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History and research approaches

To most people corals are synonymous with the bright, well-lit waters of tropical coral reefs. Yet in fact the majority of corals inhabit deep, cold waters across a diverse range of marine environments from inland fjords to the continental shelf, slope, offshore banks, seamounts and even the abyssal plain. While we have known about these cold-water corals for hundreds, or even thousands, of years it is only in the last ten years that research into the biology of the corals themselves, the ecology of the habitats they provide and the geology of the structures they form has gathered pace. Cold-water coral habitats are biodiversity rich. Recent work has revealed them as unique palaeoceanographic archives. Sadly all too many surveys have shown they have been damaged by human activity. In this book we have tried to summarise the many, varied and exciting developments in our understanding of cold-water corals. Research effort on cold-water corals is now increasing exponentially around the world and it has been challenging to compress this body of work into the pages of one book. Before we consider cold-water corals and some of these recent findings in more detail we begin with a brief historical summary and an outline of the research approaches used to study cold-water corals.

1.1 History

1.1.1 Early history and taxonomy

The history of modern research on cold-water corals goes back to the late eighteenth century. Among the first written records discussing cold-water corals are notes by the Right Reverend Erich Pontoppidan, Bishop of Bergen, in his 1755 book *The Natural History of Norway*. In Chapter 6, Sea-vegetables of Norway, Pontoppidan discusses one particularly fine coral specimen that was ‘entirely white, the flowers much larger than the former [specimen], some of them even exceeding a shilling; and likewise expanded like a flower in full

https://doi.org/10.1017/CBO9780511581588.002

bloom, for which singular beauty I caused a draught of it to be taken'. The accompanying drawing illustrates the species described three years later by Carl von Linné (Linnaeus) as *Madrepora pertusa* (= *Lophelia pertusa*) in *Systema Naturae*, the book that laid the foundation of modern taxonomy. Pontoppidan goes on to describe how 'The fishermen often sell coral bushes to the apothecaries at Bergen' but, although he believed it might have medical effects when taken internally, he sounded a little sceptical of its wider medicinal properties: 'that the little beads, made of coral . . . are endued with any such singular virtue that applied externally, or hung about the neck, . . . preservative against the apoplexy, the plague, and other contagions, I cannot admit, having no evidence of it, but must leave it to rest upon its own credit'. With an eye on the precious coral fishery in the Mediterranean, Pontoppidan concludes by wondering 'Possibly could white coral be brought into fashion, a diligent search might procure as great a quantity in our seas'. On the last point he was certainly correct, we now know that Norwegian waters support spectacular white coral (*L. pertusa*) deep-water reefs.

Studies of these Norwegian coral reefs began to appear just over a decade later when another theologian, Johan Ernst Gunnerus, Bishop of Trondheim (Colour plate 1) published his 1768 work *Om Nogle Norske Coraller* (*On Some Norwegian Corals*). One of his illustrations is reproduced in Fig. 1.1. Gunnerus was a pioneer of the natural sciences. He founded the Royal Norwegian Society of Sciences and Letters, was in frequent correspondence with Linnaeus and is famous for his descriptions of many animals from the basking shark *Squalus maximus* (= *Cetorhinus maximus*) to the roundnose grenadier *Coryphaenoides rupestris* and the gorgonian octocoral *Gorgonia resedaeformis* (= *Primnoa resedaeformis*).

The early days of cold-water coral research were dominated by efforts in Europe and North America to describe the variety of species dredged from the deep sea. The British naturalist Philip Henry Gosse was among the first to focus on the biology of living corals and sea anemones. His mid-nineteenth century descriptions encouraged fashionable Victorians to dabble in seawater aquaria and he summarised his work in his 1860 book *A History of the British Sea-Anemones and Corals* (Colour plate 2). Cairns (2001a) outlined the history of taxonomic research on the azooxanthellate scleractinians. The rate of coral description relates clearly to the research effort and comes in four major pulses: (1) the worldwide revision of the Scleractinia by Henri Milne Edwards and Jules Haime (1848–50); (2) the new species described chiefly by Louis François de Pourtalès, P. Martin Duncan and Henry N. Moseley from pioneering late nineteenth century deep-sea dredging expeditions (1867–81); (3) the new species described chiefly by Alfred W. Alcock, Emil von Marenzeller and Thomas W. Vaughan from

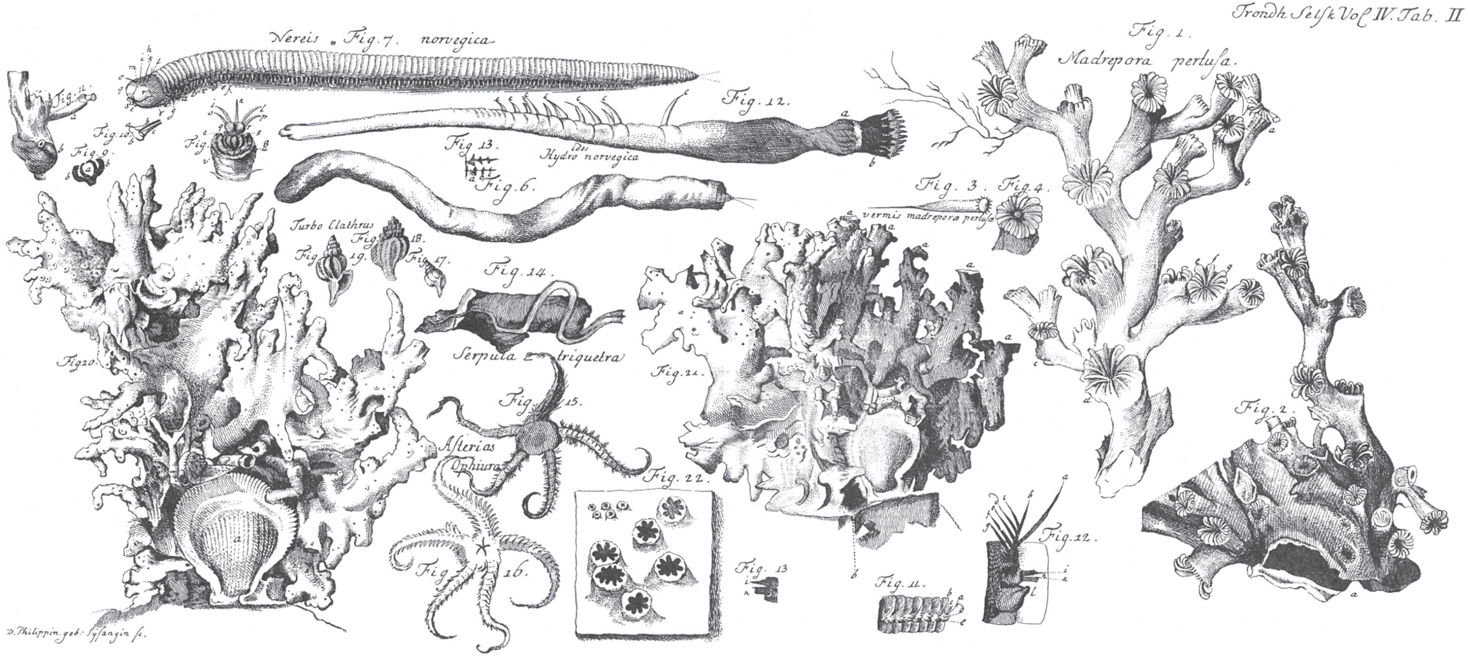

Fig. 1.1 Plate II from Gunnerus (1768) illustrates fragments of cold-water corals including *Madrepora pertusa* (= *Lophelia pertusa*) along with common associated fauna including the polychaete worm *Nereis norvegica* (= *Eunice norvegica*), gastropod molluscs and ophiuroid echinoderms.

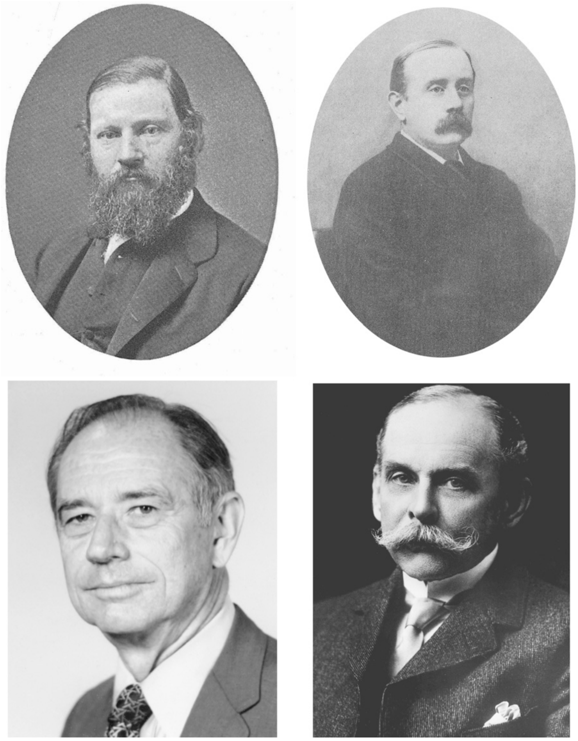

Fig. 1.2 Notable coral taxonomists, clockwise from top left: Louis François de Pourtalès (1824–80), Henry N. Moseley (1844–91), Alfred W. Alcock (1859–1933) and Frederick M. Bayer (1921–2007).

regional deep-sea dredging expeditions in the Indo-Pacific (1898–1907); and (4) the most recent pulse of descriptions based upon larger collections by vessels from France, New Zealand, the Netherlands and the USA alongside full-time research efforts by taxonomists such as Stephen Cairns and Helmut Zibrowius between 1977 and 2004. Figure 1.2 shows some notable coral taxononists.

Bayer (2001) reviewed octocoral research beginning with the first published drawings of octocoral sclerites from *Corallium rubrum* by John Ellis (1755) through to the first global monograph on 'zoophytes' by Peter Pallas (1766) and the critical recognition by Valenciennes (1855) that sclerites differed between species and so could be used as a taxonomic characteristic. Many of the sclerites described by Valenciennes were subsequently illustrated by Kölliker (1865). The early oceanographic expeditions of the late nineteenth century, such as that of *HMS Challenger*, greatly boosted the number of known octocoral species (Wright & Studer, 1889) and the early twentieth century saw a period of taxonomic revision by Kükenthal in his unfinished series *Versuch einer Revision der Alcyonaceen* (*An Attempted Revision of the Alcyonaceans*). In terms of deep-sea pennatulacean records, Kükenthal and Broch's (1911) description of specimens taken during the 1898–9 German *Valdivia* expedition from the eastern Atlantic to Antarctica, including the western Pacific is particularly notable, as was Kükenthal's (1919) account of the *Valdivia* Gorgonacea, which laid the foundation for his later revision of all Octocorallia in 1924. In the early twentieth century, Kükenthal recognised 141 certain and 134 doubtful species of Pennatulacea (Kükenthal, 1915) and 805 certain and 255 doubtful species of Gorgonacea (Kükenthal, 1924). Regional monographs and further species descriptions in the latter half of the twentieth century continued to add to this total. Of the approximately 3200 octocorals recognised today, around 75% are from deep waters (>50 m, see Section 2.2.4, p. 37).

Both octocoral and scleractinian taxonomy has been pursued by only a handful of scientists, often in their spare time. For example, alongside their taxonomic exploits many of the azooxanthellate scleractinian workers were primarily palaeontologists while others had a bewildering variety of jobs including school inspector, catholic priest and medical entomologist (Cairns, 2001a). Sadly this trend has if anything worsened and globally there are only a handful of coral taxonomists capable of identifying and describing cold-water corals. Many still pursue coral taxonomy in their spare time.

1.1.2 Pioneering deep-sea expeditions

The science of oceanography became established following the global expedition of *HMS Challenger* (1872–6) led by Charles Wyville Thomson and the epic collection of 50 scientific report volumes it subsequently generated under the auspices of John Murray. The impetus for the expedition had been to investigate Edward Forbes's azoic theory (based on dredging results from the Aegean Sea) that no animal life could persist below 300 fathoms (600 m). Having been to Norway and seen dredge hauls by Michael Sars rich in animal life from these and greater depths, Charles Wyville Thomson lost little time in joining forces with William B. Carpenter to set about persuading the British government to fund deep-sea dredging expeditions. These began in 1868 with the cruise of *HMS Lightning* to the waters between Scotland and the Faroe Islands. Both the *Lightning* and subsequent *HMS Porcupine* expeditions recovered cold-water corals in their dredges. These coral species were discussed in a series of papers to the Zoological Society of London and the Royal Society in the 1870s by P. Martin Duncan (Duncan, 1870, 1873, 1878).

Although less well known, the northwest Atlantic dredging expeditions co-ordinated through the Museum of Comparative Zoology at Harvard (USA) actually preceded the cruise of *HMS Lightning* by a year. Between 1867 and 1880 these expeditions covered over 600 deep-water stations recovering many cold-water coral specimens. Whereas the vessels *Lightning*, *Porcupine* and *Challenger* were converted British Royal Navy ships, the US expeditions used a series of US Coast Guard Steamers, the *Corwin*, *Bibb*, *Hassler* and *Blake*. Louis François de Pourtalès laid the foundations of North American cold-water coral taxonomy in his descriptions of the corals recovered during these expeditions (Fig. 1.3). Indeed of his 59 scleractinian coral descriptions, 47 remain valid today (Cairns, 2001a).

But it was the *HMS Challenger* expedition that revolutionised our understanding of the oceans. The dredge hauls taken during the expedition's circumnavigation of the globe put Forbes's azoic theory to rest once and for all – animal life was recovered from depths of 5500 m, an astonishing achievement at the time, and over 4000 new marine species were described. The *HMS Challenger* was built in 1858 as a Royal Navy corvette, a small, lightly armed and manoeuvrable warship. The *Challenger* sailed between survey stations and used her 1200 horse-power steam engine for dredging. Of her seventeen guns, all but two were removed to make space for laboratories and scientific sampling apparatus. Under Captain George Nares were a total ship's party of about 240 including 20 officers. There were just six scientists led by Charles Wyville Thomson (see Linklater, 1972 for a detailed history of the *Challenger* expedition). Henry Moseley, who joined as the expedition's naturalist, described the cold-water corals collected by *Challenger*. He subsequently outlined the voyage and his natural history observations in his 1879 book *Notes by a Naturalist on* HMS Challenger. Of the 48 scleractinian corals he described, 39 remain valid (Cairns, 2001a) and his skilful illustrations are among the finest available to this day (see Fig. 3.4, p. 72).

As mentioned, the dredging work of Michael Sars in Norway was part of the impetus for the *Challenger* expedition. Sars (1865) used dredging to describe coral banks formed by *Oculina prolifera* (= *Lophelia pertusa*) in Oslofjord. After the pioneering nineteenth-century expeditions established the science of deep-sea dredging on the high seas others were quick to take up the techniques of dredging and trawling and apply them through the remaining years of the nineteenth and first half of the twentieth centuries. There are many historical examples, summarised in Teichert (1958), including Dons (1944) from Norway and Joubin (1922) from the Irish and French margins.

1.1.3 The modern era begins

The next quantum leap in our understanding of cold-water corals came with the development of survey sonars after the Second World War, see Section 1.2.1, p. 13, and the use of manned research submersibles from the late 1960s and through the 1970s. After two hundred years of relying on sample material

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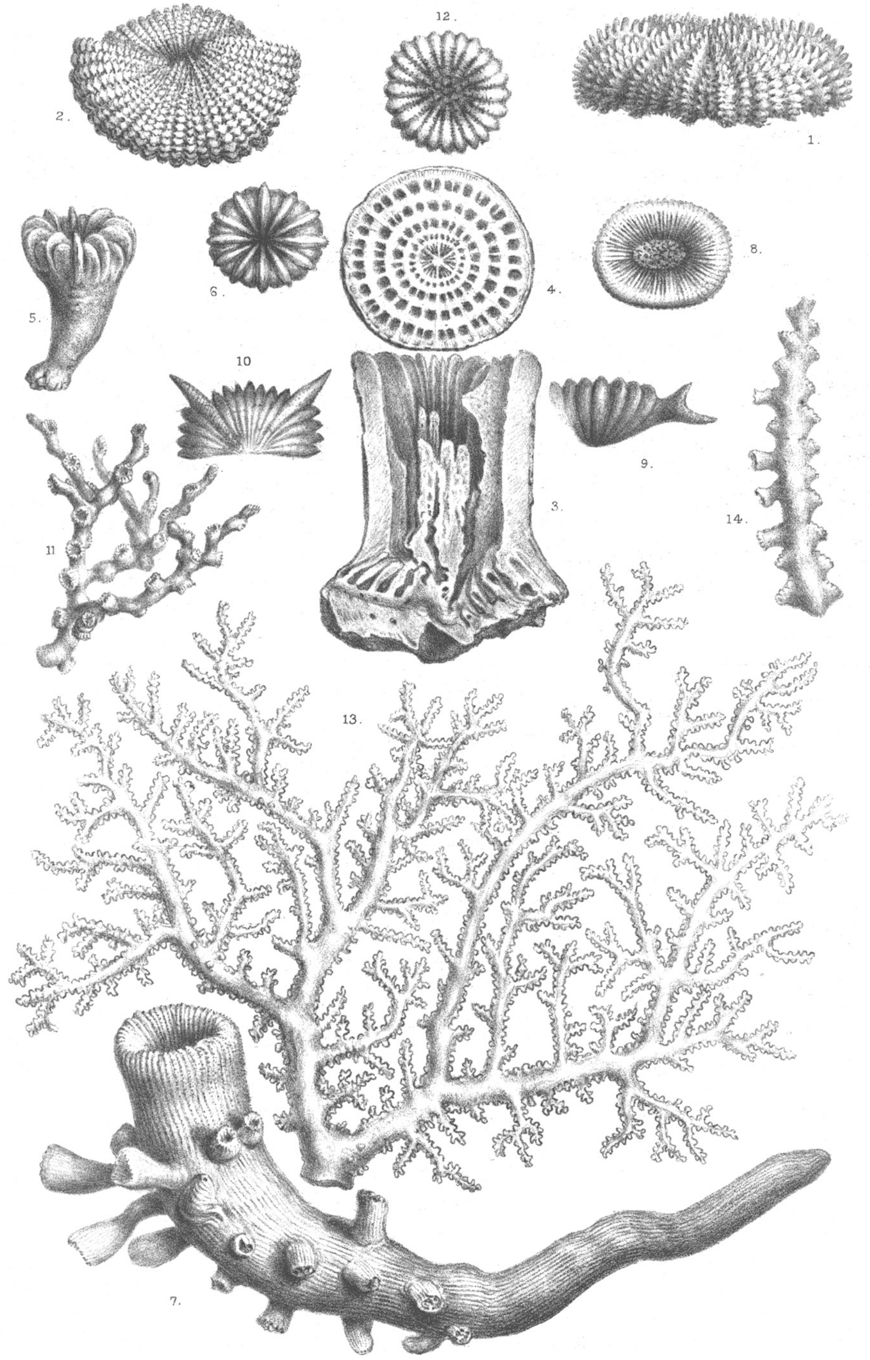

Fig. 1.3 Plate V from Pourtalès (1871) *Deep-sea Corals*, published as an Illustrated Catalogue of the Museum of Comparative Zoology at Harvard College. (1) *Diaseris crispa* (= *Fungiacyathus crispus*); (2) the same viewed

dragged from the depths and dumped onto the deck of a ship, research submersibles gave scientists the first chance to see deep-water animals in their habitats on the seafloor. The 'deep submergence vehicle' *Alvin*, named for Allyn Vine of the Woods Hole Oceanographic Institution, was brought into service in 1964. *Alvin*'s first use in cold-water coral research was to investigate mounds found on the Blake Plateau, off South Carolina (USA), following up earlier echosounder observations by Stetson *et al.* (1962). In July 1967, Milliman *et al.* (1967) dived an area of seabed mounds and found cold-water corals including *Lophelia* and *Dendrophyllia profunda* (= *Enallopsammia profunda*) along with a characteristic community of other suspension feeders. In 1971, A. Conrad Neumann dived in *Alvin* at the base of the Little Bahama Bank and northeastern Straits of Florida to depths of up to 700 m. During these dives he noted extensive areas of rocky mounds, hundreds of metres long and up to 50 m in height. These lithified mounds were richly colonised by cold-water corals and other suspension-feeding animals – subsequently Neumann *et al.* (1977) coined the term 'lithoherm' to describe them.

On the other side of the Atlantic the manned submersible *Pisces III* was used to examine cold-water corals in the northeast Atlantic (Colour plate 3). In June 1973, John Wilson surveyed *Lophelia pertusa* colonies growing on Rockall Bank and noted that they tended to form distinctive patches on the seabed, helping to explain characteristic patterns he had seen on side-scan sonagraphs. He reasoned that the colonies grew from their initial larval settlement point and gradually spread out covering a wider area, a process probably accelerated by sponge bioerosion. Using *Pisces III*, Wilson was able to document coral patches in various stages of development up to 50 m across. He subsequently summarised his observations in his classic description of cold-water coral patch development (Wilson, 1979).

The *Pisces III* submersible became infamous just two months after John Wilson's 1973 Rockall Bank dives. In August of that year the submersible was being used to help lay trans-Atlantic telephone cables approximately 100 miles west of Ireland. While being lifted back on board its mother ship, the *DE Vickers Voyager*, the submersible and its two-man crew were dropped and sank to a depth of 500 m. With life support systems for just three days an international rescue

Caption for Fig. 1.3 (cont.)
from above; (3) *Thecocyathus lævigatus* in vertical section (= *Tethocyathus laevigatus*); (4) the same in horizontal section; (5) *Desmophyllum solidum* (= *Thalamophyllia riisei*); (6) the same from above; (7) *Dendrophyllia cornucopia* (= *Eguchipsammia cornucopia*); (8) the same from above; (9) magnified portion of *Deltocyathus agassizii* (= *D. calcar*) from the side; (10) the same from below; (11) *Oculina tenella*; (12) the same from above; (13) *Stylaster filogranus*; (14) magnified branch from the same.

effort was quickly launched. Three other submersibles were flown to Ireland, *Pisces II* from England, *Pisces V* from Canada and an early remotely operated vehicle *CURV III* from the USA. After over three harrowing days several lines were attached to the stricken submersible and it was brought back to the surface. Both pilot and observer survived.

These pioneers of human exploration of the deep ocean set the stage for the work we describe in this book. Studies of cold-water corals, particularly the increased activity from the 1990s onwards, have relied on technological innovations in surveying and sampling. Many of these have been made since the 1970s, often driven by the requirements of offshore hydrocarbon development. Next we review briefly some of the methods available to cold-water coral researchers, focusing primarily on the two themes of this book, the geological and biological sciences.

1.2 Research approaches

Advances in our understanding of cold-water corals in recent decades have, in no small measure, been due to advances in submarine surveying, sampling and monitoring technologies. What was once a hostile, remote and mysterious realm is now becoming an increasingly practical area in which to observe and experiment thanks to improved deep-sea technology. Advances in genetics are also providing new insights into cold-water coral dispersal and reproduction alongside glimpses of this habitat's microbial diversity. Likewise, advances in analytical geochemistry have allowed us to use cold-water corals as environmental archives, and helped us understand biogeochemical and diagenetic processes. Many of these advances are explored in later chapters. Here we focus on how technology has enabled us to map, sample and monitor cold-water coral habitats with a concluding comment on how future advances may allow new insights and perspectives.

As recently as the 1990s, and sometimes to this day, attempts to locate cold-water coral reefs and mounds involved sampling the seabed using low-resolution echosounder data and scattered notes of coral occurrence, often from fishing records. Even knowing exactly where the research vessel was, let alone where the sampler on the seabed was relative to the vessel, was a challenge before satellite navigation through global positioning systems (GPS). Now we can not only fix the position of the ship to within a few metres but can also locate the sample with similar accuracy using through-water acoustic ultra-short baseline (USBL) navigation transponders. Improved design means research vessels can now hold position precisely over a site using dynamic positioning (employing directional thrusters). Before this vessels were often at the mercy of wind and water currents making accurate sampling a function of informed guesswork, timing and piloting skill. With a target several hundred metres beneath the ship there was a limit to what research objectives could be achieved. Once on deck, retrieved samples were usually out of context. Scientists could identify the species and sediments present but were largely left to guess at how the animals functioned and interacted with one another. Since dredges and trawls are dragged across the seafloor they give a greater chance of hitting a patchy target but such samples contain species and sediments from a number of habitats and/or facies mixed together, and are often damaged and biased towards certain organisms or grain sizes.

Advanced technologies now enable us to produce very accurate and detailed digital maps at a range of scales, and precisely sample and observe features either in person or remotely. However, before we outline these it is worth stressing that cold-water coral habitats still challenge us; for example, the fast-flowing currents that characterise these areas impose limitations on equipment and survey design. Deep waters require strong pressure housings for instrumentation, great lengths of cable on powerful winches and large deep-sea vessels capable of getting to and remaining at remote sites for weeks on end. This all makes research cruises to cold-water coral habitats costly undertakings. Observation periods may be limited to slack waters between tides, and local currents may dictate the direction in which instruments can be towed and can make manoeuvring submersibles or remotely operated vehicles (ROVs) difficult during peak tidal flows. This imposes limitations on the work that can be carried out and can cause valuable time spent offshore to be lost.

Corals grow on hard substrata and their accumulated remains may prove difficult to sample. Coral carbonate mounds can be precipitous and lithified, limiting sampling and sometimes damaging equipment (Fig. 1.4). Cold-water coral reefs

Fig. 1.4 A ‘banana core’ bent during sampling coral carbonate mound sediment.

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are both structurally and ecologically complex. Attempts to describe their structure and ecology remain challenging but technological developments allowing precise sampling with ROVs and long-term monitoring with landers and seafloor observatories are beginning to throw light on these issues. It is also important to note that while these ecosystems function seasonally, winter sea-states at high latitudes may curtail operations – often sampling, and to a lesser extent monitoring, are restricted to the fair-weather summer months.

With new technologies, the present-day cold-water coral research strategy has evolved from that of the past. The exploration phase still benefits from historical records and chance finds but now relies more on accurate regional baseline maps. These are increasingly based upon multibeam echosounder coverage with high-resolution seismic profiles (e.g. Roberts *et al.*, 2005a; see Topic box 1.1), sometimes as part of national seabed mapping initiatives. Cold-water coral reefs and mounds may become the focus of higher resolution mapping to create more accurate baseline maps using sonars deployed from ROVs or autonomous

Topic box 1.1 **Mapping with sound**

Mapping the seabed is technically more challenging than mapping terrestrial landscapes because light is readily absorbed by water, quickly negating the use of satellite remote sensing in all but the shallowest waters. Sound, on the other hand, travels great distances through water (in fact more effectively than through air) so it is possible to survey the seabed, and its underlying structure, by listening to sound reflections (or echoes) in much the same way as eyes, cameras and satellite detectors pick up reflections of light.

Low frequency (10–50 Hz) sound pulses emitted from a ship (known as industrial reflection seismics) penetrate deep into the seabed and reflect back off surfaces where there is a change in density, for example the tops of rock units or the surfaces of buried cold-water coral carbonate mounds (Fig. 1.5). The reflected echoes are received through hydrophones towed behind the ship. The depth beneath the seabed where the echo was reflected can be calculated by the difference in time between the sound pulse and its echo being received (the two-way travel time) assuming a realistic speed of sound through the seabed.

Higher sound frequencies have shorter wavelengths and can map at higher resolution allowing smaller features to be seen. But higher frequency sound does not penetrate so far into the seabed. High-resolution seismics (100 Hz–7 kHz) are ideal for mapping shallow buried (typically less than 200 m) cold-water coral carbonate mounds (Fig. 4.18). At even higher frequencies (greater than 30 kHz) most of the sound reflects directly off the seabed. By recording seabed echoes coming from either side of, as well as directly below the ship, a swath (or strip) of seabed can be imaged. Distance port and starboard from the sonar can again be calculated by time delay: the

Topic box 1.1 (cont.)

further port or starboard, the later the echo will be received. This is the principle of side-scan sonars, which are usually towed behind the vessel where it is acoustically quieter and also closer to the seabed (if desired). Higher frequencies (usually up to 500 kHz) create higher resolution images but with narrower swath, so give less coverage. The strength of the echo depends on the nature of the seabed: weak echoes return from smooth, soft seabeds and strong echoes return from rough, hard seabeds like cold-water coral reefs.

Multibeam echosounders are like side-scan sonars: the higher the frequency, the more detailed the image and the narrower the swath. Unlike side-scan sonars, they have hundreds of transducers accurately recording echoes from discrete places on the seabed to collectively generate swath coverage (Fig. 1.5). This provides *xy* coordinates for the echoes so the time delay can be used to define *z* (depth). In this way, multibeam echosounders not only produce backscatter maps, like side-scan sonars, but also bathymetry. Multibeam echosounders have become essential tools to map cold-water coral reefs and coral carbonate mounds.

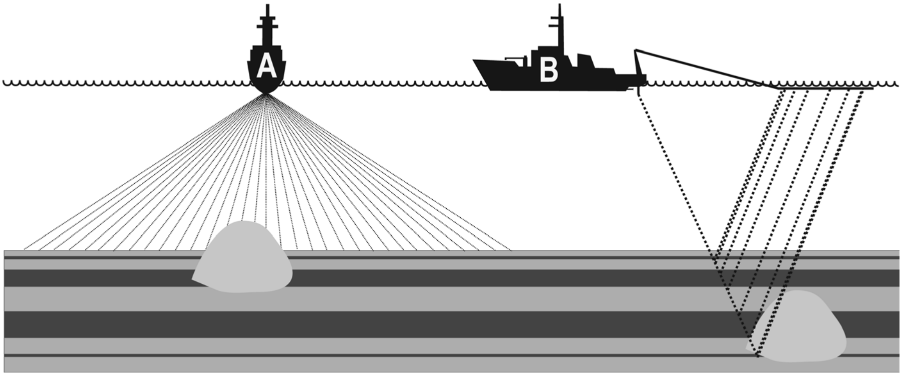

Fig. 1.5 Imaging a coral carbonate mound with sound. (a) Multibeam echosounders record a large number of discrete echoes from a swath of seabed thereby visualising seabed topography. Both the sound sources and receivers are hull-mounted. (b) Seismic imaging uses sound sources emitted near the vessel and received by a streamer towed behind. Low-frequency and high-magnitude sound sources penetrate the seabed and reflect off density contrasts (usually sediment unit boundaries and potentially buried coral carbonate mounds).

underwater vehicles (AUV) (e.g. Grasmueck *et al.*, 2006). Visual surveys are then performed using deep-towed camera frames although submersible or ROV-camera surveys are increasingly important (Colour plate 4). Submersibles and ROVs have the distinct advantages of being able to stop, wait, observe and take samples. They also allow monitoring equipment to be placed within specific macrohabitats or targeted at specific organisms. This opens new possibilities in experimental design where the organisms and habitats can be studied *in situ*. In this book we aim to capture the results of this revolution in cold-water coral research and note that in many instances this work has only just begun.

1.2.1 Exploration

The discovery of new cold-water coral reefs and mounds traces back to three primary sources: (1) chance finds and reports, often from fishing records, (2) sub-seabed seismic imaging data from frontier hydrocarbon exploration and (3) baseline regional mapping exercises.

The demand for oil and gas has made it profitable, and in some cases nationally strategic, to search for hydrocarbons with greater intensity and in deeper waters. So-called 'industrial seismics' use loud, low-frequency acoustic pulses (10 to 50 Hz) to penetrate deep into seabed rock strata to regions below the seafloor where hydrocarbon reservoirs might exist (see Topic box 1.1). Unfortunately, while low frequencies give good penetration through the seabed, they produce low-resolution datasets. On industrial seismic records, surface reefs are not visible but the more topographically expressive coral carbonate mounds, and some buried coral carbonate mounds, can be seen. In many instances, such seismic data have been detailed enough to identify mound targets for subsequent, higher resolution surveys. If hydrocarbon prospects are promising, then a closely spaced grid of seismic data (3D seismics) may be collected with interpolation between lines allowing a three-dimensional virtual seafloor to sub-seafloor block to be constructed. Buried coral carbonate mounds in the upper layers of seabed strata can be clearly imaged using this approach (Huvenne *et al*., 2007).

Once governments started to exert control over their Exclusive Economic Zones (EEZs) and seafloor territories it became necessary to map them in greater detail. To map large areas of seabed one needs a wide coverage, or swath, of the seabed. Once again there is a trade-off, but this time the trade-off is between frequency, height above the seabed and swath. To achieve a wide swath, there needs to be a longer time between sonar pings and the sonar transducers need to be flown high enough above the seabed to allow the sound to spread out. The pioneering GLORIA long-range side-scan sonar operated at 100 kHz and made the first maps of many hundreds of thousands of square kilometres of seabed around the world in the 1970s and 1980s (Somers, 1996). It is now superseded by the 30 kHz TOBI system. Many discoveries were made with GLORIA including major features such as unknown submarine canyons and seamounts as well as extensive areas of coral carbonate mounds. The coral mounds on the Blake Plateau, northwest Atlantic and Irish margin were first mapped in this way. The relatively recent development of multibeam echosounders (see Topic box 1.1) has seen another revolution with each sounding being precisely positioned (an ambiguous shortfall with side-scan sonar systems) and the great additional benefit of accurate bathymetric as well as backscatter data (Colour plates 5, 15, 16).

1.2.2 Habitat mapping

To plan detailed sampling operations and map habitat it is necessary to have sufficiently resolved site maps at a scale that shows the heterogeneity of features such as cold-water coral reef or mound surfaces. This requires multibeam echosounders (~100 kHz) and higher frequency side-scan sonars (100–1000 kHz). In shallow water, multibeam echosounders can be hull mounted and side-scan sonars towed near the surface. In deeper shelf and slope waters, lower frequencies (e.g. 12 kHz) are required, resolution drops and it becomes more desirable to deploy the transducers nearer to the seabed. This can be done by deep-towing side-scan sonars but the more motion-sensitive multibeam echosounders need to be mounted on a stable near-seabed vehicle, such as an AUV or ROV, rather than being towed. This latter approach is now producing some exquisite images of the seafloor in deep water with a level of detail never seen before (e.g. Fig. 4.17, Colour plate 15).

However, sonar images are no more than typologies with changes in backscatter intensity. To interpret and add detail the seabed must be examined visually or sampled. This ‘ground-truthing’ can be done with camera systems or by collecting physical samples (see Section 1.2.3 below). As visible light travels a short distance through water any images will show at most only a few square metres of seabed. An array of imaging systems are now available from drop, towed and submersible-mounted camera systems to towed laser line scanners. Images from seafloor surveys can be ‘stitched together’ to make video-mosaics of the survey area (Fig. 4.3).

It is not possible, or environmentally advisable, to sample every portion of a seabed survey area. However, acoustic ground discrimination system (AGDS) techniques can be used to analyse the acoustic return from echosounders or side-scan sonar data (e.g. Fosså *et al.*, 2005). This AGDS software divides the coverage into areas of seabed with similar acoustic return signals (not just the echo intensity but also its delay or how the echo fades – whether the echo is short and crisp or with a more complex, longer return). These areas are termed acoustic facies. By ground-truthing each acoustic facies it is possible to use this information to characterise the nature of the seabed across the whole survey.

This diverse collection of spatial information can be collated, organised and visualised with geographical information system (GIS) software. This software stores and visualises digital spatial data allowing different datasets to be quickly added or removed to make custom maps and views that can then easily be displayed using different scales and mapping projections. Furthermore, the information can also be examined statistically to define and manipulate spatial relationships. Geographical information system outputs can include remotely sensed data, species occurrences, survey cruise tracks and interpreted habitat maps in any combination (Wright *et al*., 2007).

1.2.3 Collecting samples

As well as providing samples for ground-truthing geophysical surveys, physical samples from the deep seabed are vital for further study. A range of deep-water sampling approaches exist (see Gage & Tyler, 1991) but not all sample cold-water coral habitats effectively, especially scleractinian reefs where substrata contain hard coral frameworks and may even be lithified. Dredges and trawls were the mainstay of deep-sea sampling in the nineteenth and most of the twentieth centuries but there is now a consensus that they should be avoided in cold-water coral habitats. Not only do these devices group organisms from a range of habitats and facies altogether, but they are also very destructive. Hydraulically damped multi- and megacorers designed to delicately sample the sediment–water interface are often inappropriate in cold-water coral habitats where coral fragments or glacial dropstones prevent cores from penetrating. Large box corers (Fig. 1.6a) penetrate with greater force and collect relatively large (up to 0.25 m^2) samples with almost intact benthic assemblages. However, fine sediment material and meiofauna are often blown away by the corer's bow

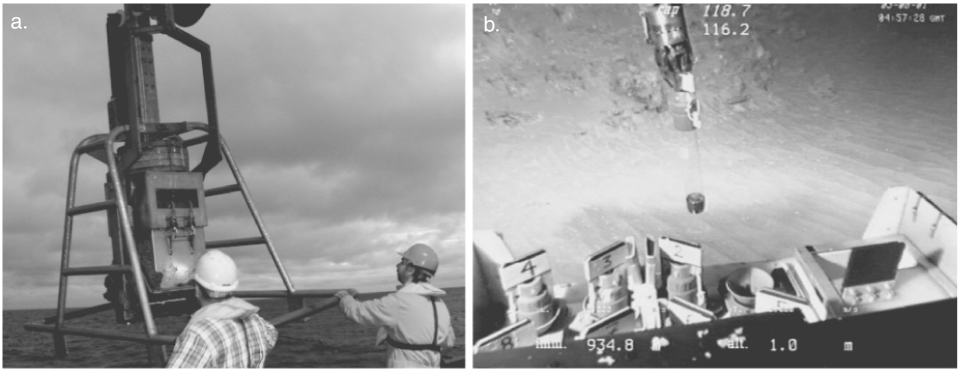

Fig. 1.6 A box corer (a) can recover up to 0.25 m^2 sediment surface area but is usually deployed without video guidance. Remotely operated vehicle push-cores (b) recover small sediment samples in a very precisely controlled manner. Image (b) courtesy of Ifremer (Institute Français de Recherche pour l'Exploitation de la Mer), Caracole Expedition 2001.

Fig. 1.7 A Russian hydraulically operated, video-directed seabed grab recovering a bottom sample from a coral carbonate mound in the Porcupine Seabight.

wave and rocks or coral fragments often prevent the corers from sealing properly. Intact box core samples are usually sub-sampled to separate surface and progressively deeper sub-surface layers and then sieved to separate species by size. Because box cores relate to area of seabed, quantified species diversity and biomass assessments can be made from intact cores. Submersibles and ROVs can sample specific habitats by either collecting selected organisms with manipulator arms or suction tubes (Colour plate 4), or by using push-cores forced into the seabed by a submersible/ROV manipulator arm (Fig. 1.6b). Recent developments in video-directed, hydraulically controlled grab sampling may allow coral colonies and reef frameworks to be sampled and stored in a sealed grab so that attached fauna are not lost as the sample is brought back through the water column (Fig. 1.7).

Continuous marine seabed deposition offers several advantages over what are typically more disrupted terrestrial records making long seabed cores valuable archives of past environmental conditions. Hemipelagic sedimentary sequences, despite low sedimentation rates, are relatively soft and easy to core with gravity or piston cores. Coral carbonate mounds have higher accumulation rates (see Section 4.4.3, p. 127) and may provide higher resolution archives, although complex sedimentation processes may restrict interpretations. The high carbonate content of these mounds provides valuable environmental proxies (coral skeletal proxies are discussed in Chapter 7). However, coral frameworks and lithification produce hard substrata that inhibit conventional coring and can bend core barrels (Fig. 1.4). This means that access to long core sequences can only be achieved effectively with drilling techniques, especially if whole mound sequences are to be sampled. Examples include drill ships like the *RV Joides Resolution* or portable deployable drilling rigs such as *MeBo* (Meeresboden-Bohrgerät; Freudenthal & Wefer (2007), see Fig. 1.8). With these devices, complete

https://doi.org/10.1017/CBO9780511581588.002

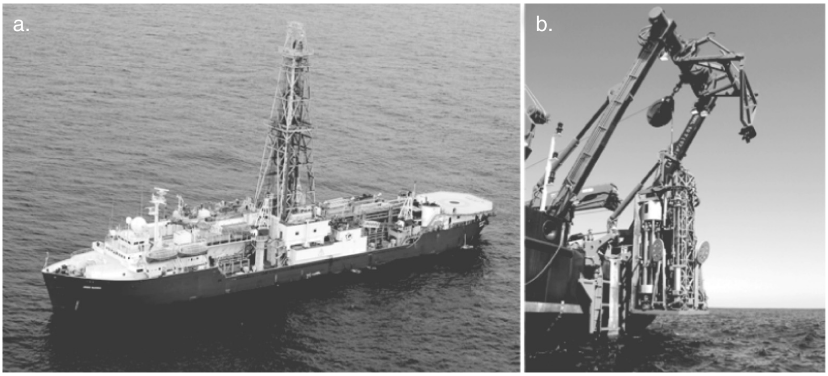

Fig. 1.8 Drilling technologies. (a) The 143 m long Integrated Ocean Drilling Program (IODP) drill ship *RV Joides Resolution* is capable of drilling up to 2000 m below the seafloor in water depths up to 8000 m. Image courtesy of the Integrated Ocean Drilling Program. (b) The German *Meeresboden-Bohrgerät* (seafloor drill rig) known as *MeBo* deployed from the stern of a research vessel. This portable system is designed to drill 50–70 m below the seafloor in water depths up to 2000 m. Image courtesy of MARUM, University of Bremen, Germany.

sequences tens of metres long can be retrieved through both soft and lithified substrata. However, the costs of these drilling approaches are substantial.

1.2.4 Monitoring

Acoustic maps and samples provide 'snapshots' of a dynamic environment. Cold-water coral habitats are strongly influenced by fast-flowing currents that flush through them. Seasonal changes affect surface productivity, which in deep-sea settings leads to seasonal changes in phytodetrital flux to the seafloor. Our snapshots of these environments are usually during spring or summer months when calmer seas make surveys possible. However, mobile sedimentary bedforms may take several years to migrate through areas where cold-water corals are present and we are just starting to appreciate decadal changes in deep-sea climate conditions.

Continuous monitoring in the deep sea can overcome this temporal sampling bias and offer us a different view of these environments – revealing periods of change, the variability of environmental conditions and possibly even infrequent, but important, extreme events. Monitoring can be done by deploying instrumented platforms (such as benthic landers, Fig. 1.9) on the seabed or moorings with strings of instruments monitoring processes in the water column. Typical instrument packages include both single-point current meters and acoustic doppler current profilers, sediment traps, fluorometers to record phytoplankton pigments, light-scattering and transmission sensors to record particle resuspension, and time-lapse cameras to monitor organism presence and activity.

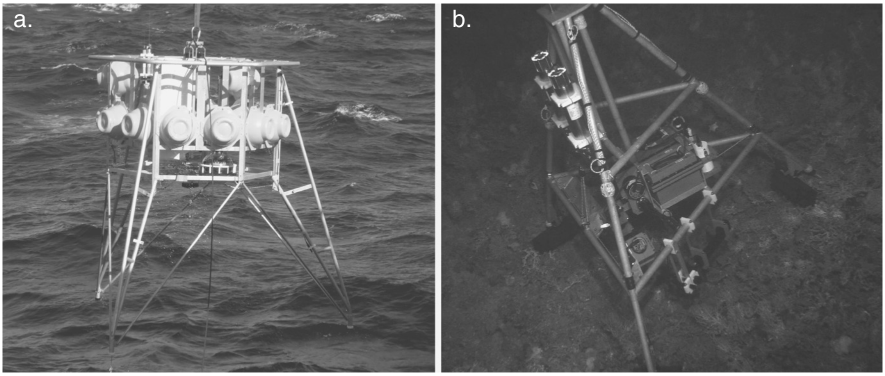

Fig. 1.9 Benthic landers allow cold-water coral habitats to be monitored through time. (a) The Royal Netherlands Institute for Sea Research BoBo lander being deployed on the Logachev Mounds, northeast Atlantic and (b) the Scottish Association of Marine Science photolander on the Galway Mound (800 m depth), northeast Atlantic. Image (a) courtesy of B. Dorschel and image (b) courtesy of the Alfred-Wegener-Institut für Polar- und Meeresforschung and the Institut Français de Recherche pour l'Exploitation de la Mer.

1.2.5 Technologies for the future

Submersibles and ROVs have already revolutionised how we interact with deep, cold-water coral environments; not only do they enable a flexible presence on the seabed, but with the development of different tools and payloads they can operate in various modes from reconnaissance and mapping to observation and sampling. Increasingly, ROVs are being used as workhorses to accurately position, maintain and retrieve experiments from the seabed. These can examine a suite of topics including animal behaviour, physiology, reproduction and larval settlement all ideally related back to long-term *in situ* monitoring information from benthic landers and moorings.

Other technologies are now being developed to the point where they can be used to study deep-sea habitats. With increasing payload capacities, AUV-based surveying is destined to become increasingly important. Autonomous underwater vehicles offer new opportunities allowing systematic surveys such as seabed mapping or water mass characterisation leaving the AUV's mother ship and scientists free to perform other activities. Benthic crawlers are now being developed to explore spatial variability in the deep sea. Rather like the Mars rovers, crawlers are small motorised machines that can drive over the seabed carrying a payload of instruments and cameras. A crawler could be remotely controlled, pre-programmed or even able to 'intelligently' explore the environment and find its way back to a docking station to recharge its batteries and download its data. This new tool may be able to explore and sample cold-water coral habitats where other tethered vehicles are constrained by fast currents.

Cabled observatories perhaps offer the greatest potential for the next revolution in the way researchers interact and study cold-water coral habitats. Cabled observatories create a real-time permanent presence in these remote environments using fibre-optic cables to relay information straight back to shore and, via the World Wide Web, to researchers around the world (Delaney & Chave, 2000). Observatories can be considered as hard-wired lander platforms and moorings but without the power and payload constraints of autonomous systems they can be much larger and more sophisticated. Cabled observatories could also monitor internal reef and mound environments, connecting down-borehole probes measuring sub-seafloor processes such as fluid flow.

Seafloor observatory nodes could also become energy supply and data download stations for AUVs and crawlers allowing them to remain deployed for prolonged periods. At the time of writing North American cabled observatory plans are being implemented in the North Pacific (the MARS, NEPTUNE and VENUS projects). In Europe plans have been laid for an observatory including coral carbonate mounds in the Porcupine Seabight (ESONET). Seafloor observatories have the potential to bring these remote environments directly into the laboratory, classroom or home in real time. Such technologies will surely change how we perceive and study these environments and initiate a new era in deep-sea exploration.