP) were carried out. These focused on the re-action of benthic fauna to sediment blanketing. A disturber was repeatedly towed along a test track, using water jets to stir up sediment and blowing pumped slurry into the water column 5 metres above the seabed (Thiel 2001). It was acknowledged that removing manganese nodules would alter the biochemical milieu of the ecosystem and disturb associated biotopes (Oebius *et al.* 2001). The cloud of re-suspended sediment and the heavy metals released with it were also found to destroy the benthos by removing sediment, contamination with toxic compounds and blanketing.

The most recent attention has focused on sulphide deposits. These are not generally found near deep-water sponge grounds; however, there is a growing interest in the mining of cobalt-rich crusts which do occur in the depth range of deep-water sponge habitat (CBD 2008b). This exploration into deep-sea mining is in its early stages, with mining contracts on the high seas controlled by the International Seabed Authority. Further long-term studies are needed to thoroughly investigate and minimize potential impacts if these operations are to be successful, sustainable and protective of the marine environment.

GLOBAL CLIMATE CHANGE

Throughout much of the 20th century, it was thought that the deep sea was buffered against the effects of changes at the sea surface with its wind- and current-driven cycles (Menzies 1965). More recent research has revealed that the deep sea is highly sensitive, closely linked to surface production and any alterations that occur (Smith and Hughes 2008). Changes in ocean currents and water temperature could strongly influence the growth rate of deep-sea organisms as well as species distribution, abundance and behaviour. Observations of melting polar ice caps and the corresponding increase in freshwater input may disrupt the thermohaline circulation by affecting water temperature and density. This has prompted speculation of the potential for a shift in global climate similar to that of the Younger Dryas cooling event around 13,000 years ago, recorded in the carbonate skeletons of deep-sea corals (Smith *et al.* 1997).

Since sponges are sessile benthic animals that use suspension feeding in order to obtain food, surface productivity from phytoplankton through to zooplankton is important in determining sponge abundance and distribution. Seasonal 'phytodetrital' deposits in the Northeast Atlantic during early spring and summer have suggested that 2-4 per cent of spring-bloom production is carried to the seafloor, revealing the seasonal fluctuations in food that seem to be associated with sponge growth (Gooday 2002). Cold-water corals have been demonstrated to thrive in areas of high surface productivity and locally accelerated currents (Roberts *et al.* 2006), and sponges may well show similarly distinctive habitat requirements (Barthel 1992). Shifts in primary surface productivity as a result of climate change could therefore alter the distribution of deep-water sponge grounds and other benthic fauna.

A change in the geochemistry of the ocean due to the increase of anthropogenic carbon dioxide in the atmosphere is another key emerging issue. The global ocean is a significant store of carbon, retaining more than five times the amount held in the atmosphere and in terrestrial systems.

As carbon dioxide dissolves in the ocean it lowers the pH, making the seawater more acidic. Organisms in shallower waters are expected to be affected first by this change in the ocean's pH, especially calcifying planktonic organisms which are crucial in carrying organic carbon to the deep seafloor. Although most habitat-forming sponges in the deep sea are silica-based, the mobility, transport and thus availability of silica as a nutrient could also be affected by changes to ocean chemistry. Modelling of global silicon cycle dynamics in the ocean is in its very early stages, but the equatorial upwelling in the Pacific Ocean and diatom blooms in the Ross Sea, Antarctica, are both thought to be important loci for ocean production cycles (Brzezinski *et al.* 2001; Chai *et al.* 2002).

ASSESSING THE RISKS

The risks to a marine ecosystem are determined by its vulnerability, the probability of a threat occurring and any mitigating measures that could be applied. All benthic marine ecosystems are vulnerable to anthropogenic disturbance to a certain degree, but some, in particular complex macrohabitats like reefs and aggregations formed by biota in deep water, are likely to lack the ability to regenerate from substantial impacts (see review in Parker *et al.* 2009). Wherever deep-water sponge grounds occur, their range of distribution is very likely to include areas within fishing depth, usually on the slopes of the continental shelf, offshore banks and seamounts. Due to the wide- and large-scale efforts of bottom trawl fisheries, the threat from this type of activity was ranked highest in the Northeast Atlantic (Hughes *et al.* 2003; Smith and Hughes 2008), though some rocky outcrops may not be easily accessible to fishing gear.

The level of threat from bottom trawling on the continental slope can be illustrated by a study of Roberts *et al.* (2000), see Figure 5.1. Off the west of Scotland between 900 and 1,300 m depth, this study recorded trawl marks in up to 12 per cent of photographs from a camera system which covers less than 100 m² per deployment. The deepest (and probably the most physically stable) stations had the highest frequency of trawl marks per deployment (12 per cent) at the deepest sites (1,300 m). A nearby site at 600-883 m depth, revisited after a decade, revealed both old and fresh trawl marks in up to 47 per cent of the pictures taken. Howell *et al.* (2007) observed trawl marks in the deep-water sponge grounds of the UK continental slope in the Faroe-Shetland Channel. Also Bett (2000), analysing photographs from the west Shetland slope, found trawl marks in many of the images examined.

Several scientific studies of sponge grounds, such as Rice *et al.* (1990), Klitgaard *et al.* (1997) and Ragnarsson and

Steingrimsson (2003), used fishing industry records of locations where fishing vessels have taken a large sponge bycatch as indicators of the distributions of these communities. A significant amount of data stems from fishery research trawls (Norway Ministry of Environment, 2005-2006; ICES 2009; Kenchington *et al.* 2009) and scientific dredging. This gear not only removes biomass from the seafloor but can also alter the sediments, as shown by Bett (2000), who encountered disturbed sediment structure with buried sponge remains in a box core sample. Given the high intensity of bottom trawling carried out on the continental margins, it is highly likely that not only the extent but also the condition of the habitat for deep-water sponges will be affected. A similar but larger-scale effect can be expected of the scouring of icebergs off Iceland, Greenland and Spitsbergen (Klitgaard and Tendal 2004 and literature therein).

Ultimately, the potential effects of global climate change on deep-water sponge habitats remain unknown. The rate of climate change worldwide and the capacity for adaptation to changing deep-sea conditions by sponges and sponge grounds are important factors to be considered. Only with more research and a greater understanding of deep-water sponge biology and ecology can the potential impacts of global climate change be examined in any detail. However, given present understanding, it seems likely that sponge grounds may be vulnerable to increased temperatures, which may promote disease outbreaks, and to any shifts in food supply.

6. Case Study 1: Glass sponge reefs off the west coast of Canada – a living fossil

Areas of the northwestern continental margin of North America host massive glass sponge reefs constructed by frame-building hexactinellid sponges of the Order Hexactinosida (Figure 6.1). The reefs were discovered in the late 1980s by the Geological Survey of Canada during reconnaissance seafloor mapping surveys (Conway *et al.* 1991). Recent work has established details of their development (Krautter *et al.* 2001, 2006), oceanography (Whitney *et al.* 2005) and distribution (Conway *et al.* 2005), and shown that they have been damaged by bottom trawling. Recent surveys off the Washington coast of the USA have recently uncovered more glass sponge reefs in the vicinity of Grays Canyon, which may also be vulnerable to bottom trawling (Bjorklund *et al.* 2008).

The reefs mapped to date form large aggregations and develop into reef complexes covering hundreds of square kilometres of seabed. At some sites they have been growing for up to 9,000 years (Conway *et al.* 1991), and have reached 25 m in height in areas with optimal conditions for sponge growth. Reef initiation depends on the stability of the deep-shelf seafloor, where glacial landforms such as iceberg ploughmarks, large glacial flutes, drumlins and moraines remain exposed on the seabed. The reefs have been found in shelf depths from 140 to 310 m and at isolated locations inshore as shallow as 50 m. These reefs are thus just below or at the boundary of the photic zone.

The reef surface is complex and forms diverse structures on the seabed, including steep-sided mounds and ridges, contributing further habitat complexity (Conway *et al.* 2007). The reefs share several characteristics and formative processes with extinct siliceous sponge reefs (Krautter *et al.* 2006) and, in fact, have more in common with these formerly widespread sponge and sponge-microbial reefs than with any extant reef type. For this reason they have been described as a type of 'living fossil'.

SPONGE REEFS IN EARTH'S HISTORY
Sponge reefs have recurred several times in Earth's history, especially during the Phanerozoic (the last 542 million years), but are geologically most well known from the Mesozoic Era, especially the Jurassic period – for example the sponge and sponge-microbial reef limestones that form distinctive and beautiful landscapes today in central and southwestern Europe. Sponge reefs were widely distributed along the northern margin of the Tethys Ocean during the Upper Jurassic (155 million years ago). The largest reef belt ever formed on Earth occurred during this time period, and rocks that record the distribution of a vast deep-water sponge reef belt (Figure 6.3) can be found in Poland, Romania, Germany, Switzerland, France, Spain and Portugal, and in the USA and Canada (Krautter *et al.* 2001).

The long-term environmental stability that these reef systems experienced resulted in thick accumulations of reef

Figure 6.1: Known distribution of hexactinellid sponge reefs in Canadian waters. Reefs may be more than 25 m in height and very large individual sponges up to 1.5 m high may completely cover the reef surface. *K.W. Conway.*
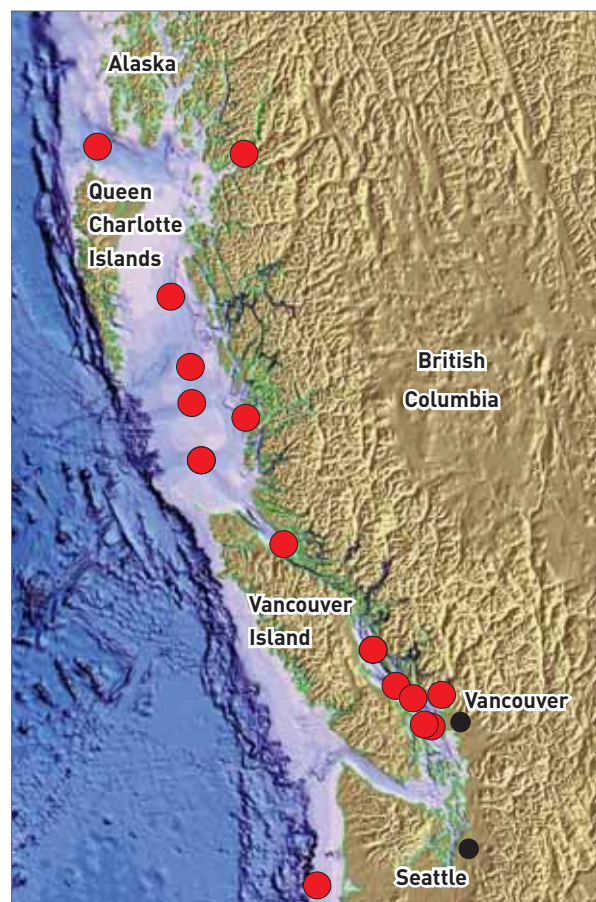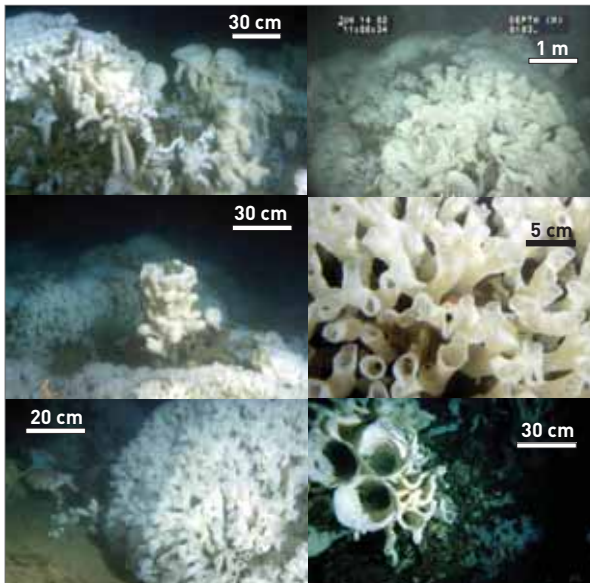
Figure 6.2: Sponge reefs in Hecate Strait, off the British Columbia continental shelf. The reefs are constructed by three reef-forming sponge species (*Aphrocallistes vastus*, *Heterochone calyx* and *Farrea occa*). These hexactinosidan sponges differ from other glass sponges in that their skeletons survive the death of the sponges, leaving a suitable surface on which subsequent sponge generations may settle and grow (Krautter *et al.* 2001). The young sponges attach to the framework of skeletons of dead sponges and over time accumulate to form large reef structures; given appropriate oceanographic and geological conditions, very large reefs and reef complexes may form after several generations of sponge growth. *K.W. Conway.*

Figure 6.3: Global distribution of sponge reefs during the Upper Jurassic. The reef belt was more than 7,000 km long. The photographs show very large sponge reef outcrops forming cliffs in the Swabian Alb, southern Germany. *M. Krautter.*

sediments and strata in many locations. The requirement for a stable shelf seabed for these reefs is shown in the rock record of what is today eastern Spain, where a vast area of much more than 70,000 km^2 was mantled by sponge reefs over a period of 5 million years (Figure 6.4).

The sponges that created many of these landscapes were of the same Order (Hexactinosida) as the sponges that build the reefs we see today off western Canada, and some of the environmental settings are inferred to have been quite similar (Krautter *et al.* 2006). Prior to the Upper Jurassic occurrences, the first siliceous sponge reefs appeared locally restricted to the Middle Triassic of southern Poland.

Deep-water sponge reefs culminated in the Upper Jurassic (Krautter *et al.* 2001 and references therein). Following Cretaceous times they were in steep decline, and are known only from smaller areas, mostly in France and Germany. The last of their kind occurred in the Middle Paleocene of northern Africa (Algeria, Morocco). No younger siliceous sponge reefs have been described and – until the discovery of the reefs off British Columbia – it was thought that this reef type had become extinct. The associated benthos includes sponge-encrusting fauna mainly consisting of brachiopods, serpulids, bryozoans, echinoderms and Foraminifera. The ecological niche of the siliceous sponge reefs off British Columbia can be characterized as ultraconservative, as it has not changed over more than 220 million years, a testament to an enduring landform.

MAPPING AND SAMPLING

Techniques that have been successfully used to map the reef areas include side-scan sonar and high-resolution seismic surveys. Analysis of the backscatter derived from side-scan or multibeam sonar is – unusually for sponge grounds – very effective at imaging these areas because a unique signature is derived from hexactinosidan reefs. The mantle of deposits on sponge grounds generally absorbs

Figure 6.4: Distribution of the Upper Jurassic sponge reefs in Spain (the Yatova Formation). The photograph, from near Frías de Albarraçín, shows the geology and geomorphology where these flat-lying, sponge-rich limestones dominate the landscape. *M. Krautter.*

soundwaves, leading to low backscatter. High-elevation features such as sand waves, ridges and moraines, however, are usually composed of acoustically reflective features with high backscatter value. So high-elevation glacial features with very low-backscatter deposits, which often have a spherical or wave form, are a good indication of sponge reefs.

Geographic information system (GIS) display tools allow overlaying of the multibeam and backscatter data, giving an accurate, geospatially correct rendering of the elevated, low-backscatter areas that have been shown to correlate to sponge reef sites (Figure 6.5). In deeper slope areas, the capacity of some systems to resolve features such as sponge reefs is limited, though improvements to multibeam technology have been rendering this issue less problematic. The reefs are readily cored by conventional piston coring methods to provide geochronology and geological understanding of reef development. Sites may be quickly selected for still camera, towed video, ROV and submersible transects using georeferenced seafloor maps that are readily derived from multibeam surveys, one of the advantages of multibeam datasets being that they are very accurately positioned.

DISTRIBUTION AND REEF FORM

Glass sponge reefs are presently known to occur along the entire length of the western Canadian margin, with the principal aggregations in shelf troughs at four locations on the north-central continental shelf between 140 and 240 m water depths (Figure 6.6). Reefs have also recently been identified off Washington State and in southern Alaskan waters. They are not known to occur elsewhere, though mapping of deeper ocean areas is still very rudimentary or absent for most regions.

Reefs may be restricted to the Pacific because associated hexactinosidan sponge fauna is richer there, and are probably found in shallow waters due to the relatively high silicate levels, which do not occur in shelf depths elsewhere (Whitney *et al.* 2005). The main reef complexes are variable in size and structure and the reefs within the complex form various shapes including mound (bioherm), bed (biostrome

Figure 6.5: Multibeam and backscatter data collected at a sponge reef complex in southern Queen Charlotte Sound (see Figure 6.6 overleaf for location). *K.W. Conway.*

~ 4 km
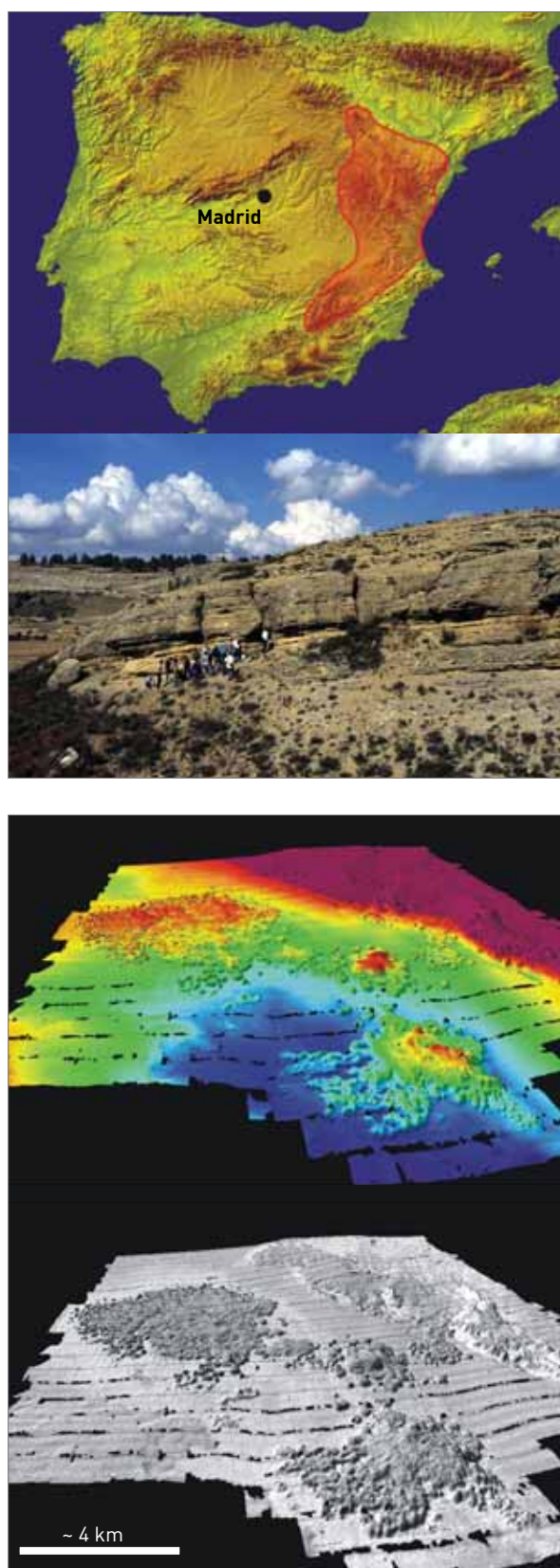
or meadow) or ridge and even wave-form. It is thought that the various complexes develop a reef distribution pattern in response to both the ambient seabed current field and the distribution of iceberg-furrowed substratum available to the reefs as they grow over millennia (Conway *et al.* 2005).

Reefs may develop in areas of elevated suspended sediments, but in all cases reef initiation requires a non-depositional seabed. This appears somewhat contradictory, and suggests a finely balanced system where some sediment is required in order to provide the reef matrix, but too much will smother the suspension-feeding sponges. The reefs have not been found on bedrock surfaces. Smaller reefs and reef complexes have been found in fjords and inshore waterways of the inner shelf, and more reefs are being found as survey data are acquired for new areas. The location of reefs is invariably associated with glaciated drumlinoid ridges or large glacial fluted surfaces and ice stream-lined and glaciated trough floors and bank tops.

In inner shelf waters, the availability of this favourable habitat is limited by sediments mantling glacial deposits. In

Figure 6.6: Sponge reef complexes on the northwestern Canadian shelf. *K.W. Conway.*

southern British Columbia, for example, where the Fraser River sediments have infilled much of the southern Georgia Basin, sponge reefs are effectively restricted. While no reefs have been discovered deeper than 310 m, collection of multi-beam data along the deeper margin only began recently. The indications of small reefs in Alaska and Washington State waters suggest that the Northeast Pacific in general may host more reefs in shelf depths and perhaps in deeper waters as well.

SPONGE REEF HABITAT AND SENSITIVITY TO HUMAN IMPACTS

Sponge reefs provide a seafloor habitat of great complexity. Mounds and ridges up to 25 m high can develop, and beds that form as the reefs grow also provide topographically variable habitat. At a finer scale, the diverse shapes of the living sponges and dead skeletons projecting from the reef surface provide micro-scale habitats (Conway *et al.* 2007). Austin *et al.* (2002) refer to the habitat as being 'amplified' by the reefs, since reef growth and the accumulation of dead sponge skeletons effectively expand the coverage of suitable habitat. The development of a diverse epifauna is dependent on the skeletons of hexactinosidan sponges remaining intact in the water for decades (Austin *et al.* 2002). *Munida* spp. (squat lobsters) and species of crabs and shrimp are commonly found on the reefs, as are other species of arthropods, while soft-bodied invertebrates such as anemones appear to be much less common.

Several species of bryozoans, serpulid worms and brachiopods are common epifauna on the dead skeletons. Juvenile rockfish are more common on the reefs than adjacent seafloor areas, suggesting a refugia function for the reefs. The red-banded rockfish (*Sebastes babcocki*) is caught in significant numbers on the reefs off the northern shelf (Conway *et al.* 2007). The large northern reef complexes are variable with respect to fish species assemblages caught, with different species prevalent at the different reef complexes. The highest levels of fish productivity, and probably the highest biodiversity, are found at the edges of the reefs and reef complexes.

A large number of sponge species inhabit the reef surface, including demosponges as well as hexactinellid sponges such as *Rhabdocalyptus dawsoni, Staurocalyptus dowlingi, Acanthascus platei* and *A. cactus* (Krautter *et al.* 2001); one new demosponge species (*Desmacella austini*) has been described from a sponge reef (Lehnert *et al.* 2005). Where the seabed is mantled with sponge reefs and reef sediments, certain taxa are notably absent, including gorgonians (octocorals). The reef sediments and living and dead sponges thus form a habitat less conducive to certain
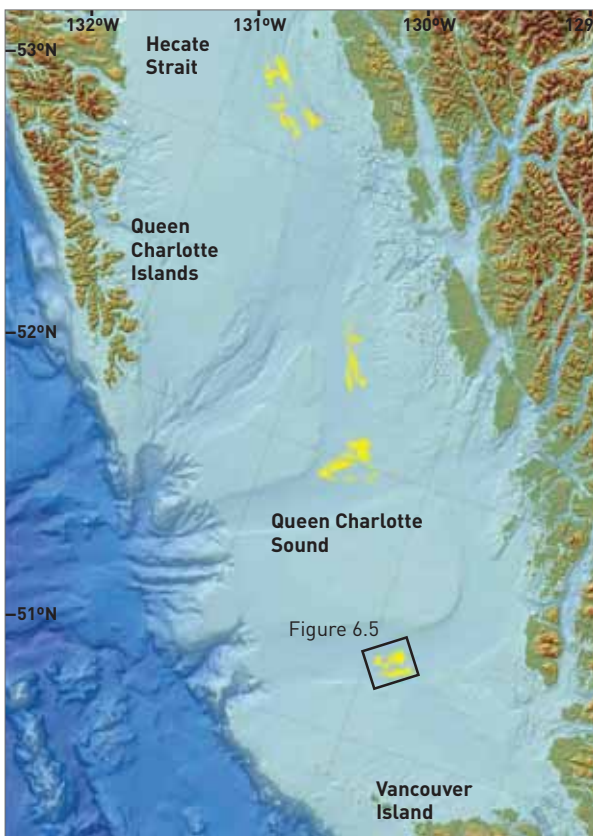
large benthic fauna than is the glacial surface which the reefs mantle.

The reefs themselves vary in species composition and may develop with one to three framework constructors. For example, sponge bioherms in Howe Sound, a fjord near Vancouver, are formed by only one sponge (*Aphrocallistes vastus*), while elsewhere in Georgia Basin *Heterochone calyx* is also involved in forming the reefs. The reefs in northern British Columbia all have *Farrea occa* as the third framework constructor. The species which form the reefs are variable in morphology and it has been noted that these species may adopt different shapes at different reefs, probably in response to local environmental variables including current velocity and sedimentation rate (Conway *et al.* 2007 and references therein).

The sponge reefs are sensitive to impacts by bottom-contact fishing gear, notably trawling, which has impacted reefs in many areas. Damage to the surface of the reefs can be variable (Krautter *et al.* 2001), probably depending on the frequency and intensity of trawling activity. The surface of reefs can be reduced to mud banks (Conway *et al.* 2007) with limited opportunity for recovery, as sediments mantle finely broken sponge skeletal debris, preventing successful attachment or growth by reef-forming sponges. Because the underlying glacial substratum is normally deeply buried by clay-rich reef sediments, once the reef-forming sponges are removed by trawling and the skeletons finely broken up, re-colonization or renewed reef growth is likely to be slow or impossible. Rockfish are less common at sponge reefs that have been mechanically damaged than at adjacent undamaged reefs.

At trawled reefs, competition for substrata may occur as many species are thought to settle and grow on the dead skeletons of the hexactinosidan sponges, including *Desmacella austini* which is normally restricted to this type of substratum (Lehnert *et al.* 2005). It is unknown how far afield sponge larvae can be transported but they are thought to be only weakly motile (Okada 1928; Boury-Esnault *et al.* 1999; Leys *et al.* 2006). Further knowledge of this factor would help determine the recovery rate of large areas of sponge reef that have been damaged, or whether they would recover at all.

Overall, the reefs represent a stable community that develops slowly over centuries or even millennia; the sponges can live to be several hundred years old (Leys and Lauzon 1998) while the reefs persist for thousands of years. The reefs experience low levels of natural disturbance due to a deep-water, relict seafloor environmental setting, which is below the wave base in areas of very limited seabed sediment transport and negligible background sedimentation rate.

7. Case Study 2: Sponge grounds in the Northeast Atlantic

Sponge grounds were first mentioned in reports from 19th-century North Atlantic expeditions. Although samples rich in sponge species had been taken before, it was only after the *Lightning* (1868) and *Porcupine* (1869, 1870) cruises that Wyville Thomson in his 1873 book *The Depths of the Sea* created the 'Holtenia ground' concept for *Pheronema carpenteri* mass occurrences found west of the Hebrides. More sponge grounds were found during the French expeditions with *Travailleur* (1880) and *Talisman* (1883), and reported by H. Filhol (1885) in his relatively unknown book *La Vie au Fond des Mers*.

Since then sponge grounds, while not always described as such, have been found in different parts of the North Atlantic by numerous cruises and expeditions from many countries including Canada, Denmark, the Faroes, France, Germany, Iceland, Norway, Russia, Spain, Sweden and the United Kingdom. The first definition of sponge grounds and broad overview of their distribution came from Northeast Atlantic studies. These compiled previously scattered literature and fisheries reports and gathered new information from the coasts of Norway, Sweden and around the Faroes. Amongst these, the Faroese BIOFAR and BIOICE projects mapped and described extensive sponge occurrences (Klitgaard *et al.* 1997). Further reviews have been made in reports from the ICES Working Group on Deep-Water Ecology (ICES 2009).

The overall result is that along the shelf edge in the North Atlantic several types of sponge grounds can be distinguished on the basis of the taxonomic composition of their sponge fauna, the hydrographical conditions and substratum. A nearly continuous belt of sponge grounds, dominated by species of *Geodia*, *Stryphnus*, *Stelletta*, *Thenea* and *Phakellia*, is found on the outer shelf from northern Norway and the Barents Sea, along the Norwegian and Swedish coasts over the Faroes, Iceland, the Reykjanes Ridge and southern Greenland, to Labrador and Newfoundland. Along this geographic transect, several variations in the sponge grounds are found.

One type of sponge ground seems to be characteristic of Norwegian, Skagerrak and Icelandic fjords. This has fewer species, dominated by *Geodia barretti*, *G. phlegraei* and, sometimes, *Thenea*, possibly under the influence of run-off and special hydrographic conditions associated with the fjordic setting. Another is found on the northern shelf edge of the Faroes, where *Stryphnus* dominates, and again the hydrographic conditions may be the reason for this since the variability of the stratification is high due to shifts in the location of the Iceland-Faroe front. There are rich sponge grounds in the Denmark Strait between Iceland and Greenland, dominated by *Geodia* species, but with a strong element of Arctic species of different genera. Geographically, the grounds seem to form a mosaic, but investigations are too few to elucidate this; explanations may again be sought in the hydrography, which is locally very complicated. Sponge grounds on the Canadian side are very extensive and seemingly dominated by *Geodia*, but the records are rather new and analysis is ongoing.

Hexactinellids are also found in the Atlantic and are mixed with demosponges, especially on the Reykjanes Ridge and in the Denmark Strait, but they are normally not among the dominant constituents of the sponge grounds. There are, however, a few areas outside 'the belt' where they play a considerable role. One north of Spitzbergen and another from the northern part of the Denmark Strait northwards along the east Greenland coast have a mixture of hexactinellids of the genera *Asconema*, *Schaudinnea* and *Trichasterina* and demosponges of the genera *Geodia*, *Stelletta* and *Thenea*; these grounds are at greater depths, of approximately 600-1,000 m. Two other kinds of hexactinellid grounds are found south of 'the belt': one on the American side dominated by *Vazella pourtales*, known as the 'Russian hat', and one on the European-African side dominated by *Pheronema carpenteri*, the 'bird's nest sponge'. The discovery of the *V. pourtales* grounds is new and investigations are ongoing (ICES 2009), but *P. carpenteri* has been known for a long time, and some investigations have been conducted (see Case study 3). Because *P. carpenteri* is a hexactinellid and dominates these sponge grounds to the degree that they can be called monospecific, further study of the basic biology and ecology of the species is needed.

8. Case Study 3: The bird's nest sponge (*Pheronema carpenteri*)

Members of the genus *Pheronema* are found worldwide and number more than 20 species. Their body form is cup-shaped, hemispherical or spherical, and they live on even, muddy or sandy bottoms in which they are usually partly buried and rooted with one or more tufts of long basal spicules.

The main distribution area of *P. carpenteri* is the Northeast Atlantic east of the Mid-Atlantic Ridge, from the southern flank of the Iceland-Faroes Ridge to the Azores, the Canary Islands and off Morocco, as well as the western Mediterranean (Reiswig and Champagne 1995). Generally speaking, the species occurs at depths between 500 and 1,600 m, but local areas differ with respect to upper and lower depth limits. The following depth ranges have been reported to date: south of Iceland 500-1,150 m; Porcupine Seabight 1,000-1,350 m; off Morocco 800-1,300 m; and the Azores 750-1,550 m.

Because the slopes inhabited by *P. carpenteri* typically have only slight inclines, the areas it colonizes may be extremely large and measured on a scale of several kilometres. The temperature for all areas falls between 5 and 11ºC, with the exception of the Mediterranean where it is 13ºC. The geographical and bathymetric distribution is by and large in accordance with the distribution of the Intermediate Mediterranean Water mass, stretching as far as the Azores and Scotland, and the Modified North Atlantic Water further to the north.

Densities of *P. carpenteri* specimens are at times so high that they fit the definitions of sponge grounds and have been found in many parts of the Northeast Atlantic. Extensive areas are reported from the west of Scotland ('*Holtenia* ground'), in the Porcupine Seabight west of Ireland and off Morocco. Smaller areas (by closer investigation they may well be classified as 'extensive') are found south of Iceland, off Portugal, around the Canary Islands and the Azores and in the western Mediterranean. Transect photography and controlled trawling in single areas have shown that the distribution is often patchy, with densities of between 0.17 and 6 specimens per square metre (Rice *et al.* 1990; Barthel *et al.* 1996). The two best documented examples of sponge grounds dominated by *P. carpenteri* are described in some detail below.

In the Porcupine Seabight southwest of Ireland, *P. carpenteri* was recorded in 1906 and 1911 in large numbers on the western side of the depression, between 900 m and 1,550 m depth. Later, between 1977 and 1986, it was again found in the area and also on the eastern flank, between 980 and 1,370 m. In biomass terms the species generally exceeds the remainder of the macrofauna by more than an order of magnitude. Investigation methods were epibenthic sledge, camera and box corer. The camera revealed about three times more specimens than the sledge. Size frequency distribution diagrams from sledge content and photographs showed identical mean diameters, but with a larger range in the photographs. Small (possibly juvenile) specimens were lacking, even if mean diameters ranged from 12 to 17 cm, and the maximum from 14 to 25 cm, maybe indicating different ages or histories of the single subpopulations. The subpopulation with the smallest specimens, between 4 and 5 cm in diameter, also showed the lowest mean diameter, of 12.1 cm. Box core samples showed that in patches with high

Figure 8.1: *Pheronema carpenteri* at about 800 m depth off Morocco. Note the transparent membranes of the osculae and the tufts of spicules anchoring the sponges in the sediment. *H. Thiel, Hamburg.*

concentrations of spicules from dead sponges, spicule mats give the bottom a special character.

Off Morocco, occurrences of *P. carpenteri* were reported in 1920, 1928, 1989 and 1996. Photo sledge transects and trawl catches revealed many specimens over a distance of 6 km at depths between 750 and 810 m. Within the last 1.4 km of the transect the number of individuals rose and then steeply decreased towards the end. Individual speci-

mens ranged from 4 to 20 cm in diameter with an average of 10 cm. Small specimens of 4 to 8 cm in diameter were very rare, and were only seen where the abundance of large individuals was highest. The largest trawl catch comprised only 14 individuals, with a relatively high proportion of small ones. Spicule heaps from dead individuals and small mat-like areas are seen in the photographs, and there are indications that large parts of these mat-like areas are covered by sediment.

9. Case Study 4: The deep Antarctic shelf, a 'sponge kingdom'

The Antarctic was called the 'sponge kingdom' in an early phase of Antarctic zoogeographical research by V.M. Koltun (1968; 1969). Since then, comprehensive biodiversity surveys have considerably increased our knowledge about the structure and function of the complex Antarctic marine ecosystem. Modern science has confirmed Koltun's statement, although it has to be noted that the Antarctic is not the only 'sponge kingdom' in the world's oceans. Also, it turned out that the Antarctic sponge fauna is not ecologically isolated, but part of a unique wider community of sessile suspension feeders (Dayton 1990; Barthel and Tendal 1994; Kunzmann 1996; Gutt *et al.* in press a).

Local densities of large sponges on the Antarctic continental shelf can reach world records in benthic wet weight biomass, with several kg per m^2 of which sponges can constitute more than 95 per cent (Barthel and Gutt 1992; Gerdes *et al.* 2008; see also Figures 9.1 and 9.2). Such sponge grounds have been found all around Antarctica, and especially in the Weddell and Ross Seas. The high densities are observed mostly at water depths between 50 and 350 m, although many of the species are also known from much greater depth. Several reasons have been suggested for the high standing stock of Antarctic sponges. Efficient predators of both juvenile recruits and adults are rare compared to around other continents. Substratum requirements are also not very specific, with sponges found on both boulders and soft sediments of poorly sorted grain sizes. Superior competitors for food and space are also rare. Generally, sponges and other suspension-feeding organisms benefit from the low turbidity resulting from the lack of terrestrial run-off in Antarctic coastal waters. In addition, Antarctic sponges living in the present interglacial might well experience what are effectively conditions of food surplus, since they would have been well adapted to the low food availability of glacial periods, with a permanent sea-ice cover over much of the past 1 million years. However, the very patchy and species-specific spatial patterns of Antarctic sponge distribution make their occurrence highly unpredictable in terms of space, time and environmental conditions. Some have even been found under the most severe conditions in areas formerly covered by permanent ice shelves, a habitat supposed to be extremely poor in food and resembling, in some respect, that of the abyss (Gutt *et al.* in press b).

Figure 9.1: Very dense sponge ground dominated by *Anoxycalyx joubini* (brown) and *Rossella racovitzae* (white and budding) up to 80 cm high. Southeastern Weddell Sea; depth 105 m. *J. Gutt, A. Starmans, W. Dimmler/ AWI/Marum, University of Bremen.*

Figure 9.2: A biomass-rich sponge ground dominated by the massive demosponge *Cinachyra barbata* (20-30 cm in diameter) and the vase-shaped hexactinellid *Anoxycalyx joubini* associated with dark-red hemichordates. Southeastern Weddell Sea; depth 235 m. *J. Gutt, A. Starmans, W. Dimmler/AWI/Marum, University of Bremen.*

Figure 9.3: Area dominated by 'lollipop' sponges of the genus _Stylocordyla_. The sponges are stalked and their bodies lifted 10-30 cm above the sediment surface. The species is typical of a later succession stage in the recolonization after iceberg disturbance. Southeastern Weddell Sea; depth 250 m. _J. Gutt, A. Starmans, W. Dimmler/ AWI/Marum, University of Bremen._

According to the Register of Antarctic Marine Species (RAMS) provided by the Scientific Committee on Antarctic Research – Marine Biodiversity Information Network (SCAR-MarBIN), 280 sponge species are known from the Antarctic.

Figure 9.4: Heavily disturbed sponge ground recolonized by fast-growing species including the thin branched _Homaxinella_, the thicker _Isodictya_ and the red _Kirkpatrickia_. Other members of the epibenthic assemblage are brush-shaped small and large orange sea-fans, pale compound sea squirts, sea cucumbers, and an intensely-coloured greenish-yellow gastropod. Western Weddell Sea off Snow Hill Island; depth 210 m. _J. Gutt, A. Starmans, W. Dimmler/AWI/Marum, University of Bremen._

By adding information from a few historical and very recent surveys, we can expect more than 300 species, as already assumed by Koltun (1970) and Barthel (1992). Interestingly, however, it is possible that the biodiversity of Antarctic sponges may be even greater than this estimate. The more intensively sampled Arctic continental shelf supports 163 known sponge species (Sirenko 2001) but covers a smaller area than that of the Antarctic shelf. Thus it is possible that the larger area of the Antarctic shelf could support three times the number of species currently known in the Arctic, a possible tally of 500 or more. The figures for both polar regions also include a small proportion of truly deep-sea species. The higher species numbers in the Antarctic can be explained, on the one hand, by a long period of environmental stability, Antarctica having existed as a cold and isolated continent surrounded by the cold circumpolar Southern Ocean for approximately 35 million years. On the other hand, recurrent environmental changes caused by the advance and retreat of inland ice might have accelerated the speciation of sponges, a phenomenon called the 'climate-diversity pump', a modification of the 'vicariance concept' (Clarke and Crame 1997). Such evolution-stimulating environmental changes have also happened around other continents and with the same frequency. However, whereas in most other places species came and went, in the Antarctic the generally slow ecological processes might be the cause of low extinctions rates.

Despite the fact that all sponges occurring in high concentrations in Antarctic waters belong to the Demospongiae or Hexactinellida, and despite the relatively homogenous environmental conditions on the deeper shelf, the variety of sponge life forms is astonishingly wide. Besides the many epifaunal species found on the surface of the seafloor, a few infaunal sponges, such as _Monosyringa longispina_, can also be abundant in the sediment. Not only do sponges settle on and in the sediment, some even grow on other sponges: _Tetilla leptoderma_, for example, can grow on _Rossella nuda_ and _Anoxycalyx joubini_. Some hexactinellid sponge species are known to grow extremely slowly in contrast to the very fast-growing demosponge _Mycale acerata_ and the fast-recruiting _Homaxinella_ species. The most abundant shape of Antarctic hexactinellid sponges is vase- or barrel-like ('volcano-sponges', Figure 9.1), reaching an impressive height of up to 2 metres. The more spherical, cabbage-shaped demosponges such as _Cinachyra barbata_ (Figure 9.2) or _C. antarctica_, and a variety of branched forms, also occur.

Stalked 'lollipop sponges' of the genus _Stylocordyla_ can be very abundant locally. These occur in a spherical (Figure 9.3) and an elongated form. Partly encrusting and partly erect-

growing sponges include the species *Kirkpatrickia variolosa* (Figure 9.4) and *Mycale acerata*, whereas others look like a fan or the ear of an elephant, for example *Isodictya toxophila*. The colour of Antarctic sponges is mostly beige, but with a variety ranging from intense yellow or shining red, pink and dark brown to almost white. Between, and even within, some hexactinellid species – for example *Anoxycalyx joubini* or *Rossella racovitzae* (Teixidó *et al.* 2006) – the co-occurrence of asexual budding (Figure 9.1) and sexual reproduction can be interpreted as an adaptation to the glacial periods when the benthos lived in small isolated refuges due to most areas being covered by grounded ice shelves. Under such conditions, the short-distance dispersal of offspring associated with budding might ensure a successful recruitment within small areas, while the long-distance dispersal of larvae associated with sexual repro-duction allows them to reach other refuges, which might be important for species survival in an environment shaped by the shift between glacials and interglacials. At the end of a glaciation period, when the shelf became exposed and available for benthic colonization again, long-distance dis-persal allowed fast recolonization of pristine areas.

With their high biomass and three-dimensional structure, Antarctic sponges play a significant role for other com-ponents of the benthic ecosystem. The sponge body can provide a protected microhabitat for many other species (Kunzmann 1996; Amsler *et al.* 2009; Figure 9.5). The amphi-pod *Polycheria antarctica*, for example, uses narrow, pouch-like cavities in the surface of the sponge *Polymastia* sp. as a safe place to gather food by filter feeding. Isopods live inside the sponge tissue and polychaetes hide behind the outer layer of the umbrella-shaped spiculae of *Rossella antarctica*, which acts like a protection shield. The osculum of hexactinellid sponges is used by isopods, polychaetes, amphipods, nudibranchs and gastropods as habitat. In some of these cases, species such as nudibranchs and gastropods feed on sponge tissue; in other cases the sponge provides an obligatory habitat for the organisms, which means they are only found on these sponges. Dayton *et al.* (1974) discovered on the shallower shelf of McMurdo Sound in the Ross Sea an unusually dynamic benthic assemblage maintaining a local equilibrium, in which the sponge *Mycale acerata* grows extremely fast, providing a food source for predatory asteroids, which in turn are controlled by other predators. In some cases, the sponge seems to benefit from a true symbiosis, for example when the tiny gastropod *Margarella* living on the sponge cleans its surface by feeding. Large sponges often provide habitat for mobile species such as crinoids, sea-cucumbers and ophiuroids, and also offer other sponges the opportunity to reach an elevated position to get access to food particles. Feeding on such particles is

Figure 9.5: Hexactinellid sponges of the genus *Rossella* provide a preferred substratum or microhabitat for other benthic organisms such as crinoids, dendrochirote holo-thurians and gastropods (white dot on the sponge surface, right side). Southeastern Weddell Sea; depth 155 m. *J. Gutt, A. Starmans, W. Dimmler/AWI/Marum, University of Bremen.*

much more efficient a few decimetres above the sea-bed than at the sediment surface (Gutt and Schickan 1998). Some *Trematomus* fishes have been observed to use the upper rim of sponges to rest on, save energy and observe the surroundings for potential prey or predators. In case of danger, they hide inside the osculum of the sponge, where some species even lay their eggs (Barthel 1996).

The growth, diversity and development of sponges and sponge grounds in the Antarctic seem to demand both envi-ronmental stability and a certain dynamic in the ecosystem. Despite high environmental stability in most variables, ice-berg scouring and anchor ice formation can be major local disturbance factors for Antarctic benthic ecosystems. Some sponges, such as *Homaxinella* spp. (Figure 9.4) and *Tedania tantula*, are obviously well adapted to respond to such events and recruit much faster than other organisms and, thus, determine locally the further succession of the benthic development after an ice impact. Other sponges are most abundant in later stages of recolonization, like species of *Stylocordyla* (Figure 9.3), whilst slow-growing, large, adult hexactinellid sponges are good indicators of a long period without disturbance. As a consequence, a broad variety of sponges contribute to a high species turnover (beta-diversity), especially in areas with a heterogeneous environ-ment and patchy, overall moderate levels of disturbance. According to the Intermediate Disturbance Hypothesis (Connell 1978), a higher frequency of disturbance would generally lead to poorer communities, consisting only of a few pioneer species among sponges and other taxa

Figure 9.6: Close-up of a *Tetilla leptoderma* with extended osculum, which is normally contracted in caught specimens. This massive demosponge is up to 20 cm in height and rather common. It is often found in recolonization areas, and in later stages of sponge ground development living on other sponges. Western Weddell Sea off Snow Hill Island; depth 305 m. *J. Gutt, A. Starmans, W. Dimmler/AWI/Marum, University of Bremen.*

as observed in single iceberg scour marks (Gutt and Piepenburg 2003). Competitive displacement due to low disturbance rates would allow the sponge *Cinachyra barbata* in rare cases to locally dominate the benthic assemblage, and consequently overall biomass and abundance is high, but diversity is low (Figure 9.2).

When hexactinellid sponges die, their skeletal remains form spicule mats. These mats provide a unique substratum for the next generation of benthic animals. Not only tiny meiobenthic species, but also young sponges and other large sessile organisms, benefit from such a development. Due to their slow metabolism, most sponges do not contribute considerably to a global marine carbon budget despite their high standing stock. However, their ability to convert dissolved silicate to solid opal, which forms the skeleton of hexactinellid and abundant demosponge species, has been calculated to exceed that of silicate-shelled plankton such as diatoms (Barthel 1995, Maldonado *et al.* 2005). But it has to be noted that this finding can only be applied to the regional spatial scale along the Antarctic coast, the 'sponge kingdom'.

In summary, the entire Antarctic shelf provides a potential habitat for demo- and glass sponges. The occurrence of sponge grounds in Antarctic coastal waters is caused by complex environmental conditions in combination with species-specific environmental demands. As a consequence, Antarctic sponge 'hot-spots' are frequent and scattered all around the continent. Although generally moderate in diversity, sponges can locally dominate the entire macrobenthic fauna. Even so, sponges usually do not rival or outcompete other organisms. Instead, they provide habitat and attract a multitude of other species, which is a major factor and contribution to the relatively high biodiversity of Antarctic shelf ecosystems. Because more than 50 per cent of the Antarctic sponge species are endemic, the 'sponge kingdom' is particularly vulnerable, and these important and fascinating habitats must be protected from direct and indirect anthropogenic impact.

10. Uses of sponges

HISTORICAL PERSPECTIVES

In antiquity sponges were already known for their medicinal and health properties and were as highly valued as silks, perfumes and spices (Bernard 1968). Classical texts by Homer and Aristotle refer to their use in medicine and beauty regimes and show early knowledge of sponge biology. Aristotle believed that evolution from plant to animal was a continuum and that the sponges, apparently showing characteristics of both, were good evidence of this (Voultsiadou 2007). Sponges have been used as disinfectants in surgery and sponge biomatrix has also been also used as plaster and as bone/tissue replacement (Müller *et al.* 2004).

Sponges have been one of the most successful phyla on Earth both environmentally and economically (Hooper and van Soest 2002). Until the 1950s, only shallow-water sponges were accessible enough to be investigated and used, supporting a thriving sponge fishing industry centred on the Mediterranean from Croatia to Greece. The Greek island of Kalymnos became rich from its commercial bath sponge fishery, reaching its peak between 1800 and 1960 when it was renowned as a world centre (Bernard 1968). With the demise of the Mediterranean sponge fishing industry, some Greek sponge divers emigrated to Tarpon Springs, Florida, where commercial shallow-water sponges thrive in the Gulf of Mexico (Stevely and Sweat 2000). A local shallow-water sponge fishing industry still operates there today.

From 1960 onwards, the invention of synthetic sponge materials threatened natural bath sponge fisheries since the latter were more costly to collect. At first, continued demand for natural sponges in the ceramic and leather tanning industries remained high, but as the absorptive and textural qualities of synthetic sponges improved, the market for natural sponges declined. Currently, sponge fishing occupies a small niche market catering to high quality applications such as impact absorbers in industrial machinery.

CURRENT USES IN BIOTECHNOLOGY

The long evolutionary history of the phylum Porifera over a billion years means that a rich coevolution has produced diverse morphologies and a variety of secondary metabolites. Systematic analysis for bioactive compounds in sponges began in the early 20th century when Richet (1906)

demonstrated how an aqueous extract from *Suberites domuncula* displayed toxic effects on dogs and rabbits; we now know that the active molecule is the protein suberitin (Müller *et al.* 2004). Some of the first nucleosides from the Caribbean sponge *Cryptotethya crypta* were isolated by Bergmann and Feeney in 1949 and were later shown to have antiviral properties (Thakur and Müller 2004). The synthesis of these nucleosides led to the production of the first anti-viral compound arabinosyl-adenine (Ara-A) which is active against herpes, and arabinosyl-cytosine (Ara-C) which is effective in leukaemia treatment. The latter compound is currently sold by the company Pharmacia & Upjohn under the brand name Cytosar-UR.

As a result of pioneering research in marine natural products drug discovery by the Roche Research Institute of Marine Pharmacology during the 1970s, scientists began to explore the chemical diversity found in marine organisms

Figure 10.1: Photograph of a sponge diver. *South Atlantic Humanities Center archive (http://sahctest.lib.vt.edu).*

and the potential for discovery of new drugs from the marine environment. Marine invertebrates are the most reliable sources of useful bioactive compounds and, among these, sponges are the most prolific. Since they are sessile and attached to the seabed they have evolved a sophisticated and unique chemical communication and defence system based on secondary metabolites. These metabolites also interact with receptors and enzymes involved in human disease processes. For example, the secondary metabolite macrolide lactone FK506 acts as an effective immunosuppressant both in sponges and humans by preventing allograft (tissue transplant) rejection (Müller *et al.* 2004).

A major emphasis has been on the discovery of marine-derived anticancer compounds, due in large part to the availability of funding to support marine-derived cancer drug discovery. In the United States of America, the National Cancer Institute has led this effort through its programmes to support both single-investigator and multi-institutional research for the discovery of cancer drugs based on natural products. As a result, several marine-derived compounds have advanced to human clinical trials for the treatment of cancer. One example is a compound named discodermolide, a polyketide isolated from the deep-water sponge *Discodermia*, which inhibits cancer cell proliferation by interfering with the cell's microtubule network (Ter Haar *et al.* 1996). While emphasis has been on identifying new anticancer compounds, marine natural products have also been found to have other biological activities, including mediating inflammatory responses.

The intermediary metabolism created by the association between sponges and microorganisms (which often constitute more than 40 per cent of their volume) has allowed the evolution and development of secondary metabolites in the defence against pathogens and the control of disease (Müller *et al.* 2004). The ancient, highly specialized relationships between the host sponge and its associated microorganisms mean that it remains unclear whether the secondary metabolites and compounds are produced by the microorganisms, the sponge itself or an interaction between the two. This relationship should thus not be assumed immediately to be a mutually beneficial one. This uncertainty is in part a consequence of sponges being used in the laboratory as source material for the isolation of microbes in drug screening and discovery programmes (Hill 2004). The ecological dynamics and relationships between the microorganisms and the sponge *in situ* have been somewhat neglected, contributing to some of the challenges that researchers face when studying these relationships *in vitro*. The context and scientific understanding behind these drug discovery ventures are thus of great significance for long-term pharmaceutical development and depend on cooperative collaboration between drug discovery and basic biology.

The highly bioactive compounds of sponges are extremely valuable (Figure 10.2). Although there is a major effort by pharmaceutical companies in the design of synthetic chemicals for drug discovery, marine natural products still provide unusual and unique chemical structures on which molecular modelling and chemical synthesis of new drugs can be based. With such a long evolutionary history, the biochemistry of sponges has been optimized so that natural compounds obtained from sponges will almost always be superior to combinatorial chemistry trials in the laboratory.

Searching for useful and as yet unknown potentially useful bioactive compounds from sponges is fraught with specu-

Table 10.1: Sponge metabolites discovered and used in drug development research.
Adapted from Pomponi 2001.

Organism	Metabolite	Location	Discoverer	Current status
Sponge: *Discodermia dissoluta*	Discodermolide	Caribbean	Gunasekera & Longley, Harbor Branch Oceanographic Institute, USA	Licensed to Novartis
Sponge: *Lissodendoryx* sp.	Isohomo-halichondrin B	New Zealand	Munro & Blunt; Univ Canterbury, NZ	Licensed to PharmaMar SA
Sponge: *Jaspis* sp.	Bengamide	Fiji	Crews *et al.* Univ California, Santa Cruz, USA	Synthetic derivative licensed to Novartis
Sponge: *Cymbastella* sp.	Hemiasterelins A & B	Papua New Guinea	Andersen, Univ British Columbia, Canada	Licensed to Wyeth-Ayerst
Sponge: *Pseudaxinyssa cantharella*	Girolline	New Caledonia	Poitier, France	Licensed to Rhone Poulenc

Table 10.2: Drug products derived from marine sponges.

Adapted from Pomponi 2001.

Product	Application	Original source species	Method of production
Ara-A	Antiviral drug	*Cryptotethya cryta*	Microbial fermentation of analogue
Ara-C	Anticancer drug	*Cryptotethya cryta*	Chemical synthesis of analogue
Manoalide	Molecular probe: phospholipase A2 inhibitor	*Luffariella variabilis*	Wild harvest of sponge

lation, high risk and expense. Most of the deep sea is yet to be explored. The reason for this deficiency is primarily financial: oceanographic expeditions are expensive, and funding is inadequate to support missions focused on bio-discovery. Sample collections have been made from targeted deeper-water sponge grounds using closed-circuit re-breather diving, dredging, trawling and submersibles. Increased sophistication in the tools available to explore the deep sea has expanded the habitats that can be sampled and has greatly improved the opportunities to discover new species and the chemical compounds they produce. As discussed in Chapter 2, new and improved platforms (such as autonomous, remote, and human-occupied underwater vehicles) to take us farther and deeper are currently in development. These platforms need to be equipped with even more sophisticated and sensitive tools (e.g. cameras,

sensors and manipulators) to allow researchers to identify an organism as new, to assess its potential for novel chemical constituents and, if possible, to non-destructively remove a sample. Tools and sensors that have been developed both for space exploration and for diagnostic medicine also need to be applied (Pomponi 1999). A number of miniaturized biosensors and probes to study human disease processes are in development. Adapting or developing new biosensors and probes for rapid, *in situ* screening of marine organisms would create specialized tools enhancing our ability to probe the expression of metabolites in

Figure 10.2: High value of natural secondary metabolites (evochemistry) compared with compounds obtained with traditional synthetic (combinatorial) chemistry. *Müller* et al. *2004/Springer publishing.*
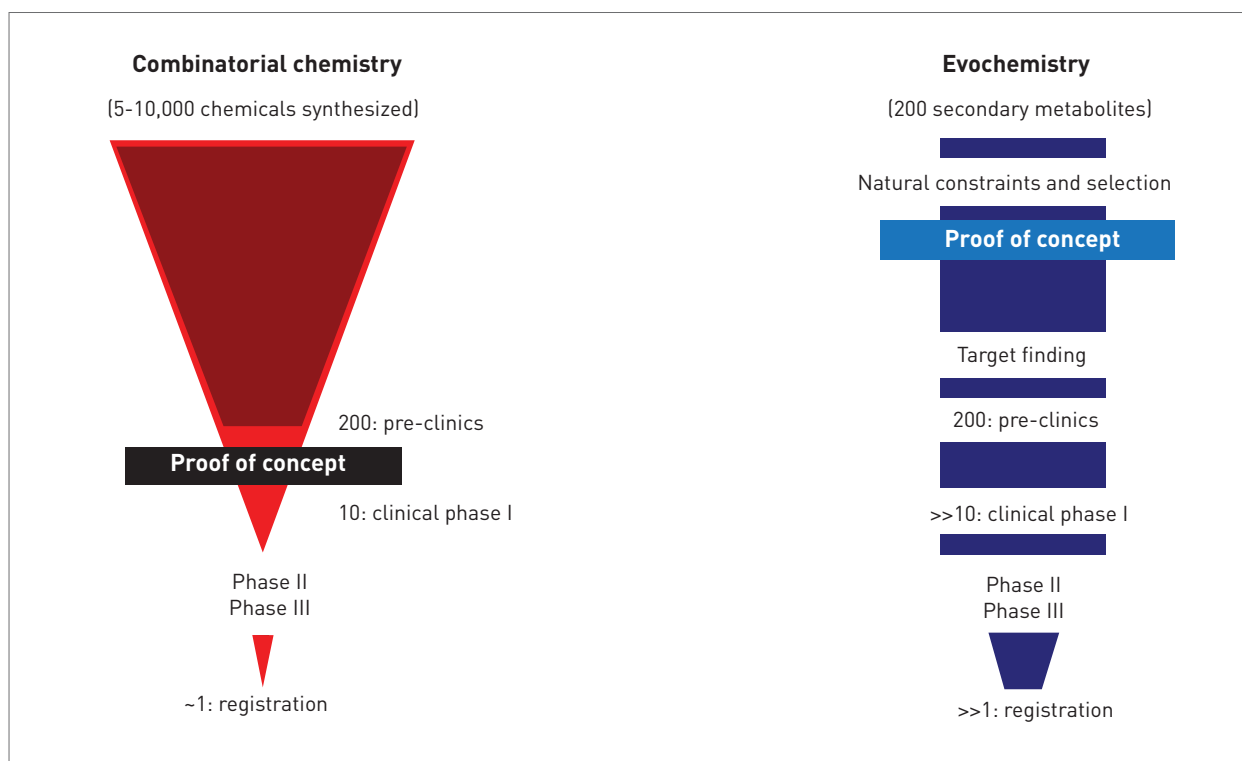
response to various stimuli. In turn this would lead to a better understanding of the role of secondary metabolites in nature, and perhaps provide clues to the potential bio-medical utility of these compounds (Pomponi 1999).

A major challenge that researchers face in developing bioactive compounds from sponges is in their synthesis and cultivation. As the metabolites are often produced in trace amounts, it is not possible to obtain the quantities needed for clinical applications from wild harvest of the source sponges. This is known in colloquial terms as the 'supply problem'. Four approaches have been used as solutions to this: chemical synthesis, microbial fermenta-tion, cell cultivation and aquaculture. Discodermolide, for example, was produced using chemical synthesis. Cell cul-tures of *Axinella corrugata* that underwent cell division in response to mitogenic stimulation by the plant lectin phyto-hemagglutinin continued to produce the bioactive meta-bolite stevensine in culture. Biosynthesis of stevensine in primary cultures of *A. corrugata* was further verified by incubation of enriched archaeocytes with radiolabelled amino acid precursors and subsequent detection of incorporation of the precursors into stevensine (Andrade *et al.* 1999). 'Primmorphs' are three-dimensional cell aggre-gates that can differentiate and proliferate. The synthesis of

a sponge secondary metabolite in a bioreactor was first achieved with primmorphs from the sponge *Dysidea avara* that produced the antiviral compound avarol. These trials have been successful and have progressed steadily over recent years. Aquaculture has a long history in shallow-water sponges, yet for deep-water species different con-ditions such as low temperature and high pressure need to be replicated (Pomponi 2001). A New Zealand sponge, *Lissendoryx* sp., which produces bioactive halichondrins, has been successfully cultivated at shallower depths than those it usually inhabits.

The difficulty in cultivating sponge bioactive compounds has led to approaches to identify biosynthetic pathways and develop recombinant methods for production. For example, genome analysis has been used to identify and express arrays of genes present in the sponge genome. These genes encode chains of enzymes involved in the synthesis of the bioactive compounds existing in gene clusters (Thakur and Müller 2004). Interesting trials using fluorescence *in situ* hybridization (FISH) with rRNA-targeted oligonucleotide probes on thin sections of sponge tissue may avoid the need for culturing microorganisms in analytical stages (Osinga *et al.* 2001). Denaturing gradient gel electrophoresis is used to determine the differential characteristics of the recovered microorganism and the structural encoding of the bacterial community. Results so far have been mixed, indicating the intricate specialization of the relationship between the micro-organism and its sponge host. This is a rapidly developing

Figure 10.3: A diagram demonstrating the systematics of gene expression in the sponge *Verongia aerophoba*. *Müller* et al. *2004/Springer publishing.*
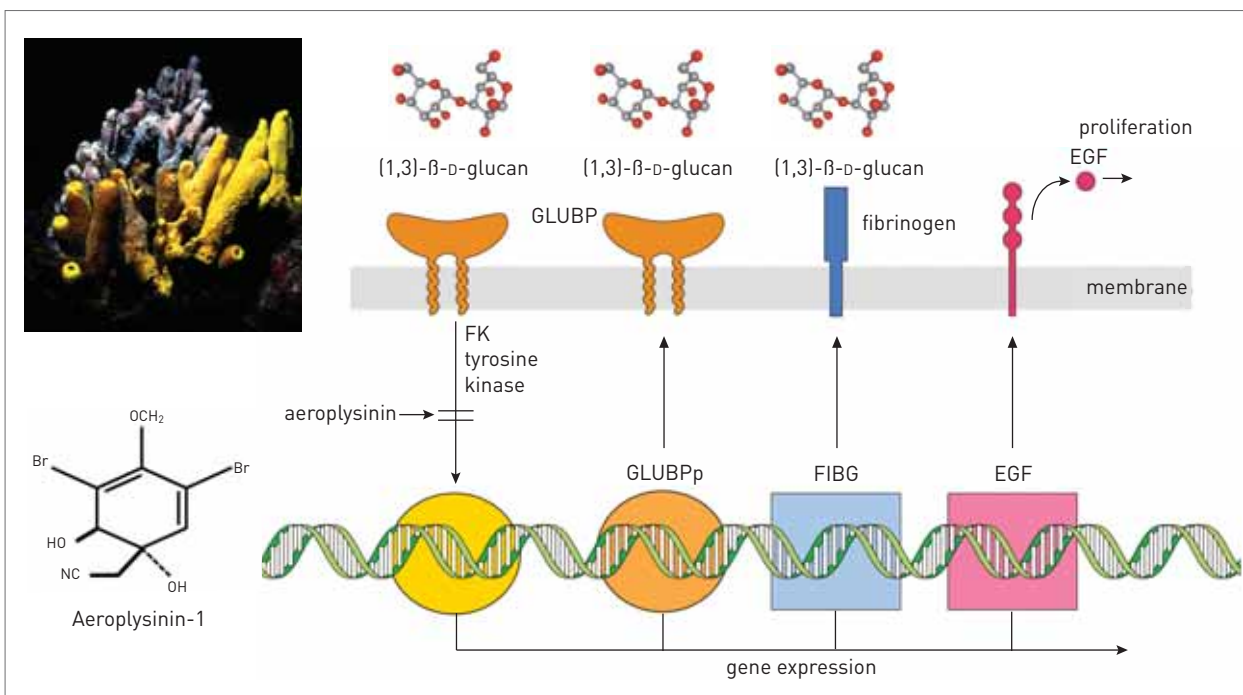
field of research and the studies carried out so far are the beginning of a promising enterprise that only started in the last decade.

The biological evaluation of marine-derived extracts and pure compounds for pharmaceutical development has been based on assays developed by the pharmaceutical industry for high-throughput screening of large libraries of synthetic compounds. They measure a number of end-points, such as activation or inhibition of enzymes or receptors involved in human disease processes, inhibition of growth of human pathogenic microorganisms, and toxicity against human cancer cells. As our understanding of the biochemistry behind a variety of diseases has improved, better methods have been developed for rapidly determining the biomedical potential of the metabolites produced by marine organisms.

As model systems, marine organisms offer the potential to understand and develop treatments for disease based on the normal physiological role of their secondary metabolites. For example, the mechanisms of action of the toxins of *Conus*, the poisonous snail, are well known, and are currently being applied to the development of new classes of drugs to treat diseases such as epilepsy.

Marine organisms have already demonstrated their utility as biomedical models, the results of which have been applied to understanding normal and disease processes in humans. Can we continue to apply this knowledge to our rapidly increasing understanding of the human genome and human disease processes? Or perhaps a more relevant question is: can we use our rapidly increasing understanding of the human genome and human disease processes to guide our discovery of novel marine-derived chemicals that can be used against newly-discovered disease targets? Considering the evolutionary conservation of molecular signalling pathways, one can hypothesize that our understanding of molecular pathways and disease targets in mammalian systems can not only help us to elucidate the ecological roles of marine-derived metabolites, but can also provide a more rational approach to the discovery of drugs to treat a variety of diseases. How does a sponge, through which seawater and associated bacteria, fungi, and viruses constantly flow, defend itself against microbial infections? How does it signal its cells to divide rapidly enough to heal a damaged surface in a few hours, or spread out over a substratum in a matter of days or weeks, yet control this proliferation so that the sponge itself does not get cancer? How, with only a primitive immune system, does it recognize an invading organism as 'non-self' and send out chemicals to kill the invading cells, without killing its own cells? We know little about these processes in the organisms from

which we have identified literally thousands of chemicals with biomedical potential.

Molecular tools and approaches that have been developed to understand similar processes in mammalian systems must be applied to understanding these processes in marine organisms. A multidisciplinary approach to the study of marine-derived drugs involving molecular biologists, pharmacologists and chemical ecologists will promote the discovery of unique bioactive chemicals and new ways to address the treatment of human disease in the future.

FIBRE OPTICS, ENGINEERING AND DESIGN

In recent years, as well as the importance of sponges as a source of pharmaceutically-active compounds, their wider biotechnological potential in providing new designs for fibre optics, glass, civil engineering and semiconductors has also been recognized.

In the USA, researchers have found that the fragile yet remarkably resilient skeletal structures of marine sponges correspond to the fundamental mechanical properties used in famous landmarks such as the Swiss Re Tower in London, the Eiffel Tower in Paris and the Hotel Arts in Barcelona. Might the skeleton of marine sponges lead to the development of new concepts in materials science and engineering?

In fibre optics, synthetic composite fibres developed from insights into sponge architecture with high mechanical strength have opened new approaches within this technology (Aizenberg *et al.* 2005). In the sponge *Euplectella*, known as Venus' flower basket, a hierarchy of structural levels has been identified in which the lattice pattern of the skeleton is arranged and strengthened by fibres that run at a diagonal in two directions through alternate intersections at square corners (Aizenberg *et al.* 2005). This same architecture is often found in high-rise buildings and freestanding shelving to prevent shear stresses which would otherwise cause an unreinforced square structure to collapse. Even though sponge skeletons may appear fragile, the structures they create can be remarkably strong.

Recently, the biomolecular mechanisms that control the ability of sponges to fabricate silica at a nanoscale have been examined. Photovoltaic and semiconductor nanocrystals of titanium dioxide, gallium oxide and other semiconductors could be directly synthesized using similar techniques derived from sponges (Morse 2007). As marine sponges produce many silica spicules, mimicking the way they construct skeletal glass spicules at a nanoscale should be a significant step forward in accomplishing this goal.

A protein named silicatein from the filament of sponge spicules controls their synthesis. After cloning and sequencing the DNA of the gene that coded this protein, it was discovered that this protein also functioned as an enzyme that catalysed formation of glass spicules. This was the first time that a protein had been shown to act as a catalyst for a glass material of a biomineral. Hence silicatein plays two roles almost simultaneously, promoting the formation of the silica spicule whilst serving as a template to guide the shape in which the biomineral glass grows. One major advantage of discovering this enzyme is that it operates at the relatively low temperatures inhabited by the sponge, so offering the prospect of developing synthetic materials at lower temperatures, thereby reducing both energy expenditure and cost.

Sponges have also demonstrated a method of producing fracture-resistant glass rods and fibres, and trials to apply these findings to practical engineering are under way. Biological processes from sea urchins have been studied to produce flexible ceramics, and abalone shells are being studied to help engineer more efficient solar panels (Weaver *et al.* 2007). Thus sponges are not the only group of marine invertebrates at the forefront of a new explosion of interest in using marine species in engineering applications.

11. International actions

At the time of writing, only 0.7 per cent of the oceans and 5.9 per cent of territorial seas were protected as some form of marine protected area (MPA) (UNEP-WCMC World Database on Marine Protected Areas: http://www.wdpa-marine.org), with none designed to conserve deep-water sponge grounds in particular. There are, however, a number of national and international fisheries closures for bottom fishing gear which may also help to protect deep-water sponge grounds. For example, in the Northwest Atlantic, evidence of sponge grounds from research trawl bycatch data led the regional fisheries management organization NAFO (Northwest Atlantic Fisheries Organization) to close several areas on the continental slope of Canada (NAFO 2009b) (see map of closures under http://www.fao.org/fishery/topic/16204/en).

Without precautionary action, effective conservation management relies on a sound scientific understanding of marine ecosystems. However, our understanding of deep-sea ecosystems is in its infancy. What is known about deep-sea fauna is that it is generally adapted to a low-food environment which favours the life-history strategies of typical 'K-strategists': slow growth, large size and limited and infrequent fecundity. This slow mode of life makes the fauna of the deep seafloor particularly vulnerable to any rapid changes, such as human impacts from bottom fishing, waste disposal, minerals mining or pollution, and the effects of natural disturbances such as submarine landslides, iceberg scouring or a shift in the temperature patterns of ocean currents. Although some sponges may be more resilient to change, the deep-water sponge grounds of various types reviewed in this report are typically composed of large individuals (some reaching more than a metre in size and weighing over 20 kg) that may attain great ages (up to 220 years).

With growing knowledge, and in particular when the first visual observations of cold-water corals showed significant habitat destruction by bottom trawling, concern for deep-water conservation reached a new urgency. Since 1999, when Norway enacted fisheries closures to protect cold-water coral reefs, a new conservation framework has been developed and agreed internationally which addresses threats from deep-water fisheries (United Nations General Assembly (UNGA) Resolution 61/105 on sustainable fishing in the high

seas). Since the World Summit on Sustainable Development in 2002, this also aims to provide protection to a global network of MPAs by 2012 (WSSD 2002). Although both avenues are in their early development, the structural basis has now been laid for finding solutions to conflicts between the legitimate use of the sea and the conservation of its resources for humankind.

Because deep-water bottom trawling has damaged deep-water sponge grounds and great efforts have been made in recent years to understand and control trawl damage, this chapter of the report will focus first on the international conservation framework and then critique recent proposals put forward to limit damage to deep-sea benthic habitats. As discussed in Chapter 5, it appears likely that deep-water sponge grounds may be vulnerable to the effects of global climate change, particularly local changes in seawater temperature. That said, the international actions currently proposed to limit climate change and control anthropogenic carbon dioxide release are beyond the scope of this report.

The WSSD 2002 global agreement to implement an ecosystem approach to managing human activities was instrumental in introducing the precautionary approach to guide action in the case of insufficient knowledge. In the case of fisheries management, the ecosystem approach introduced a holistic view on fish populations as part of a wider ecosystem. To consider how these broad goals may apply to the conservation of deep-water sponge grounds we begin by summarizing the roles of relevant international agencies and organizations.

UNITED NATIONS GENERAL ASSEMBLY AND UNCLOS

The UNGA is the main decision-making body for a number of UN agencies, conventions such as the United Nations Convention on the Law of the Sea – UNCLOS (established in 1982), and affiliated instruments and organizations with a mandate for regulating aspects of the resources of the sea and uses of the ocean, including the protection of vulnerable marine ecosystems (VMEs), especially in international waters.

UNGA Resolution 61/105 on sustainable fisheries, adopted in December 2006, called on states and regional fishery

management organizations (RFMOs) to implement, among others, the following measures by 31 December 2008, or else not authorize high-seas bottom fishing (paragraph 83 of Resolution 61/105):

■ conduct impact assessments of individual high-seas bottom fisheries to ensure that 'significant' adverse impacts on VMEs would be prevented or else not authorize bottom fishing to proceed;

■ close areas of the high seas where VMEs are known or likely to occur to bottom fishing, unless bottom fisheries can be managed in these areas to prevent significant adverse impacts on VMEs;

■ require fishing vessels to move out of an area of the high seas where 'unexpected' encounters with VMEs occur. 'Unexpected' means in areas where the occurrence was not previously known.

In 2009, on revising implementation of the 2006 resolution, the UNGA reaffirmed and strengthened the goals set in 2006. States and RFMOs were found to be slow to implement the measures requested by the 2006 resolution, which called for the management of high-seas bottom fisheries to protect VMEs. The UNGA will review, in 2011, the actions taken by states and RFMOs to implement the 2009 resolution.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO)

The Food and Agriculture Organization of the United Nations (FAO) is the responsible global fisheries management organization of the UN. For many years, FAO has delivered guidelines and technical advice on implementation of the ecosystem approach and the precautionary approach in fisheries management. The FAO guidelines for the implementation of UNGA Resolution 61/105 of 2006 (FAO 2009) were developed in consultation with a wide range of stakeholders.

GLOBAL CONVENTIONS AND PARTNERSHIPS

The Ninth Conference of the Parties to the Convention on Biological Diversity (CBD) in 2008 adopted Decision IX/20/8 (CBD 2008a) which, *inter alia*:

■ 'Urges Parties ... to identify ecologically or biologically significant and/or vulnerable marine areas in need of protection ... and implement conservation and management measures, including the establishment of representative networks of marine protected areas in accordance with international law, including the United Nations Convention on the Law of the Sea.'

■ 'Urges Parties ... to undertake further research to improve understanding of marine biodiversity ... paying special attention to those ecosystems and critical habitats that are relatively unknown.'

Annex II of this decision sets out guidelines on selecting areas to establish representative networks of MPAs including sponges and other deep-sea habitats under five headings: ecologically and biologically significant areas; representativity; connectivity; replicated ecological features; and adequate and viable sites. Further details of this decision and its appendices can be found at http://www.cbd.int/decision/cop/?id=11663.

Significant progress has been made since 2008: a global biogeographic system (Global Open Oceans and Deep Seabed (GOODS) Biogeographic Classification) was developed by the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) in response to the request of the Conference of the Parties in paragraph 6 of Decision IX/20. The applicability of the CBD selection criteria for 'ecologically or biologically significant and/or vulnerable marine areas' was tested for a wide range of areas and presented to a CBD workshop in 2009 (CBD 2009). Guidance has been developed for the use and further development of both the biogeographic classification systems and the identification of areas beyond national jurisdiction.

INTERNATIONAL UNION FOR CONSERVATION OF NATURE (IUCN)

The International Union for Conservation of Nature (IUCN) (formerly IUCN–the World Conservation Union) is a global intergovernmental organization working for conservation. It has a global marine programme which has produced a large number of guidelines, documents and papers related to the conservation, management and sustainable use of marine ecosystems and the design of effective MPAs. The IUCN Congress in Durban in 2003 marked a paradigmatic shift in management from viewing MPAs as 'islands of conservation' towards a global network approach including areas 'beyond boundaries' (Laffoley *et al.* 2008). IUCN is key to the strong momentum towards implementing the ecosystem approach to fisheries globally and to enable the establishment of MPAs beyond national jurisdiction.

EUROPEAN UNION

The Council of the European Union and the European Commission were given powers by Member States to regulate the exploitation of fisheries resources under the Common Fisheries Policy (Council Regulation (EC) No. 2371/2002), supplemented by several regulations for the conservation of fishery resources through technical measures for the protection of juvenile marine organisms (Council Regulation (EC) No. 850/98). This competence applies in the exclusive economic zones (EEZs) of Member States outside the 12 nm border demarcating territorial water under

national legislation and to the vessels flying a European flag in all waters. Council Regulation (EC) No. 1005/2008 has reinforced earlier regulations, setting out, *inter alia:*

- ´The objective of the Common Fisheries Policy ... is to ensure exploitation of living aquatic resources that provides sustainable economic, environmental and social conditions. For this purpose, the Community shall apply the precautionary approach in taking measures designed to protect and conserve living aquatic resources, to provide for their sustainable exploitation and to minimize the impact of fishing activities on marine eco-systems´ (Extract from Article 2 Objectives).

Emphasis in this regulation was placed on suitable levels of monitoring and enforcement which are perceived to have been lacking in previous reviews. Deep-water sponge grounds are not yet mentioned in their own right on the lists of natural habitat types of community interest in the Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora (Habitats Directive (92/43/EEC)), which is legally binding on all European Union Member States and which mandates the designation of special areas of conservation. However, sponge grounds, if occurring on hard substratum, can be treated as a ´reef´ habitat, and as such are of European interest through the EC Habitats Directive. It is a requirement of this directive to protect and improve to favourable conservation status such reef habitats, including by designating MPAs (here called Special Areas of Conservation) to comprise an ecologically coherent network of sites (the Natura 2000 network). The aspirations of the Marine Strategy Framework Directive go even further and call for establishing a ´good environmental status´ in European waters by 2020.

Since the closure of the Darwin Mounds off Scotland set a precedent in the implementation of the ecosystem approach to fishing through the Common Fisheries Policy, several other areas have been closed to bottom fishing activities (for review see Hall-Spencer *et al.* 2009). The largest among these is the permanent closure for bottom fishing of the Azores EEZ since 2005.

OSPAR CONVENTION FOR THE PROTECTION OF THE MARINE ENVIRONMENT OF THE NORTH-EAST ATLANTIC

Under the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic, ´deep-sea sponge aggregations´ have been listed as a habitat under immediate threat and/or decline in the OSPAR area since 2003 (OSPAR 2008). The habitat has been defined for mapping purposes and in particular mentions the genera *Geodia* and *Pheronema*, which are the predominant habitat-forming

species in the region (see Case studies 2 and 3). So far no particular measures to protect the habitat have been taken by any contracting Party, although MPAs are recognized as one effective tool to increase protection of these sponge habitats. The extent to which the habitat benefits from fisheries closures within and beyond national jurisdiction has not been assessed. A baseline assessment report on the regional distribution, state and threats to deep-sea sponge aggregations in the OSPAR area has been prepared (OSPAR in press). OSPAR, in conjunction with obligations arising from European Union regulations and frameworks, will start monitoring and assessing the state of deep-water habitats.

Since 2003, OSPAR contracting Parties are committed to establishing an ´ecologically coherent network of well-managed marine protected areas´ in the OSPAR area by 2010. Such a network will necessarily have to include a representative fraction of the ´deep-sea sponge aggregations´ within the OSPAR region. In 2008, OSPAR adopted a code of conduct for scientific research in open-ocean and deep-water environments with the goal of avoiding unnecessary damage to species and habitats from scientific research sampling. Currently, none of the MPAs nominated for inclusion in the OSPAR network of MPAs by contracting Parties include deep-water sponge grounds.

INTERNATIONAL COUNCIL FOR THE EXPLORATION OF THE SEA (ICES)

The International Council for the Exploration of the Sea (ICES) promotes and encourages research and investigation of the marine environment and its living resources in the North Atlantic and adjacent seas, and responds to requests for advice from statutory organizations such as OSPAR, the North East Atlantic Fisheries Commission (NEAFC) and NAFO. The ICES Working Group on Deep-Water Ecology has reviewed and compiled the available literature and has drawn attention to the vulnerable state of habitat-forming sponges (ICES 2007, 2008 and 2009).

ACADEMIA

The VII World Sponge Symposium, entitled Porifera Research: Biodiversity, Innovation and Sustainability, took place in Brazil in 2007 (http://www.poriferabrasil.mn.ufrj.br/iss). This provided an opportunity for research scientists to present their advances in sponge diversity, behaviour and function and how these have the potential to be applied to biotechnology, taxonomy for measuring biodiversity, genetics and pharmacology, amongst others. It also stimulated an urgent call to governments to protect severely threatened sponge ecosystems and to urge the UN to establish a moratorium on bottom trawling in the high seas. This highlighted continued research and mapping as well as the creation and

management of MPAs that include sponge communities and coral reefs in which sponges exist. The next world conference on sponge ecosystems is in Girona, Spain on 20-24 September, 2010 (www.spongeconference 2010.org).

The most significant contributions to knowledge of the sponge fauna in the northern Atlantic have come from the nationally funded programmes BIOICE and BIOFAR systematically sampling the fauna around Iceland and the Faroe Islands, as well as Canadian and Norwegian investigations. The current MAREANO mapping programme of Norwegian waters will certainly produce a wealth of new knowledge on this and other benthic habitats. Several other national research programmes are under way to identify VMEs.

WORLD WIDE FUND FOR NATURE (WWF)
The World Wide Fund for Nature (WWF) has several international and regional campaigns and initiatives highlighting the urgency for the conservation and management of vulnerable marine ecosystems (VMEs) which include sponge aggregations in both national and international waters. The organization is active in national, regional and global policy and lends its support to regional initiatives, such as OSPAR and NEAFC, and aids the implementation of conservation measures and recommendations. Further information is available at www.ngo.grida.no/wwfneap and www.panda.org.

DEEP-SEA CONSERVATION COALITION
Almost 50 non-governmental organizations from around the world collaborate in the Deep-Sea Conservation Coalition to protect seamounts, cold-water corals and vulnerable deep-sea ecosystems. In 2006 the Deep-Sea Conservation Coalition called on the UNGA to secure a moratorium on high-seas bottom trawling. This, alongside large petitions gathered at scientific conferences, led to the adoption of UNGA Resolution 61/105 in late 2006. Further information is available at www.savethehighseas.org

12. Conservation considerations

The risks to a marine habitat are determined by its vulnerability, the probability of a threat occurring and the mitigation measures applied to the threat. All benthic marine habitats are vulnerable to anthropogenic disturbance to some degree; however, some, in particular complex macrohabitats like reefs and aggregations formed by biota in deep water, are likely to lack the ability to regenerate from substantial impacts (see review in Parker *et al.* 2009). Wherever deep-water sponge grounds occur, their range of distribution is very likely to include areas within fishing depth, usually on the slopes of the continental shelf, offshore banks and islands. Due to the wide- and large-scale effort of bottom trawling fisheries, the threat from this type of activity was ranked highest in the Northeast Atlantic (Hughes *et al.* 2003; Sheppard 2006 in Smith and Hughes 2008), though some rocky outcrops may not be easily accessible to fishing gear. In this chapter we outline the case for deep-water sponge grounds to be considered 'vulnerable marine ecosystems' (VMEs) in the context of United Nations General Assembly (UNGA) Resolution 61/105.

ARE DEEP-WATER SPONGE GROUNDS VULNERABLE MARINE ECOSYSTEMS?

The *International Guidelines for the Management of Deep-Sea Fisheries in the High Seas* (FAO 2009) provide a range of recommendations on how to identify vulnerable marine ecosystems and assess significant adverse impacts. A marine ecosystem should be classified as vulnerable on the basis of the characteristics that it possesses. States and regional fisheries management organizations and arrangements (RFMO/As), and as appropriate the Food and Agriculture Organization of the United Nations (FAO), should assemble and analyse relevant information on areas under the competence of such RFMO/As or where vessels under the jurisdiction of such states are engaged or plan to be engaged in deep-sea fisheries.

The following list of characteristics has been proposed as criteria to identify VMEs. The list could be adapted and additional criteria could be developed as experience and knowledge accumulate, or to address particular local or regional needs. It is important to note that the guidelines (as with UNGA Resolution 61/105) explicitly take a precautionary approach, emphasizing that where site-specific information is lacking, other information that is relevant to inferring the likely presence of vulnerable populations, communities and habitats could be used. This will help lead to the identification of areas where the habitat is 'likely to occur'.

Uniqueness or rarity – *an area or ecosystem that is unique or that contains rare species whose loss could not be compensated for by similar areas or ecosystems. These include:*
- *habitats that contain endemic species;*
- *habitats of rare, threatened or endangered species that occur only in discrete areas; or*
- *nurseries or discrete feeding, breeding or spawning areas.*

Deep-water sponge grounds are neither unique nor rare features when taken as a mass phenomenon. However, they occur in particularly limited areas where temperature, substratum, currents and the provision of planktonic food are favourable, currently mapped as distinct patches and often separated by wide distances, although this pattern remains poorly understood (Klitgaard *et al.* 1997; Klitgaard and Tendal 2004). The community composition of each patch varies across sites, notably with regard to the dominance and composition of sponge species and associated fauna. Next to a large number of facultative associates, there is also a substantial proportion of obligate associate species which would not be present without the sponge habitat (e.g. Klitgaard 1995, and see below).

Deep-water sponges also have biochemical and genetic properties, some of which show biomedical potential. These characteristics might be considered rare or even unique (see Chapter 10).

Functional significance of the habitat – *discrete areas or habitats that are necessary for the survival, function, spawning/reproduction or recovery of fish stocks, particular life-history stages (e.g. nursery grounds or rearing areas), or of rare, threatened or endangered marine species.*

Sponge grounds can increase the physical heterogeneity of habitat and the number of available microhabitats in deep-sea ecosystems through their morphology by adding structure and complexity to the physical habitat. This creates additional space for fish and invertebrates in terms of

shelter and other needs. An enhanced level of structure and complexity has been demonstrated to be of particular importance during times of reproduction and for juvenile life-stages (Auster 2005), or at night for diurnal species (Brodeur 2001). For more information see Chapter 4.

Fragility – an ecosystem that is highly susceptible to degradation by anthropogenic activities.

Fragility as defined here is determined by the sensitivity of the species or habitat due to its life-history traits, including its regenerative capacities. ICES (2007) considered structural sponge habitat as being ´*extremely vulnerable to commercial trawling suffering immediate declines through direct removal of sponges and further reductions in population densities of sponges due to delayed mortality´*

(Freese 2001). In the case of direct removal, sponges tipped out on deck, even if they appear undamaged, will be drained of water and are unlikely to recover if they are thrown back into the sea. Even sponges brought to the surface and released before hauling on deck are unlikely to survive as sponges sinking *en masse* may settle upside-down or on the wrong type of seabed (Klitgaard and Tendal 2004).

The large-sized sponge species, which dominate the species composition of deep-water sponge grounds such as those in the North Atlantic, are particularly vulnerable to human impacts due to their body volume and erect position. Individual sponges, in particular those of warmer, shallower waters, can tolerate to some extent being wounded, older sponges having the better ability to regenerate tissue compared to younger ones. Juvenile sponges may not be

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Table 12.1: Summary of the prognosis for recovery of structure-forming deep-water sponges according to various disturbance types associated with fishing activities. Recovery assessment is based on individual sponges as opposed to community-based. *ICES 2009.*

DISTURBANCE TYPE	COMMENTS	PROGNOSIS FOR RECOVERY
Mechanical damage		
Minor tearing of body wall	Sponges showing tissue repair have been collected; increased risk of infection; distal wounds appear to heal faster than wounds on lateral surfaces	Excellent
Large wounds relative to body size	Incomplete regeneration; increased risk of infection; impaired reproduction and growth	Moderate
Breakage at base	No signs of recovery after one year during experimental trawling in Alaska	Very poor or no recovery
Dislodgement		
Minor change to orientation, position relative to currents not strongly affected	Sponges can lay new growth down to adapt to minor change in current direction	Unaffected
Significant change to orientation, position relative to currents strongly affected	Sponges likely to die if food availability is restricted as a result of dislodgement	Poor
Sponge dislodged on bottom, free-floating		No recovery
Sponge brought up on deck and returned	When the aquiferous system is drained very few sponges can refill it; air in the chambers causes the sponges to float	No recovery
Crushing	Turning over of substratum commonly seen in trawl tracks	No recovery
Sedimentation		
Light accumulation of sediments in incurrent aquiferous system, no serious damage to aquiferous system	Ability to clear sediment; sediment accumulation can be viewed in cross sections with concentrations near ostiole	Very good
Repeated accumulation of sediments in incurrent aquiferous system	Sponge death or impairment	No recovery

able to regenerate tissue (Simpson 1984; Henry and Hart 2005). Larger and more complex sponge morphology favours regeneration, provided the wound extent does not exceed a certain ratio in relation to overall size (Henry and Hart 2005). Smothering can also be tolerated to some degree; however, the raised energetic costs affect regeneration abilities (Henry and Hart 2005), see Chapter 5. The type of damage that may occur to an individual sponge through fishing disturbance and a subjective expert evaluation of the recovery potential is given in Table 12.1. (ICES 2009). However, it is important to note that ICES (2009) emphasized that habitat recovery is very different from the ability of an individual to regenerate tissue.

Despite the regeneration abilities of individual sponges, deep-water sponge grounds as a habitat may remain destroyed for very long time periods. Experimental trawling on sponge communities in the Gulf of Alaska demonstrated that damage is significant (30-60 per cent of the remaining sponges of the principle species were damaged). No damaged sponges in the trawl paths showed signs of repair or regrowth after one year and damage to some had been so severe that necrosis, probably as a result of bacterial or fungal agents, had led to death (Freese 2001).

Life-history traits of component species that make recovery difficult – *ecosystems that are characterized by populations or assemblages of species with one or more of the following characteristics:*
- *slow growth rates;*
- *late age of maturity;*
- *low or unpredictable recruitment; or*
- *long-lived.*

The dominant species of sponge grounds are long-lived and slow-growing, and therefore slow to recover from impacts. Studies in boreal waters have not yet verified any regeneration in trawl paths. Reproductive patterns and larval phases are largely unknown and, at least for the dominant boreal species, reproduction is assumed to be infrequent. Klitgaard and Tendal (2004) suggest that the dominant ostur species (a type of sponge ground in the Northeast Atlantic dominated by *Geodia* spp.) are slow-growing and take at least several decades to reach the sizes commonly encountered. In general, they are found in relatively constant environmental conditions, suggesting dependence on a certain stability with respect to water mass characteristics, kinds and amount of particles in the water, and low physical disturbance.

Very little is known about the sexual reproduction of geodiids and ancorinids from the Northeast Atlantic, although some information has recently been published on reproduction in *Geodia barretti* (Spetland *et al.* 2007), see section on reproduction in Chapter 3. Few small specimens were found by Klitgaard and Tendal (2004), leading them to suggest that reproduction in boreal ostur areas is infrequent, making ostur vulnerable to changes in hydrographic regime (e.g. induced by climate change) as well as to the direct impacts of trawling.

Structural complexity – *an ecosystem that is characterized by complex physical structures created by significant concentrations of biotic and abiotic features. In these ecosystems, ecological processes are usually highly dependent on these structured systems. Further, such ecosystems often have high diversity, which is dependent on the structuring organisms.*

ICES (2009) summarizes that deep-water sponge grounds give a three-dimensional structure to the seabed which can provide a surface for animals to live on and both a hunting ground and a refuge from predators and strong currents, see also Chapter 4. The fauna associated with the sponge grounds is rich and has a higher diversity compared to surrounding bottoms. The associated fauna is dominated by epifaunal groups such as encrusting sponges, hydroids, zoanthids, bryozoans, and ascidians that use the sponges as a substratum (Klitgaard 1995; Klitgaard and Tendal 2004). The spicule mats associated with the sponge communities also support increased biomass of macrofaunal species (Bett and Rice 1992).

The foregoing clearly indicates that there is a strong case for considering deep-water sponge grounds as vulnerable marine ecosystems. Given this, it is important to consider how states identify such areas before developing conservation measures. As a first step to identify such locations, flag states and RFMO/As are advised to assemble and analyse all relevant data on known or likely occurrences of VMEs in areas where their fisheries currently operate or plan to expand their operations. The FAO guidelines indicate that, when designating an ecosystem as vulnerable, habitats and ecosystems should be evaluated against the criteria, individually or in combination, using the best available scientific and technical information. Characteristics should be weighted according to their relative contribution to an ecosystem's vulnerability.

In areas where VMEs have been designated, or are known or likely to occur on the basis of seabed surveys and mapping or other best available information, states and RFMO/As should close such areas to deep-sea fisheries until appropriate conservation and management measures
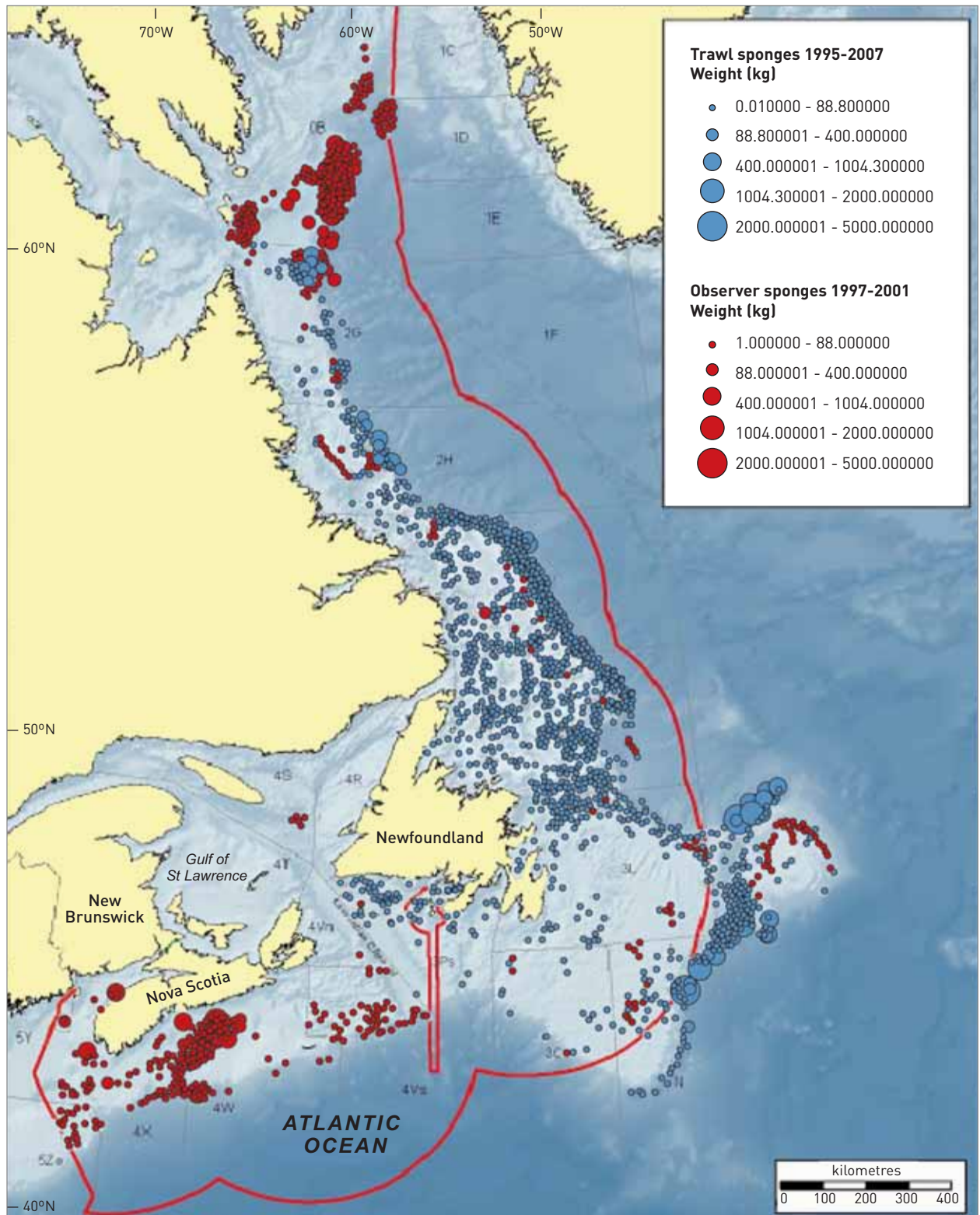
Figure 12.1: Volumes of sponge bycatches registered in the NAFO area. Canadian Trawl Survey Data (1995-2007) and Maritimes Fisheries Observer data (1977-2001). *NAFO 2008.*

have been established to prevent significant adverse impacts on VMEs and ensure long-term conservation and sustainable use of deep-sea fish stocks.

As of 2009, temporally limited area closures have become effective in the management areas of several RFMO/As (for up-to-date state of closures see http://www.fao.org/fishery/topic/16204/en). Most of these were implemented on the grounds of limited knowledge and on a precautionary basis. An exception is in the Northwest Atlantic, where the Northwest Atlantic Fisheries Organization (NAFO) implemented fisheries closures for the protection of deep-water sponge grounds. These areas were based on a hierarchical system of scientific advice which included analyses of an extensive set of observer and survey data from various sources that identified a number of high-density areas on the slopes of the Grand Banks and Flemish Cap (Kenchington *et al.* 2009; NAFO 2009b; see Figure 12.1).

ASSESSMENT OF 'SIGNIFICANT ADVERSE IMPACTS'

Further to the designation of VMEs within areas of current or future fishing activities, flag states and RFMO/As should conduct assessments to establish whether these deep-sea fishing activities are likely to have 'significant adverse impacts' in a given area. The FAO guidelines define significant adverse impacts as those that compromise ecosystem integrity (i.e. ecosystem structure or function) in a manner that: (i) impairs the ability of affected populations to replace themselves; (ii) degrades the long-term natural productivity of habitats; or (iii) causes, on more than a temporary basis, significant loss of species richness, habitat or community types. Impacts should be evaluated individually, in combination and cumulatively (FAO 2009 paragraph 17).

When determining the scale and significance of an impact, the following six factors should be considered:
- the intensity or severity of the impact at the specific site being affected;
- the spatial extent of the impact relative to the availability of the habitat type affected;
- the sensitivity/vulnerability of the ecosystem to the impact;
- the ability of an ecosystem to recover from harm, and the rate of such recovery;
- the extent to which ecosystem functions may be altered by the impact; and
- the timing and duration of the impact relative to the period in which a species needs the habitat during one or more of its life-history stages.

Temporary impacts are defined as those that are limited in duration and that allow the particular ecosystem to recover over an acceptable time frame. Such time frames should be decided on a case-by-case basis and should be of the order of 5-20 years, taking into account the specific features of the populations and ecosystems. In determining whether an impact is temporary, both the duration and the frequency at which an impact is repeated should be considered. If the interval between the expected disturbances of a habitat is shorter than the recovery time, the impact should be considered more than temporary. In circumstances of limited information, states and RFMO/As should apply the precautionary approach in their determinations regarding the nature and duration of impacts (FAO 2009 paragraphs 19-20). This is a knowledge-demanding approach which shifts the burden of proof to those parties who exploit the resources of a particular area. As such, this is a strong move towards applying the precautionary approach in ocean management.

Currently, the contracting Parties to the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) and to the newly adopted Convention on the Conservation and Management of High Seas Fishery Resources in the South Pacific (SPRFMO) have to follow a formal impact assessment procedure to get permission for demersal longline, and bottom trawl and longline fishing in the Convention areas, respectively. New Zealand has currently published the only full-scale impact assessment of its fisheries on the high seas of the South Pacific (New Zealand Ministry of Fisheries 2009), concluding in an assessment of the potential impacts and issues of concern associated with various fishing gears in relation to site, duration, intensity, cumulative effects and overall significance ranking.

All other national or regional fisheries management bodies currently concentrate their efforts on determining short-term procedures to avoid further significant impacts on VMEs in ongoing fishing operations outside the current closures, using 'move-on rules' or 'encounter protocols'.

MITIGATION MEASURES

In areas where VMEs are known or likely to occur, flag states and RFMO/As should, based on the results of assessments, adopt conservation and management measures to achieve long-term conservation and sustainable use of deep-sea fish stocks, ensure adequate protection, and prevent significant adverse impacts on VMEs. These measures should be developed on a case-by-case basis and take into account the distribution ranges of the ecosystems concerned. The range of potential measures given by FAO (2009) that can be taken to achieve these objectives includes temporal or spatial restrictions or closures next to technical fisheries measures.

Deep-sea sponge grounds

In the event that all available information is insufficient to indicate the presence, or likelihood of presence, and the likelihood of significant impact, deep-sea fishing activities shall only be authorized to proceed if in accordance with:

- conservation and management measures to prevent significant adverse impacts;
- a protocol for encounters with VMEs, which determines in advance how fishing vessels operating in deep water should respond to encounters in the course of fishing operations with a VME, including defining what constitutes evidence of an encounter;
- measures to reduce uncertainty including ongoing scientific research, monitoring and data collection.

Therefore, the FAO (2009) guidelines do not set explicit target values for the determination of what constitutes a vulnerable marine ecosystem (e.g., based on diversity, biomass per unit area, etc.) nor does it define what an

encounter is meant to be, or what kind of actions will have to follow. The agreement on these significant details is left to the states and RFMO/As.

In summary, in the absence of an impact assessment and without detailed knowledge of where seabed habitats occur, a fast-track procedure is envisaged which enables continued demersal fisheries outside fisheries closures. The required protocol for encounters with VMEs, together with pre-defined management actions to be agreed by the nationally and regionally responsible fishing bodies, shifts the strategy to a practicable, evidence-based definition of a 'move-on' for fishing operations encountering likely VME bycatch. Threshold levels are used to trigger management action. Although generally the vessel concerned has to stop its fishing operations in the area, it remains open to others at least on a temporary basis. There are different procedures towards evaluating and enacting an eventual full closure of an area.

Table 12.2: A summary of 'move-on' encounter thresholds for cold-water corals and deep-water sponge grounds

	CCAMLR Commission for the Conservation of Antarctic Marine Living Resources	NEAFC North East Atlantic Fisheries Commission	NAFO Northwest Atlantic Fisheries Organization	SEAFO South East Atlantic Fisheries Organisation
Region	Southern Ocean	Northeast Atlantic	Northwest Atlantic	Southeast Atlantic
Source	CCAMLR (2009)	NEAFC (2009)	NAFO (2009a)	SEAFO (2006, 2009)
Date	2008, revised 2009	2008, revised 2009	2008, revised 2009	2006, 2008, revised 2009
Definition VME	Here called VME indicator organisms: any benthic organism listed in the *Benthic Invertebrate Classification Guide*		Indicator species of coral identified as antipatharians, gorgonians, cerianthid anemone fields, *Lophelia*, and seapen fields or any other potential VME element	Antipatharians, gorgonians, cerianthid anemone fields, *Lophelia*, and seapen fields or other VME elements
Area closures	None 2009	Yes	Yes	Yes
Impact assessments	Yes	No	No	No
Observers	100% coverage	Only in operations in new fishing areas	100% coverage	Only in operations in new fishing areas
Threshold level corals	10 or more VME indicator units (one unit corresponds to 1 litre/1 kg of VME indicator organisms)	60 kg of live coral	60 kg of live coral	60 kg
Threshold level sponges	10 or more VME indicator units (one unit corresponds to 1 litre/1 kg of VME indicator organisms)	800 kg of live sponge	800 kg of live sponge	800 kg of live sponge

In particular, CCAMLR follows a precautionary strategy. Further to prohibiting commercial bottom trawl fishing and gillnetting in the high seas area of the Convention zone where no conservation measures are in place (conservation measure 22-5, 2008), application of the move-on rule led to the closure of seven or eight areas to demersal longlining by March 2009. Contrary to the current threshold levels set by, for example, NEAFC and NAFO, the encounter rules of CCAMLR are more likely to prevent significant adverse impacts on VMEs because of lower bycatch volumes, a better gear differentiation and 100 per cent observer coverage of all fishing trips.

During the early stages of transposing UNGA Resolution 61/105 into national and regional action, researchers provided advice on what may constitute a 'significant adverse effect' on deep-water sponges or other habitat-forming epifauna (Rogers et al. 2008). It was argued that the significance of bycatch by commercial fishing gear depends not only on the type of organisms encountered (which have different distributional patterns) and the quantity of bycatch, but also on the frequency of encounters. The guidance summarized below was meant to provide an overall indication of the factors and levels to be considered in national and regional VME encounter rules. With respect to deep-water sponges, Rogers et al. (2008) recommended the following thresholds:

- a single haul with gear used in commercial fishing activities constituting > 5 kg of sponge or other habitat-forming epifauna;
- two or more consecutive hauls containing > 5 kg of sponges or other habitat-forming epifauna on the same trawl track or setting area for fishing gear or where consecutive trawling tracks or sets intersect;
- > 10 encounters of > 2 kg of sponges or other habitat-forming epifauna in an area (1 km^2) within one year;

SPRFMO (adopted November 2009) Convention on the Conservation and Management of High Seas Fishery Resources in the South Pacific	New Zealand (for vessels flying the New Zealand flag in the high seas of the South Pacific)	North Pacific RFMO (not yet adopted)	SIOFA (not yet in force) Southern Indian Ocean Fisheries Agreement
South Pacific	South Pacific	North Pacific	Southern Indian Ocean
SPRFMO (2009)	Penney et al. (2008, 2009); Parker et al. (2009)	Bensch et al. (2008); NWP RFMO (2007)	
2007	2007	2007	
Seamounts, cold water corals and sponge gardens	Taxonomic groups distinguished		
Interim closure new fishing areas and deepwater gillnetting	Yes	A small proportion of one seamount agreed to be closed	Voluntary closure of 11 deep-sea areas (SIODFA)
Yes	Yes	Yes	
100% coverage on bottom trawlers, 10% other gear types	See SPRFMO	100% coverage	
	1-6 kg of coral depending on taxa	50 kg (only Japan)	
	50 kg		

■ >15 per cent of hauls of any gear within an area (10-100 km²) containing sponges or other habitat-forming epifaunal taxa.

Compared with the 'move-on' encounter rules currently agreed by several regional fisheries management bodies (see Table 12.2), the threshold levels described above are very conservative. Penney *et al.* (2009) consider that the choice of the trigger mechanism and eventually the threshold value for bycatch is essentially a management choice between the extremes of presence/absence (any occurrence of a vulnerable species in a catch would be considered to be evidence of a VME) and high weight thresholds (only the largest recorded vulnerable species by-catch weights would qualify as evidence of VMEs).

Introducing bycatch thresholds as indicators for the presence of vulnerable marine ecosystems raises a set of fundamental questions in relation to deep-water sponge grounds, summarized below.

What is the philosophy behind setting threshold values for determining 'significant adverse impacts' on benthic ecosystems? Although many sponge taxa occur in low density and are widely distributed, sponge grounds can only be found in ecologically favourable places (ICES 2007, 2008 and 2009; NAFO 2008). Because they are densely aggregated, these sponge grounds are more susceptible to local depletion than more widely spread individuals. The best protection for such dense aggregations is spatial closure (e.g. NAFO 2009b). Closing sponge grounds will also protect the abundant but low-biomass species that are associated with them (ICES 2009). But what of the remaining areas where these same sponge taxa may be less dense but still play an important role in benthic habitat heterogeneity and ecosystem function? Also of concern is the role smaller sponge species play in turf communities and their vulnerability to trawling. The only protection for these cases is through the encounter provisions and 'move-on' protocols for commercial vessels. These same protocols must also protect sponge grounds in unfished areas when exploratory fishing occurs. It may be impossible to provide protection for all of these scenarios with the same set of threshold values. In the NAFO context, the current threshold value of 800 kg is unlikely to be caught in commercial tows within the fishing footprint, given the parallel protection of the sponge grounds. Equally, this same threshold should detect sponge grounds in the first pass through such habitat in new fishing areas. However, threshold levels of any magnitude will not protect communities of smaller taxa, which may be vulnerable to the indirect effects of bottom-tending fishing gear. Short of banning bottom trawling, in these

situations effective protection may be through closure of representative areas under the criteria of the Convention on Biological Diversity (CBD).

Does the biogeographic heterogeneity of sponge ground communities allow the setting of quantitative threshold levels over larger regions, such as the management areas of regional fisheries management organizations? The tentative answer is no: if considered to be an appropriate tool, then threshold levels for significant impacts on sponge grounds should be set on ecologically based subregions. For example, in the Northeast Atlantic several different types of deep-water sponge grounds exist – a polar, a boreal and a more southern type – each dominated by a different set of species, and each occurring in different quantities (see Case study 2). Whereas the boreal type of *Geodia*- and/or *Stryphnus*-dominated sponge grounds produces patches of mass occurrences in oceanographically limited locations on gravelly ground, the *Pheronema*-type sponge grounds on the continental slopes and offshore banks south of 60°N occur on deep muddy bottoms on spicule mats in much less density and biomass (See Case study 3). Sponge grounds of small-sized calcareous sponges and other types also occur (see review in ICES 2008). In addition, all rocky outcrops, no matter what size, on seamounts, offshore banks and structures on the continental slopes and canyons, are likely to provide habitat for (coral and) sponge-characterized communities (see e.g. Klitgaard *et al.* 1997; Klitgaard and Tendal 2004).

How does the patchiness of occurrence of sponge grounds influence the bycatch scheme? Parker *et al.* (2009) did not find a correlation between tow duration and benthic invertebrate bycatch. This is likely to be an expression of the patchiness of invertebrate occurrence, resulting in short tows potentially causing the same damage as long tows.

What are the implications of thresholds for live sponges only? The wisdom of setting threshold levels of significance for live sponges only is questionable: most sponge species, at least the large species that dominate many deep-water sponge grounds, will arrive on deck fragmented, collapsed and dead (Klitgaard and Tendal 2004). The only remnants of dead sponges are eventually mats of spicules which, similarly to a dead coral framework, provide a very important habitat for the settlement of new sponge recruits to become the nucleus of a new sponge ground (Rice *et al.* 1990; Henrich *et al.* 1992; Barthel *et al.* 1996; Klitgaard and Tendal 2004). Therefore, the disturbance and removal of spicule mats or other appropriate habitat for sponge grounds will not only cause damage to the present distribution of sponges, but also

prevent future recruitment and recovery of the three-dimensional structural sponge habitat.

Is the bycatch in a commercial trawl an appropriate basis for estimating the damage occurring on the ground? No, the damage on the ground cannot be estimated from bycatch in fishing gear but only by visual observation, as only an unknown fraction of the damaged organisms will be retained in the net or on the hooks of the fishing gear. Freese *et al.* (1999) found that 67 per cent of the sponges occurring in the path of a single trawl were damaged, and detected no signs of recovery a year later (Freese 2001). Heifetz *et al.* (2009) encountered damaged fauna in 88 per cent of their video transects covering 65,000 m² within the fishery footprint in the Aleutian Archipelago, and 40-50 per cent of the sponges encountered in 100-400 m depth were damaged.

Should the bycatches recorded in research trawls be scaled up to the area swept by commercial trawls? On the basis of the bycatch analyses of a large number of fisheries research trawls along the Canadian continental slope, Kenchington *et al.* (2009) identified a sponge weight of more than 75 kg per research trawl tow to indicate the presence of high-density sponge areas (NAFO 2009b). Before a scientific threshold estimation, the regional fisheries management organization NAFO scaled this value up to match the size and duration of commercial fishing operations and then fixed the threshold value for the move-on rule to become operative at 800 kg per tow (NAFO 2009a). This was done as an interim measure until the NAFO Scientific Council could provide advice to the Fisheries Commission. There are a number of problems with this approach: first, the method used to determine the threshold to identify significant sponge grounds was optimized to detect high concentrations (Kenchington *et al.* 2009); and second, any scaling-up procedure assumes a positive linear relationship between the tow duration and sponge bycatch. This is clearly not the case as the premise for the spatial analysis to detect significant concentrations is built upon a highly aggregated distribution. Scaling-up exercises should demonstrate *a priori* a significant positive relationship, explaining a meaningful amount of the variance between tow duration and sponge bycatch before use. Auster *et al.* (in review) discuss the consequences of extrapolating research vessel bycatch volumes to commercial tows on the example of coral taxa in the Northwest Atlantic: only the highest catch rates of large gorgonian corals might meet or exceed the threshold value for the move-on rule (shorter tows would almost never trigger the rule). No catches composed entirely of small gorgonians, seapens and cup corals, or other soft corals, would ever exceed a threshold

value of 1,000 kg (NAFO 2008), even though there are areas where such taxa dominate.

What is the catch efficiency of commercial fishing gear for invertebrate bycatch and how does it vary with the quantity of fish caught, substratum, and fragility and rarity of the organisms? What arrives on board in a fishing net is selected in terms of predominance of large, less fragile, abrasion-resistant organisms and pieces thereof (Auster *et al.* in review). Freese *et al.* (1999) quantified the catch efficiency of trawl-caught invertebrates by comparing density estimates based on area swept by the trawl with density estimates from seafloor imagery at deep-water sites (206-274 m depth) off southeast Alaska. The trawl caught less than 1 per cent of the asteroids, echinoids and molluscs and 4.6 per cent of the holothurians, compared to the visual observations, and octocorals and sponges could not even be quantified in the bycatch, which the authors assumed to be because of the size and fragility of specimens encountered. Also, Penney *et al.* (2009) argue that bottom trawls do not retain invertebrate taxa efficiently, and report seamount trawls taken from areas with dense and diverse structural fauna which arrive on deck with little or no coral by-catch. Auster *et al.* (in review) calculated the consequences of different gear configuration and catch efficiencies for retaining invertebrates on the biomass of corals and sponges impacted by that gear: using the preliminary 2008 threshold values of 100 kg of live coral or 1,000 kg of sponge that requires vessels to move on in the NAFO and NEAFC regions of the North Atlantic as reference points, Auster *et al.* (in review) predict that at a 10 per cent catch efficiency level for both corals and sponges, 1,000 kg of coral and 10,000 kg of sponges are actually impacted. At 1 per cent efficiency, a level more in accordance with the study by Freese *et al.* (1999), 10,000 kg of coral or 100,000 kg of sponge would be impacted. Gear with a net opening two-thirds as wide as another with a 120 m opening requires a 50 per cent higher invertebrate biomass per unit area to trigger the move-on provision – or impact larger areas. Auster *et al.* consider it therefore essential to determine the move-on provisions on the basis of gear configuration, catch efficiency, tow time and distribution of indicator taxa.

Where do the vessels move to when being forced to stop fishing because they encounter likely VMEs? The current rules set by various fisheries management bodies require vessels to move 2 or 5 nm away from the likely position of the encounter (NEAFC) or the end of the trawl path (NAFO). However, this will only induce fishing in potentially previously unfished areas. However, demersal fishing effort concentrates in areas of complex topography, mixed sediments and the upper depth strata such as on the slopes of the

continental margins, canyons, seamounts and offshore banks. Moving a mile from a previous trawl track will thus not prevent significant adverse impacts from occurring but rather run the risk of spreading the impacts to a wider area. Auster *et al.* (in review) calculated that the relatively flat trawlable summits of three Northwest Atlantic seamounts could be completely trawled with between 32 and 61 tows, respectively, when applying the current NAFO move-on rules.

PROSPECTIVE

The conclusions to be drawn from the above considerations can only be that the move-on rules as agreed by NAFO and NEAFC will be inefficient in preventing significant adverse impact to deep-water sponge grounds in the course of fishing operations. The rules set by CCAMLR (2009) and New Zealand in 2009 (Parker *et al.* 2009; Penney *et al.* 2009) are likely more precautionary and use significantly lower and better resolved threshold values. In particular, New Zealand complements these measures with a representative network of closed areas formulated on a precautionary basis (Penney *et al.* 2009).

Although deep-water bottom fishing does not contribute to human nutrition in any significant way (e.g. the EU deep-water demersal fleet catches approximately 1 per cent of the total EU catch and employs less than 3 per cent of people working in the sector, MRAG *et al.* 2008) and involves extremely high operational costs, the current political consensus is that some deep-water bottom fishing should continue. Therefore, the most efficient, and most cost-efficient, solution to preventing impacts on deep-water benthic ecosystems – the cessation of demersal deep-water trawling – is not presently part of the debate about the implementation of UNGA Resolution 61/105.

Technical solutions for avoiding impacts from fishing gear in contact with the seafloor do however exist. Modern net acoustic monitoring allows the nets to be operated above ground; however, this will preclude for example the fishing of orange roughy, and may reduce catch efficiency for the target fish. Fishery observers could be used to verify the operation and survey the catch (Auster *et al.* in review).

Another way of reducing risks would be to greatly reduce the threshold levels set, or even consider a presence/absence scheme. However, given the inefficiency of fishing gear catches for fragile invertebrates, and the overlap of fishing areas with structural habitats such as corals and sponges, this approach may not greatly reduce the likelihood of future encounters (Auster *et al.* in review), and so seems of limited conservation value.

The currently agreed requirement of the vessels to move 2 or 5 nm away from the likely position of encounter with the likely VMEs is also of limited conservation value. Satellite-tracked maps of vessel activity demonstrate that demersal fishing activities concentrate on large seabed features of complex topography in the upper 2,000 m of the water column, such as seamounts, offshore banks and the continental slope (see Figure 12.2). The multitude of ecological niches provided by such structures and their importance as stepping stones of dispersal qualify the whole feature as a potential VME. Moving on for just 2 or 5 nm may therefore simply impact another area likely to contain VMEs (Auster *et al.* in review).

An ecologically more appropriate procedure, also matching the scale of best knowledge (Williams *et al.* 2009) would preclude demersal deep-water fishing from operating on whole topographic features or clusters likely to host VMEs (see e.g. Probert *et al.* 2007), or at least to a system of areas partly closed and partly open to trawling, based on the precautionary approach (Penney *et al.* 2009). On the basis of the long-term fishing effort data of its fleet, together with all ecological and physical information available, New Zealand has implemented a scheme of representative fisheries closures, areas where the move-on rule applies and areas open to trawling (those which had the highest historical fishing effort, assuming the highest impacts on biodiversity) within its historic footprint beyond EEZs in the South Pacific (Penney *et al.* 2009).

An important component of a strategy to protect VMEs from the impacts of demersal fishing is to implement a step-wise strategy away from the freedom of fishing anywhere to a permission system which directs the activity to where it is desired (Hourigan 2009). As a first step, the current 'footprint' of the different demersal fisheries has to be determined at as fine a scale as possible. Several regional fisheries organizations have started to do so, yet mostly on a relatively coarse scale. Based on this, the expansion of the current fisheries footprint has to be halted – which will prevent the application of the move-on rule leading to impacts in yet unexplored fishing areas or depths. In parallel, areas known or likely to host vulnerable marine ecosystems such as sponge grounds within the current footprint have to be considered for closure (e.g. Heifetz *et al.* 2009) and, in addition, representative areas have to be designated as part of the global network of marine protected areas (MPAs), to be established by the 2012 target date of the 2002 World Summit on Sustainable Development (WSSD). Auster *et al.* (in review) argue that in particular large-scale closed or protected areas are effective tools which will need to be an integral and precautionary

component of each regional fishery management strategy for deep-sea fisheries.

If deep-water demersal fishing is to continue, this will bring high costs for associated management, including monitoring, surveillance, enforcement and additional baseline research. Supplementing the essential *in situ* research on the quality and extent of sponge grounds (and other VMEs), mapping at high resolution, and predictive modelling will be essential prerequisites for making informed decisions in the future. In the case of sponge grounds, it seems possible to at least roughly predict the potential habitats based on topography, slope inclination, current pattern and substratum, as has been done for cold-water coral habitats (Davies *et al.* 2008; Tittensor *et al.* 2009). However, predictive mapping is unlikely to indicate the preferred habitat for other, less abundant and dense sponge aggregations, such as on the rims and edges of seamounts. Even the best resolved bathymetric maps will lack the detail to direct fishing on a 2-nm basis.

ARE DEEP-WATER SPONGE GROUNDS ECOLOGICALLY AND BIOLOGICALLY SENSITIVE AREAS?

The Parties to the 1992 CBD have adopted the goal of establishing a global, representative system of MPAs by 2012, including in areas beyond national jurisdiction (under the 2002 WSSD). Whereas in marine areas under national jurisdiction, national and eventually regional efforts have been made to implement this commitment, in areas beyond national jurisdiction no agreed mechanisms for establishing MPAs exist to date. However, the Conference of the Parties to the CBD, in 2008 (Decision IX/20: CBD 2008a), made a significant step towards achieving the 2012 target by adopting the scientific criteria (Annex I to the decision) for identifying ecologically or biologically significant marine areas in need of protection, and the scientific guidance (annex II) for designing representative networks of MPAs.

Designation of these MPA networks shall follow a two-step process, starting with the identification of 'ecologically and biologically sensitive areas' (EBSAs). In October 2009, the scope of the selection criteria and guidelines on their practical application for identifying ecologically and biologically sensitive areas were made (CBD 2009). The criteria rank areas in terms of priority for protection, and not as a binary choice between significant or not significant. As such, applying absolute thresholds for most criteria is inappropriate.

Here, the scientific selection criteria for MPAs is related to deep-water sponge-ground habitat in order to examine whether such habitats can be considered 'ecologically and
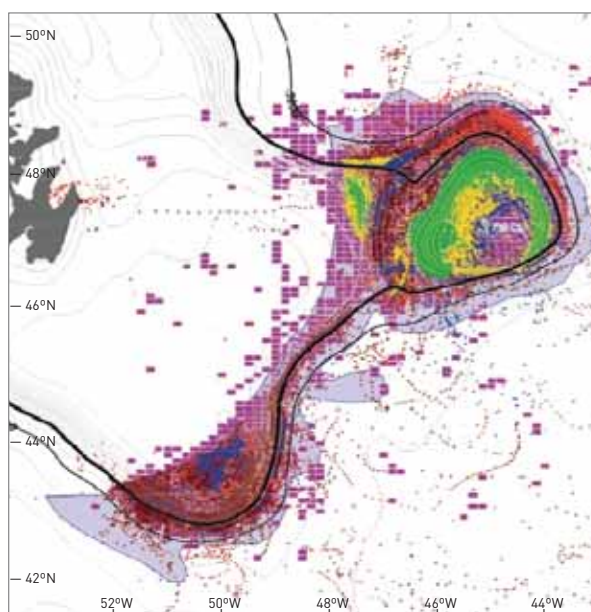
Figure 12.2: The footprint of bottom trawl fisheries in the NAFO area as inferred from overlaid fishing positions and/or areas from 1987 to 2007 submitted by NAFO contracting Parties as geo-referenced information by September 2008. Also included is information from the NAFO Vessel Monitoring System (2003 to 2007). *http://www.nafo.int/fisheries/regulations/nafo-footprint.pdf*

biologically sensitive areas' qualifying for designation as MPAs under conservation legislation.

1. **Uniqueness or rarity.** Area contains either (i) unique ('the only one of its kind'), rare (occurs only in few locations) or endemic species, populations or communities, and/or (ii) unique, rare or distinct habitats or ecosystems; and/or (iii) unique or unusual geomorphological or oceanographic features.

CBD (2009) does not set limits to determining rarity or uniqueness, but leaves it to expert knowledge applied on a variety of scales, including the global, ocean basin, regional or local scale. While 'uniqueness' by definition cannot be judged on a relative scale (i.e. an object is either unique, or it is not), 'rarity' may be judged relative to other species or habitats.

Sponge grounds probably do not qualify under this criterion as they are not rare *per se* (see Case study 2).

2. **Special importance for life-history stages of species.** Areas that are required for a population to survive and thrive.

3. Importance for threatened, endangered or declining species and/or habitats. Area containing habitat for the survival and recovery of endangered, threatened or declining species or area with significant assemblages of such species.

CBD (2009) clarifies that the second criterion is intended to identify specific areas that support critical life-history stages of individual species. It incorporates all the life-history stages of a species or population, but leaves open the question of how an area can be determined to be 'required' for survival and reproduction. As such there is overlap with the third criterion, focusing on the same functional importance but for threatened/endangered or declining species and habitats.

Deep-water sponge grounds may well fulfil these criteria, as discussed in Chapter 4. They appear to play an important role in local functional ecology, but given the scarcity of *in situ* observations to date – and likely in the future – it is not possible to determine the reliability, persistence and criticality of these functional relationships for different species and life stages with any degree of certainty. In particular, many benthopelagic fish species seem to use the three-dimensional structural habitat provided by deep-water sponge grounds, but trophic or other less obvious competitive advantages of associating with this structure are much more difficult to document. CBD (2009) highlights the problem of applying the criteria in data-deficient situations such as the deep sea, and emphasizes the need for a precautionary approach based on risks to the species determined from their life-history traits.

4. Vulnerability, fragility, sensitivity, or slow recovery. Areas that contain a relatively high proportion of sensitive habitats, biotopes or species that are functionally fragile (highly susceptible to degradation or depletion by human activity or by natural events) or with slow recovery.

CBD (2009) clarifies that this EBSA criterion is focused on the inherent sensitivity of habitats or species to disruption. The core concept here is that resilience to perturbations (physical or chemical) varies amongst habitats and species; for example, species with low reproduction rates exhibit an inherently higher level of vulnerability to impacts than other species. Assessing the vulnerability of benthic ecosystems in relation to bottom contact fisheries has been elaborated upon by the FAO (2009).

Sponge grounds clearly qualify for protection measures under this criterion. The justification for this is outlined in Chapters 3 and 5.

5. Biological productivity. Area containing species, populations or communities with comparatively higher natural biological productivity.

CBD (2009) clarifies that this criterion shall identify regions in the open oceans which regularly exhibit high primary or secondary productivity. These highly productive regions are here assumed to provide core ecosystem services and are also generally assumed to support significant abundances of higher trophic-level species. The phrase 'comparatively higher' emphasizes the relative (rather than absolute) nature of this criterion. How much 'higher' is left open to interpretation.

The productivity of benthic deep-water features such as sponge grounds is unknown. Relative to the surrounding seafloor, sponge aggregations and associated species certainly exhibit a comparatively higher productivity, however this may not have been meant by the criterion.
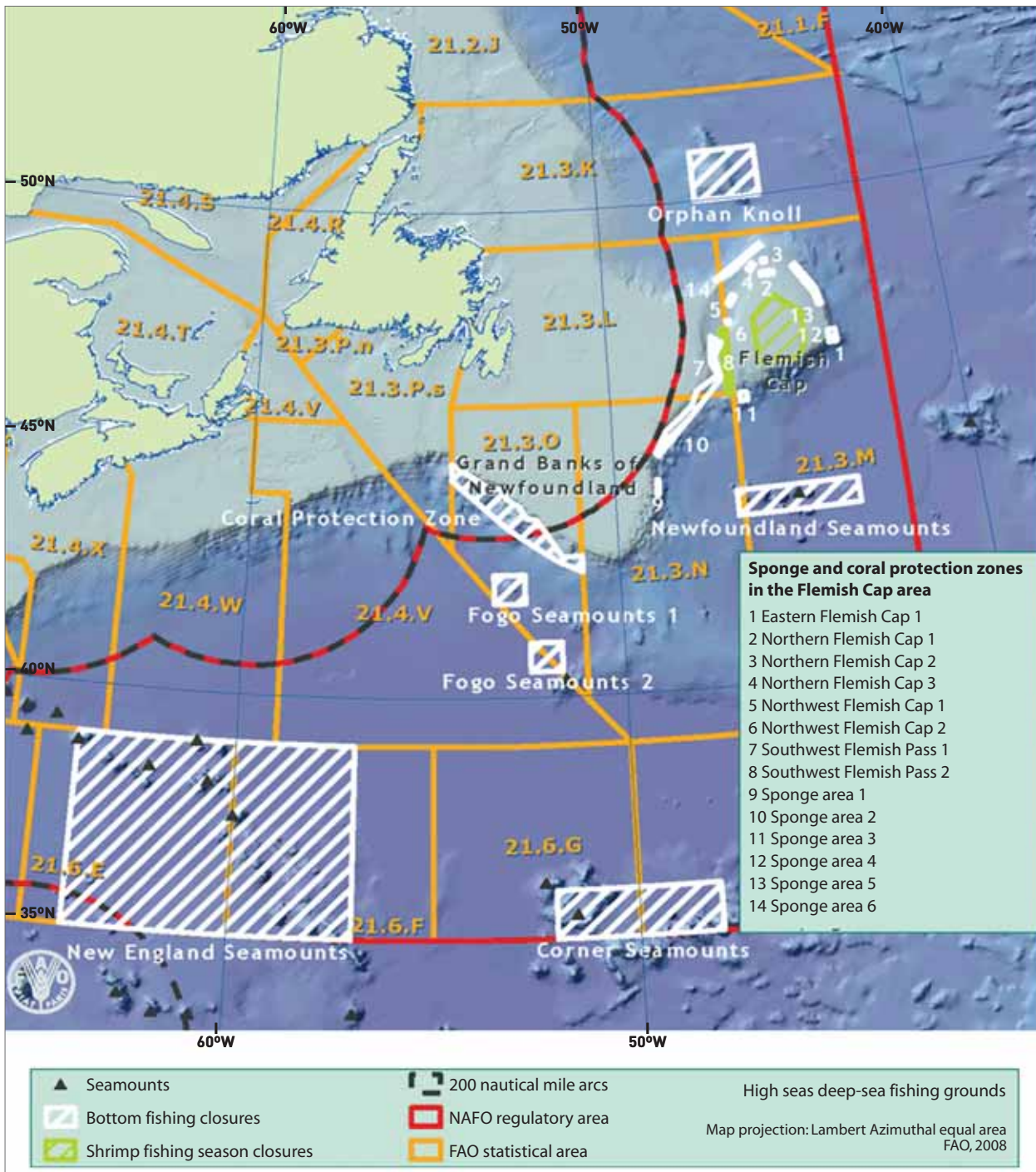
6. Biological diversity – Area containing comparatively higher diversity of ecosystems, habitats, communities, or species, or has higher genetic diversity.

CBD (2009) points to the volume of literature on this subject and the fact that not even the term 'diversity' has an agreed standard interpretation and working methodology. Measures of diversity generally consider one or more of the following factors: (i) number of different elements (species, communities, etc., also referred to as 'richness'); (ii) the relative abundance of the elements ('evenness' and other related measures); and (iii) how different or varied the elements are when considered as a whole (e.g. taxonomic distinctness).

In deep-sea environments, only a few targeted investigations may be able to provide the necessary data for applying statistically rigorous diversity measurements. The normal situation is one of data scarcity and diversity has to be extrapolated from other indicators. There is general agreement that owing to the greater number of possible niches, habitats of higher complexity (heterogeneity) are believed to also harbour higher species diversity.

Deep-water sponge grounds are a structurally complex habitat created site-specifically by a multitude of sponge species, with a large number of associated species and the capacity to create new habitat for the settlement of other macro- and megafauna (see Chapter 4).

7. Naturalness – Area with a comparatively higher degree of naturalness as a result of the lack of or low level of human-induced disturbance or degradation.

Figure 12.3: Chart showing sponge and coral protection zones established in the Northwest Atlantic within the NAFO regulatory area. *http://www.fao.org/fishery/topic/16204/en.*

CBD (2009) clarifies that this criterion measures the relative 'naturalness' of open-ocean and deep-sea areas compared to other representative examples of the habitat type. Therefore, it is not required that an area be pristine in order for it to be identified as an EBSA. However, at least some information on historic states of the ecosystems where the criterion is being applied is required.

Currently, most if not all scientific knowledge on deep-water sponge grounds comes from invasive sampling – be it fishing trawls, research trawls or dredges. As such, the

sponge grounds identified are already impacted to some degree. Only large-scale visual surveys would enable the distinction between more or less natural sponge grounds. Monitoring programmes such as those planned in the Northeast Atlantic may eventually lead to new discoveries and the establishment of relative measures of sponge ground 'naturalness'.

In summary, based on the current knowledge of sponge grounds, areas hosting one or several types of this feature qualify for inclusion in a network of MPAs under criteria 4 (vulnerability, fragility, slow recovery) and 6 (biological diversity). The criteria elaborated by CBD (see above) aim to qualify areas based on valuing the local ecosystems according to a man-made scale of higher or lower value. The degree of threat to the respective ecosystems does not play a role in the selection process, favouring rather more natural than more threatened areas. As a result, the priority for conservation of a sponge ground within and below fishing depth would be the same.

At least in the North Atlantic, deep-water sponge grounds are under threat and decline, primarily from the impacts of bottom fishing. High-biomass occurrences such as the ostur areas described by Klitgaard and Tendal (2004) are entirely within fishing depth. Sponge grounds made of glass sponges may, however, also occur down to the bottom of the ocean on the deep ridges, seamounts and lower continental slopes (see e.g. Tabachnik and Collins 2008).

CAN DEEP-WATER SPONGE GROUNDS BE DESIGNATED MARINE PROTECTED AREAS?

The criteria for the identification of ecologically and biologically sensitive areas (CBD EBSA criteria), as presented above, were explicitly based on the expertise and experience available at the national and regional scale. Therefore, the EBSA criteria have much in common with the prior national and regional criteria. However, some differences exist. For example, the approach taken by the contracting Parties to the OSPAR Convention in the selection of sites for the regional MPA network in the Northeast Atlantic (OSPAR 2003) includes the criteria 'threatened or declining species and habitats/biotopes' and 'representativity', which are not part of the EBSA criteria. The criterion 'threatened or declining species and habitats/biotopes' refers to the species and habitats listed by OSPAR as being regionally under immediate threat and/or subject to decline. The habitat 'deep-sea sponge aggregations' has been listed here since 2003 (OSPAR 2008), on the basis of evidence presented and reviewed by ICES. Despite this, there is to date no MPA designated for the conservation of deep-water sponge aggregations, although some protection zones have been established around the Flemish Cap area of Atlantic Canada (Figure 12.3).

13. Recommendations

The previous chapters have demonstrated that deep-water sponge grounds are diverse and important resources of marine biodiversity. They also play important roles as fish habitat and have provided novel drugs to help treat human diseases including cancer. But our understanding of these habitats is still fragmentary and incomplete. However, we do know that sponges are globally distributed, that they are long-lived and slow-growing, and that ancient sponge reefs exist off the west coast of Canada adjacent to British Columbia. We also know that the increasing exploitation of resources in the deep sea, in particular by commercial bottom trawling and oil exploration, poses a serious threat to their future.

Urgent actions and measures are needed to protect those deep-water sponge grounds known today from human impact. There are likely to be many more, as yet unknown, and this knowledge gap needs to be addressed by scientific research programmes and surveys. The tools exist to designate deep-water sponge grounds and those areas where this habitat is likely to occur in waters beyond national jurisdiction as 'vulnerable marine ecosystems' (VMEs) (UNGA Resolution 61/105, FAO 2009). In line with the resolution, bottom fishing activities should cease in those areas in order to prevent further damage. The equivalent of this resolution should be transferred to fisheries management within national jurisdiction. Likewise, deep-water sponge grounds qualify as 'ecologically and biologically sensitive areas' (EBSAs) according to the CBD criteria (CBD 2008a), and the selection criteria of many states and regions such as OSPAR should therefore be considered in the designation of marine protected areas (MPAs) contributing to the global representative network of MPAs (under the 2012 target of the 2002 World Summit on Sustainable Development). Currently, no single MPA is known to be designated for the protection of deep-water sponges.

More research is urgently required to gain better insight into distribution patterns and to fully understand and appreciate the role, function and value of deep-water sponge grounds as unique marine habitats. This is a vital component of any successful conservation strategy. The full potential of sponge grounds and their functions has not yet been explored, and conservation monitoring programmes and further research must be implemented as a long-term commitment. This must be supported with coordinated efforts at both national and international levels.

The following recommendations provide a 'toolbox' of options put forward to improve the conservation, monitoring and research of deep-water sponge grounds. They are intended to address all stakeholders including academia, non-governmental and intergovernmental organizations, and national and international policy decision makers from developed and developing countries to business and industry. This toolbox is provided to support and complement existing guidelines and actions for other similar marine ecosystems. The recommendations have been numbered for ease of reference; this does not reflect priority.

Recommendation 1
Establish and adopt regulations and measures that are precautionary to conserve, monitor and research deep-water sponge ecosystems so that they are protected against both accidental and deliberate damage caused by anthropogenic activity. On the basis of current knowledge, implement fisheries closures in areas where deep-water sponge grounds are known to exist within and beyond areas of national jurisdiction, based on the requirements set by UNGA Resolution 61/105. Deep-water sponge grounds are a characteristic feature of various deep-water biogeographic zones and need to be represented in the future global network of MPAs. Therefore, selecting representative sites and designating areas under national legislation is required, whereas the processes required for the implementation of MPAs beyond national jurisdiction are still developing.

Stakeholders from science to industry can positively contribute to all issues around successful conservation of vulnerable habitats like sponge grounds. Therefore a constructive dialogue with stakeholders should be initiated, establishing cooperation based on an improved mutual understanding of views and concerns. For example, in relation to deep-water sponge grounds, the fishing industry could provide valuable data on present and past location and likely extent of the habitat.

Recommendation 2
Encourage the active involvement of relevant stakeholders in a dialogue with national governments and advisory bodies.

For science, this needs to be supported by a framework and funding for enabling researchers to work on the science-policy interface.

The compliance of stakeholders to existing and proposed regulations and measures is essential for an effective implementation in the marine environment, and especially on the high seas. Today, satellite monitoring of fishing vessels provides an effective means of policing and control of conservation measures (vessel monitoring system, VMS). However, on-the-ground observations by local coast guards or overflight are required to establish a non-compliance – both rather expensive tools with more local impact which need sufficient funding to be effective. Several regional fisheries organizations already request full observer coverage during fishing operations. Where observers have already been introduced in the past and bycatch was recorded, government agencies now take decisions on conservation based on such long time-series bycatch data, for example in Canada or New Zealand.

Recommendation 3
Establish 100 per cent coverage of demersal fishing operations with observers to help the enforcement and provide important data on bycatch during the fishing operations. Sufficient logistical and financial resources in areas that are far off-shore or in waters beyond national jurisdiction are needed for monitoring and legislation enforcement.

The distribution of deep-water sponge grounds is poorly known on a global scale, with only small regional pools of data available, such as for the Northeast Atlantic (see Case study 2). Most location records are held by individual experts and scientific institutions, or by companies exploring the deep sea for commercial purposes. Thus this scattered distributional information needs to be integrated and maintained so that it is accessible to all stakeholders. Building models for the potential distribution of deep-water sponge grounds will form the focus of further research together with the mapping of habitats where *in situ* observations have been limited. As deep-sea investigations are costly, this focus will help to deploy the latest deep-sea technology and instruments most effectively. The outcomes obtained from such mapping and research activities should be verified with existing observations and records and disseminated to as many stakeholders as possible.

Recommendation 4
Address the 'known': initiate a regional or global inventory for sponges, potentially building on existing taxonomic databases (such as the World Porifera Database, van Soest *et al.* 2008). A publicly accessible meta-database for the

results of sponge research, from taxonomy and ecology to genetics, will be instrumental to mapping of data, and in particular modelling predicted suitable locations for deep-water sponge grounds and other sponge groups. Periodic status reports, preferably in combination with an assessment of impacts and threats, will help to communicate progress.

Recommendation 5
Address the 'unknown': initiate deep-water habitat surveys (including visual and sampling survey as well as recording of a range of physical factors) to investigate systematically (in conjunction with other vulnerable deep-water habitats) the occurrence and quality of the deep-water sponge grounds. Chart locations of this habitat as precisely as possible and enter them on fishing and navigation charts as areas to be avoided.

In this context, the contribution of stakeholders is important. Research and government bodies should set up consultations with industry to gain access to additional data not yet provided via environmental impact assessments. If need be, funded research projects can help to retrieve data from not easily accessible sources such as historic logbook data.

Bycatch of sponges in commercial and research trawls (and other gear) is a valuable source of information. Therefore, a full inventory of all bycatch occurring in fishing operations is required, best provided by observers on board, or by freezing subsamples for identification and analysis on shore.

Recommendation 6
Address the 'unknowable': provide a funding stream which allows research projects to investigate the environmental preferences of deep-water sponge grounds and other deep-water habitats on global and regional scales in order to contribute to the modelling of potential distribution patterns.

Recommendation 7
Consolidate deep-water sponge research through increased coordination of activities at national, regional and global scales. Countries with high levels of expertise and modern deep-sea research, exploration and habitat-mapping facilities (e.g. research vessels, multibeam echosounders, remotely operated vehicles) should be encouraged to assist and cooperate with countries that lack such expertise and tools.

Recommendation 8
Develop a code of practice for *in situ* research and bioprospecting to minimize impacts on deep-water sponge

grounds; this can build upon existing codes, such as that established by OSPAR. Improve the definition of regulations regarding research for biotechnological purposes to better control bioprospecting in national and international waters.

Recommendation 9
Coordinate sources of research funding so that deep-water sponge grounds can be researched at broad, ocean-basin scales and investigated *in situ* using the best available technology by sharing expensive offshore research vessel and submersible infrastructure internationally. The newly established trans-Atlantic cold-water coral research pro-gramme 'TRACES' and European Science Foundation component 'EuroTRACES' offer a suitable model (see www.lophelia.org/traces and www.esf.org/eurotraces).

Currently there are very few fishery closures which offer protection to deep-water sponge grounds. All such deep-water closure measures were taken only recently, and no monitoring has yet been carried out to assess their success. In addition there are few, if any, baseline surveys to compare any possible recovery or restoration in these closed areas. Unless these closures are made permanent, and similar habitats identified by survey are closed as well, programmes for the monitoring and assessment of deep-water sponge grounds will be required (in conjunction with other deep-water habitats).

Therefore it will be increasingly important to compile and share information about the different management stra-tegies adopted by individual countries and organizations in implementing further regulations and measures. In evalu-ating and redefining these approaches, regular monitoring and assessment tools must be developed in order to protect deep-water sponge grounds effectively. The monitoring of remote deep-water sponge grounds is challenging and requires both cost-effective and practical methods and equipment which can be applied to local conditions. Monitoring programmes should aim to describe the status of sponge grounds that are undisturbed, the state and regeneration of damaged grounds, as well as the effects of conservation, monitoring and research on the socio-economic context of the marine area and environment. This will be an aid to guiding countries in their efforts to develop robust strategies for managing deep-water sponge grounds, especially those countries which have fewer resources for basic research.

Recommendation 10
Coordinate and fund a long-term regional survey and monitoring programme which delivers periodic assess-ments of habitat distribution, occurrence and quality.

Recommendation 11
Periodically review the effectiveness of the range of existing and new regulations and measures to conserve, monitor and explore deep-water sponge grounds and make proposals for improvements.

Recommendation 12
Establish practical strategies and guidelines for low-impact monitoring and research of deep-water sponge-ground habitats *in situ*.

Recommendation 13
Denote deep-water sponge grounds as a key ecosystem in existing and planned international monitoring and assess-ment programmes such as the Global Ocean Observing System (GOOS) and other relevant programmes under Regional Seas Conventions and Action Plans.

Currently, the scientific engagement for the conservation of sponges and sponge grounds is limited to individuals or small groups at national and regional levels. International events such as the World Sponge Symposium bring the scientific community together. However, these meetings are not sufficient in bringing together all interested parties to share the information needed for deep-water sponge conservation.

In addition, a more effective science-policy interaction platform is required, which could serve all sides by exchanging knowledge and experience. Access to such a forum would help disseminate knowledge and solutions to problems, especially for countries with less developed research and management infrastructure. Such a forum should become active for resolving the particular questions and problems of conservation management.

With regard to awareness-raising with other stakeholders, a dedicated international forum which includes all stake-holders from academia, industry and business would help to establish cooperative strategies in managing deep-sea sponge ecosystems.

Recommendation 14
Acknowledge the advice of researchers given to govern-ments or other bodies on questions of marine conservation in their national scientific assessment exercises.

This change in performance philosophy can be initiated by national and international funding agencies, including governments, and would shift the scientific 'culture' towards one that engages more readily with the difficult issues of marine and high-seas conservation.

Deep-sea sponge grounds

Recommendation 15

Establish an international science-policy interaction initiative for information exchange and solution development for deep-water ecosystems.

Recent observations and scientific studies have made a significant contribution towards raising awareness of deep-water sponge grounds at national, regional and international scales. Increasing recognition on agendas at international meetings associated with the conservation of the marine environment has also helped to highlight the need for urgent action. Yet much work remains to be done in order to propagate information about the existence, distribution and importance of deep-water sponge grounds, as some governments may be unaware of the existence of deep-water sponges in their waters.

Recommendation 16

Promote the awareness of deep-water sponge grounds and the urgent need to conserve, monitor and research these habitats sustainably within relevant national governments, Regional Seas Conventions, intergovernmental organizations and the wider public.

Future generations of researchers, engineers, artists and scientists as well as our children should have the opportunity to study, benefit from and wonder at deep-water sponge grounds as unique habitats. In order to achieve this, it is crucial that we develop fuller knowledge and understanding of these habitats together with raising awareness amongst the general public about the threats they face and why deep-water sponge grounds are important.

Acronyms

AUV	Autonomous underwater vehicle
BIOFAR	Marine Benthic Fauna of the Faroe Islands
CBD	Convention on Biological Diversity
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
DSCC	Deep-Sea Conservation Coalition
EBSA	Ecologically and biologically sensitive area
EC	European Commission
EEZ	Exclusive economic zone
FAO	Food and Agriculture Organization of the United Nations
FISH	Fluorescence *in situ* hybridization
GIS	Geographic information system
GOOS	Global Ocean Observing System
GPS	Global positioning system
HBOI	Harbor Branch Oceanographic Institution
ICES	International Council for Exploration of the Sea
IUCN	International Union for Conservation of Nature (formerly World Conservation Union)
JSL	Johnson-Sea-Link manned submersible
MPA	Marine protected area
NAFO	Northwest Atlantic Fisheries Organization
NEAFC	North East Atlantic Fisheries Commission
NOAA	National Oceanographic and Atmospheric Administration, USA
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
RFMO/As	Regional fisheries management organizations and arrangements
ROV	Remotely operated vehicle
SEAFO	South East Atlantic Fisheries Organisation
SIODFA	Southern Indian Ocean Deepwater Fishers' Association
SIOFA	Southern Indian Ocean Fisheries Agreement
SPRFMO	Convention on the Conservation and Management of High Seas Fishery Resources in the South Pacific
TRACES	Trans-Atlantic Coral Ecosystem Study
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNGA	United Nations General Assembly
VME	Vulnerable marine ecosystem
VMS	Vessel monitoring system
WWF	World Wide Fund for Nature/World Wildlife Fund (USA)

Glossary

Abyssal plain: An extensive, flat region of the ocean bottom from 4,000 m to 7,000 m depth.

Archaeocytes/amoebocytes: Amoeboid cells found in sponges and located in the mesohyl. They have varied functions depending on the species (totipotency).

Backscatter: A reflection phenomenon of energy in which a non-reflective surface, which is a surface that does not reflect energy coherently, randomly scatters energy in all directions, including back in the direction from which it came.

Bathyal zone: The benthic environment between the depths of 200 m and 2,000 m. It includes mainly the continental slope and the ocean ridges.

Bathymetry: The measurement of ocean depth.

Bathyscaph (precursor of submarine): Free-diving submersible which sinks by a weight into deep water and is suspended below a float.

Benthic: Relating to the seafloor, including organisms living on or in the seabed.

Biodiversity: Assemblage of living organisms from all sources including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part.

Bottom-trawls: Non-selective method of fishing in which a large bag-shaped net is dragged or trawled. The mouth of the bag is kept open by various methods such as a wooden beam (beam trawl) or large flat board (otter trawl).

Box core: A coring device designed to take relatively undisturbed samples of the deep seabed, usually 0.25 m².

Bycatch: Fishes or other animals caught by accident in fishing gear. Bycatch is usually thrown back into the water dead or dying.

Cold seep: Where cold water seeps slowly from the seafloor (the opposite of hot, hydrothermal vents); often rich in hydrogen sulphide, a compound toxic to most animal life.

Community: A group of organisms of different species that co-occur in the same habitat or area and interact through trophic and spatial relationships.

Continental shelf: A gently sloping area extending from the low-water line to the depth of a marked increase of slope around the margin of a continent or island.

Continental slope: A relatively steeply sloping surface lying seaward of the continental shelf.

Cyanobacteria: Photosynthetic blue-green algae, intermediate between bacteria and higher plants.

Deep water: The water beneath the permanent thermocline (pycnocline) from 200-2,000 m that has a fairly uniform temperature.

Demersal: Environments and organisms near to and influenced by the seafloor.

Diversity: The number of taxa in a group or place.

Drill cuttings: Inert pieces of rock, gravel and sand removed from a well during drilling.

Drilling fluid/drilling mud: Fluid pumped down a well bore during drilling; has multiple functions such as to cool and lubricate the drill, inhibit corrosion and remove drill cuttings from the hole.

Ecological engineering: The ability of certain marine organisms such as corals and sponges to form or modify structural habitat.

Ecosystem: All the organisms in a biotic community and the abiotic environmental factors with which they interact.

Electrophoresis: The migration of charged colloidal particles or molecules through a solution under the influence of an applied electric field.

Epibenthic: Animals that live on the ocean bottom, either attached or moving freely over it.

Epifauna: Animals living on the surface of the seafloor (see also *infauna*).

Fecundity: The potential reproductive capacity of an organism or population, measured by the number of gametes (typically egg cells) or asexual propagules.

Foraminifera: Protozoa of the Order Foraminiferida which are abundant in the plankton and benthos of all oceans and possess a protective shell usually composed of calcium carbonate.

Gamete: Sex cell; special haploid cell or nucleus which unites with one of the opposite sex to produce a (diploid) zygote.

Gametogenesis: The meiotic process by which mature gametes (eggs and sperm) are formed. Oogenesis refers specifically to the production of eggs and spermatogenesis to the production of sperm.

Habitat: Place and its living and non-living surroundings where an individual or population lives.

Habitat-forming species: The living species physically 'being' the habitat or producing the material constituting it, or a combination thereof (Tendal and Dinesen 2005). Remarks: In case all individuals die, the structure and

other characteristics of the habitat may change considerably and within a short period of time. Also, a number of other species may occur in the habitat simply because the specific locality is suitable for them to sustain life rather than due to the presence of the habitat-forming species.

Habitat-modifying species: Species which by their presence, activity or products modify a habitat such as to create more room for other species, or space for more species, so abundance and diversity become higher than in surrounding areas (Tendal and Dinesen 2005).

High seas: In municipal and international law this term denotes the continuous body of salt water in the world that is navigable in its character and that lies outside territorial waters and maritime belts of countries; also referred to as the open seas.

Hydrocarbon seeps: Where hydrocarbons seep slowly from the seafloor.

Infauna: Animals living in seafloor sediments (see also *epifauna*).

Larvae: A juvenile phase differing markedly in morphology and ecology from the adult.

Megafauna: Animals exceeding 2 cm in length, typically those easily seen on deep-sea photographs.

Niche: The relational position of a species in its ecosystem to another; describes how an organism responds to the distribution of resources and competitors.

Offshore: The comparatively flat submerged zone of variable width extending from the breaker line to the edge of the continental shelf.

Overfishing: Applying a fishing effort beyond that which will generate a desirable, sustainable stock level. For long-lived species, overfishing starts well before the stock becomes overfished.

Pelagic: Open water environments and organisms.

Phylum: A taxonomic rank at the level below Kingdom and above Class in biological classification.

Pinacoderm: The outermost layer of cells in Porifera, equivalent to the epidermis in other organisms.

Population: A group of organisms of the same genus inhabiting a prescribed area.

Predation: The consumption of living tissue by another organism; commonly used to imply capture of one animal by another animal.

Pseudopodia: A temporary projection from the cell of an amoeboid used for feeding and locomotion.

Recruitment: Refers to the addition of new individuals to a population.

Remotely operated vehicle (ROV): Unmanned submersible connected to the research vessel by a cable; carries camera systems, manipulators or other devices.

Salinity: The concentration of salt in water, usually measured in parts per thousand (ppt).

Secondary metabolite: A substance produced by an organism that is not essential for its own survival but often has important secondary functions (e.g. in defence and protection).

Sediment: Particles of organic or inorganic origin that accumulate in loose form.

Sediment resuspension: Current- or wave-induced uptake of sediment into the water column.

Shallow water: Water of depth such that surface waves are noticeably affected by bottom topography. Typically this implies a water depth equivalent to less than half the wave length.

Spawning: The release of gametes into the water column.

Speciation: Evolutionary processes which lead to an increase in the number of species.

Sponge grounds: 'Different combinations of geological, hydrological and biological conditions allow certain large-sized sponge species to develop in abundance, and form a habitat of their own. Sponge-dominated habitats have variously been called sponge beds, sponge fields, sponge accumulations, sponge grounds, sponge associations, sponge mass occurrences, ostur, and sponge reefs. None of these terms are unambiguous, although the last three are to some degree delimitated in the literature. For the wider, general conception, use of the term 'sponge ground' is suggested, to be circumscribed by the species dominating in bodysize and abundance, and often also by accumulation of skeletal remains.' (Hooper *et al.* 2002)

Substrate: The material on the sea-bottom which usually consists of sand, rock, mud and gravel.

Suspension feeder: An organism that feeds by capturing particles suspended in the water column.

Symbiosis: The close association between two organisms which live together. The relationship may vary on a continuum from parasitism to mutualism.

Syncytia: Specialized forms of cells which have several nuclei within them.

Systematics: The study of evolutionary and genetic relationships or organisms.

Thermocline: Layer of water column in which temperature gradient is pronounced.

Totipotency: Attributed to cells which have the ability to differentiate themselves into different cell types according to the functions they are required to fulfil in any one species.

Upwelling: The process by which deep, cold, nutrient-laden water is brought to the surface, usually by diverging equatorial currents or coastal currents that pull water away from the coasts.

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Deep-sea sponge grounds

This report draws together scientific understanding of deep-water sponge grounds alongside the threats they face and ways in which they can be conserved. Beginning with a summary of research approaches, sponge biology and biodiversity, the report also gives up-to-date case studies of particular deep-water sponge habitats from around the world. These include the spectacular giant glass sponge reefs of British Columbia – a relic of the time of the dinosaurs – and the diverse sponge kingdom of Antarctica. Long-overlooked, recent research now shows that deep-water sponge grounds form complex, slow-growing and long-lived habitats in many parts of the global ocean. As well as forming local biodiversity centres, deep-water sponges are also storehouses of novel chemical compounds, some of which show promise in the fight against cancer and other diseases.

Despite their inherent and biotechnological value, deep-water sponge grounds have been damaged by bottom fishing. This report considers the international policy context in which deep-water sponge grounds can be conserved and concludes with a series of expert recommendations for conservation managers and international policy makers. The recommendations set out a series of actions so that these vulnerable marine ecosystems can be conserved for future generations.