

Chapter 51. Biological Communities on Seamounts and Other Submarine Features Potentially Threatened by Disturbance

Contributors: J. Anthony Koslow, Peter Auster, Odd Aksel Bergstad, J. Murray Roberts, Alex Rogers, Michael Vecchione, Peter Harris, Jake Rice, Patricio Bernal (Co-Lead members)

1. Physical, chemical, and ecological characteristics

1.1 *Seamounts*

Seamounts are predominantly submerged volcanoes, mostly extinct, rising hundreds to thousands of metres above the surrounding seafloor. Some also arise through tectonic uplift. The conventional geological definition includes only features greater than 1000 m in height, with the term “knoll” often used to refer to features 100 – 1000 m in height (Yesson et al., 2011). However, seamounts and knolls do not appear to differ much ecologically, and human activity, such as fishing, focuses on both. We therefore include here all such features with heights > 100 m.

Only 6.5 per cent of the deep seafloor has been mapped, so the global number of seamounts must be estimated, usually from a combination of satellite altimetry and multibeam data as well as extrapolation based on size-frequency relationships of seamounts for smaller features. Estimates have varied widely as a result of differences in methodologies as well as changes in the resolution of data. Yesson et al. (2011) identified 33,452 seamount and guyot features > 1000 m in height and 138,412 knolls (100 – 1000 m), whereas Harris et al. (2014) identified 10,234 seamount and guyot features, based on a stricter definition that restricted seamounts to conical forms. Estimates of total abundance range to >100,000 seamounts and to 25 million for features > 100 m in height (Smith 1991; Wessel et al., 2010). At least half are in the Pacific, with progressively fewer in the Atlantic, Indian, Southern, and Arctic Oceans. Identified seamounts cover approximately 4.7 per cent of the ocean floor, with identified knolls covering an additional 16.3 per cent, in total an area approximately the size of Africa and Asia combined, about three-fold larger than all continental shelf areas in the world’s oceans (Etnoyer et al., 2010; Yesson et al., 2011).

Seamounts can influence local ocean circulation, amplifying and rectifying flows, including tidal currents, particularly near seamount summits, enhancing vertical mixing, and creating retention cells known as Taylor columns or cones over some seamounts. These effects depend on many factors, including the size (height and diameter) of the seamount relative to the water depth, its latitude, and the character of the flow around the seamount (White et al., 2007).

Where flows are sufficiently vigorous, they provide a sufficient flow of organic matter to support suspension feeding organisms, such as corals and sponges. Such currents also winnow away the sediment, providing hard substrate necessary for most suspension feeders to settle and attach. Depending on depth and current regime, the seamount benthos may be dominated by an invertebrate fauna typical of the surrounding sediment-covered slope or abyssal plain or a more specialized fauna adapted to high-energy, hard substrate-dominated deep-water environments.

Seamounts that rise to mesopelagic depths or shallower ($\leq \sim 1000$ m) often have an associated fish fauna adapted to feed on the elevated flux of micronekton and zooplankton, as well as vertical migrators intercepted by the seamounts during their downward diel migrations (Koslow, 1997; Clark et al., 2010b). More than 70 fish taxa have been commercially exploited around seamounts (Rogers 1994), although the number of species that are found only or principally on seamounts is closer to 13 – 16 (Clark et al., 2007, Watson et al., 2007). Some, such as pelagic armorhead, orange roughy, alfonsino, oreos, and others, are found in substantial aggregations around seamounts, making them efficient targets for fisheries.

Many seamounts are rugged, topographically complex environments, difficult to sample with conventional gear, such as nets. Wilson and Kaufmann's (1987) review reported only 596 invertebrate species recorded from seamounts to that date, with 72 per cent of these species from studies of only five seamounts. Seamount studies ramped up in the 1990s, initially based on concerns about the impacts of deep-water trawl fishing for orange roughy and oreos on seamounts. Based on more intensive and comprehensive sampling, Richer de Forges et al. (2000) reported more than 850 species associated with cold-water coral and sponge communities on seamounts in the Tasman and Coral Seas of the Southwest Pacific, with potentially high levels of endemism. Seamount studies have since been carried out worldwide, significantly stimulated by collaborative efforts such as the Census of Marine Life CenSeam project. A recent review found 1,222 fish species recorded from 184 seamounts (Kvile et al., 2013), approximately doubling the number of seamounts investigated and the number of species recorded from this environment since Wilson and Kaufmann's (1987) review. Overall species richness on seamounts cannot yet be estimated, with < 1 per cent of seamounts sampled and only a few per cent of those intensively studied. The number of species recorded from seamounts continues to increase roughly in proportion to sampling effort, with no evidence yet of levelling off (Richer de Forges et al., 2000; Stocks and Hart, 2007; Castelin et al., 2011). Due to the limited sampling, the proportion of species endemic to this habitat is controversial. Some seamounts appear to represent biodiversity hotspots (Samadi et al., 2006; McClain et al., 2009), but variability is extensive, and other studies conclude that species richness is comparable on seamounts and nearby slope habitats (Consalvey et al., 2010; Howell et al., 2010; Castelin et al., 2011).

Biogeographically, seamount faunas generally appear related to the faunas of adjacent basins or continental slopes (Wilson et al., 1985; Parin et al., 1997; Mironov et al., 2006). For seamount fishes, which have been the best studied group of organisms, biogeographical patterns appear to follow the distribution of dominant water masses,

such as Antarctic Intermediate Water and North Atlantic Deep Water (Koslow et al., 1994; Clark et al., 2010a and b). Whereas the dominant genera and families of deep-sea demersal and midwater fishes tend to have global distributions, the dominant fish species on seamounts in different ocean basins are often from entirely different genera, families, and even orders. This indicates that seamount-associated fishes in different ocean basins were reproductively isolated and evolved independently. Their similar morphologies and adaptation to the seamount environment is a striking example of convergent evolution (Koslow, 1996).

Seamounts are the source of significant ecosystem services. In addition to their biodiversity, seamounts often host substantial aggregations of fishes, which have been subject to commercial fisheries. These include species for which seamounts are their primary environment as well as a larger number for which seamounts account for a smaller proportion of their global catch. Annual landings of primary seamount species have fluctuated around 100,000 t since the 1990s, dominated by oreosomatids and orange roughy (Clark et al., 2007; Watson et al., 2007).

Seamounts, along with ridges and plateaus, host ferromanganese crusts that contain cobalt, nickel, and rare earth elements used in high-tech industries and which may have commercial potential, although they are not presently exploited (Hein et al., 2010).

1.2 Ridges and plateaus

One of the more prominent features of the global ocean is the 75,000 km long network of mid-ocean ridges, defined as “the linked major mid-oceanic mountain systems of global extent” (IHO, 2008), essentially created at plate boundary spreading zones, where new crust is being formed as tectonic plates move apart. The most prominent is the Mid-Atlantic Ridge that runs down the middle of the Atlantic from the Arctic to the Southern Ocean, where it connects to the more complex system of ridges in the Indian Ocean and the Pacific Ocean. Mid-ocean ridges in the South Pacific comprise 1.87 million km², the largest area in a single ocean (Harris et al., 2014). Ridge features may include islands (e.g. the Azores archipelago (Portugal) and Iceland) and seamounts. Harris et al (2014) distinguish mid-ocean ridges from other ridge features that are isolated, elongate, narrow, steep-sided and at least 1000 m in height. These may overlap with plateaus and seamounts. Hydrothermal vents, which are treated in Chapter 45, are often associated with mid-ocean spreading ridges (Baker and German, 2013).

Studies of ridge features have increased significantly in recent years. Notable among them are studies of the Nazca and Sala y Gomez ridges in the Southeast Pacific (e.g. Parin et al., 1997; Pakhorukov, 2005), the MAR-ECO and ECOMAR studies of the Mid-Atlantic Ridge in the North Atlantic (e.g. special issues of Deep-Sea Research II 55 (1). (2008). and 98 Part B (2013), Bergstad et al., 2008; Vecchione et al., 2010; Priede et al., 2013), as well as studies of the Mid-Atlantic Ridge in the South Atlantic (Perez et al., 2012).

Ridges typically contain seamounts and sedimented slopes; not surprisingly, similarities in the abundance, diversity, and species composition of ridge habitats are found with both seamounts and continental margins (Priede et al., 2013). Priede et al. (2013) also noted that a deep ridge system, such as the mid-Atlantic Ridge (mostly deeper than 1000 m), does not appear to significantly enhance oceanic productivity, although it greatly extends the area of available lower bathyal habitat.

Plateaus and banks are geologically not as well defined or as extensive as ridges, but comprise relatively less steep and comparatively shallow features separated from continental shelves by deep channels. In terms of shape and size, plateaus are wider and much larger than seamounts. Harris et al. (2014) mapped 184 plateaus in the world's oceans, comprising 5.1 per cent of the ocean area. They figure most prominently in the Indian and South Pacific Oceans; Challenger, Campbell, and Kerguelen Plateaus and Chatham Rise around New Zealand are the largest such features. Despite being mostly deeper than 200 m, plateaus may be recognised as oceanic shallows or banks because they are disconnected from continental shelves and coastal waters.

Plateaus share many diversity characteristics and faunas with nearby continental shelves and slopes, and ecosystem services from plateaus are also similar to those of shelves. Most plateaus are nearer to land and are considered richer in terms of harvestable resources than oceanic ridges. Both shallow and deep fisheries on plateaus and banks are therefore relatively substantial. Indeed, most of the deep-water fisheries being conducted at present are either on upper continental slopes or on slopes of plateaus (Koslow et al., 2000; Watson et al., 2007). In addition to fishing, mining and hydrocarbon exploration/extraction are emerging activities on plateaus and ridges (Rona 2003, Ramirez-Llodra et al., 2011).

1.3 Submarine canyons

Submarine canyons are defined as “steep-walled sinuous valleys with V-shaped cross sections, axes sloping outward as continuously as river-cut land canyons, and relief comparable to even the largest land canyons” (Shephard, 1963). Recent estimates of their number and extent vary widely, depending on mapping criteria, from 448 to about 9500 canyons in the global ocean with a total extent ranging from 25,000 to 389,505 km (Ramirez-Llodra et al., 2010; De Leo et al., 2010; Harris and Whiteway, 2011; Harris et al., 2014). Because they cut across the continental shelf and slope, canyons are the deep-sea environment closest to human occupancy, making them convenient to study but also rendering them vulnerable to human stressors.

Canyons have been recognized as distinct topographic features for approximately 150 years (Dana 1863 in Ramirez-Llodra et al., 2010). However, their rough topography compared with nearby slope areas has made studying them difficult. Technological developments of the past few decades, along with international programmes like the Census of Marine Life Continental Margins, or Continental Margin Ecosystems (COMARGE) programme (Menot et al., 2010), and the long-term programme of the

Monterey Bay Aquarium Research Institute (MBARI) in Monterey Canyon have led to a renaissance in canyon studies (e.g. Huvenne and Davies, 2013). Whereas most canyons globally have received little or no scientific attention from any discipline, some individual canyons (e.g., Monterey – western North America, “The Gully” – eastern North America, Kaikura – New Zealand, Nazaré – western Europe) have been studied by multidisciplinary teams.

With steep walls and depositional environments along their axes, canyons are geologically complex, including hard substrates and soft sediments, depending on the slope of the walls. Because canyons cut into the ancient sediments of continental margins, many have hydrocarbon seeps and their associated specialized chemosynthetic communities. They also exhibit complex hydrography, intersecting and diverting along-slope and along-shelf currents. The steep bottom topography can intensify these flows by topographic channelling and constriction. Density-driven flows result in episodic cascading down-canyon, transporting shallow waters into the deep sea along with associated material. The intensified currents can result in higher physical disturbance of the benthos relative to nearby slope areas.

Canyons concentrate both biogenic and anthropogenic material along their deep axes and can transport these materials either onto the shelf or into the deep abyssal environment, depending on local flow conditions. Such material includes organic matter produced in the overlying photic zone, as well as pollutants and other anthropogenic material, either inadvertently discharged or deliberately disposed of. The concentration of sinking surface productivity enriches benthic communities along the canyon axes and can result in high biomass. Flow may similarly enhance recruitment of early-life-history stages of both sessile and mobile fauna by local topographic concentration of eggs and/or larvae in particular areas (Vetter et al., 2010).

The hard substrates and particulate transport in canyons can support abundant, diverse sessile suspension-feeding communities (hard and soft corals, sponges) and associated fauna, whereas areas of sediment accumulation support communities of deposit feeders, scavengers and their predators (De Leo et al., 2010). Canyons are also hotspots of pelagic activity, supporting feeding concentrations of air-breathing marine vertebrates (mammals, birds, turtles), including many protected species. Canyons are also targeted by longline, trap and trawl fisheries. Some of these fisheries can damage or destroy both hard- and soft-substrate benthic communities, which may include very long-lived and slow-growing species. As with other bathyal habitats, canyons will be affected by climate change because of changes in circulation, stratification, primary productivity, expansion of oxygen-minimum zones (OMZs), and acidification. Canyons may also serve as conduits to the deep sea for pollution (including trash) or sediment mobilized by mining or bottom trawling (Ramirez-Llodra et al., 2011).

1.4 Trenches

Trenches are defined as “long, narrow, characteristically very deep and asymmetrical depressions(s) of the seafloor, with relatively steep sides” (IHO, 2008). In addition to featuring steep terrain with typically hard substrates, often narrow terraces and the deepest ocean depths, the trenches have flat floors with accumulated fine sediments. Trenches are formed as oceanic plates collide with continental plates; the heavier oceanic plates are subducted, creating a trench. Trenches are generally narrow (<40 km wide), V-shaped in cross-section and are found near and parallel to island-arc systems and continental land masses (Jamieson et al., 2010). High current velocities (10-32 cm/sec) have been recorded near the bottom in trenches, as have collapsed walls with massive sediment slides and inferred turbidity currents (Ramirez-Llodra et al., 2010). These processes are responsible for the accumulation of sediments and organic matter in the axes of the trenches, similar to what occurs in canyons.

Harris et al. (2014) mapped 56 trenches in the world ocean. Trenches comprise a total area of about 2 million km², less than 1 per cent of the total ocean area. About 80 per cent of all trenches, by area, are found in the North and South Pacific Oceans. The seafloor of most trenches is at hadal depths (>6000 m) but some trenches, such as the Hellenic Trench in the Mediterranean, are shallower (Ramirez-Llodra et al., 2010).

Trenches are probably the most poorly-known deep-sea habitat, because of the cost and difficulty of sampling at such depths. The first biological samples from the trench environment were obtained during the 1948 Swedish *Albatross* Expedition, which was soon followed by the Danish *Galathea* and Soviet *Vityaz* Expeditions, which sampled several trench environments. Bruun (1956) first defined the hadal zone (depths > 6000 m) as distinct from the abyss, based on a marked transition in species composition, presumably because of the need to adapt to increased pressure. Hadal depths are also below the carbonate and opal compensation depths. Some animal groups with carbonate or siliceous skeletons are therefore excluded (non-holothurian echinoderms and non-actinarian Cnidaria) or are characterized by decreased skeletal strength compared to their shallower relatives (gastropods and bivalves). As a result of the discontinuities between trenches and apparent difficulties of dispersion, high levels of endemism exist both within the hadal environment as a whole (56 per cent as estimated by Belyaev (1989)) and within individual trench systems at the species level (Vinogradova, 1997; Blankenship-Williams and Levin, 2009). The hadal environment is often considered to have low biodiversity, but Blankenship-Williams and Levin (2009) note that trenches contain diverse habitats (e.g. cold seeps and hydrothermal vents, steep walls) that have been particularly poorly sampled.

A few broad generalities can summarize what little is known about trench fauna. Foraminifera are common even at the very deepest extremes. Patterns of metazoan diversity vary among communities based on substrate and food sources: fine sediments on ledges and the trench axis support infauna, such as macrofaunal polychaetes and meiofaunal nematodes, as well as deposit feeding epifauna dominated by holothurians; hard substrates of the walls are characterized by non-calcified sessile fauna like

anemones and their mobile benthic associates (e.g., amphipods); communities near hydrothermal vents and cold seeps are dominated by metazoans dependent on symbiotic chemosynthetic microbes. An assemblage of mobile scavengers is dominated by amphipods, some remarkably large (Jamieson et al., 2013), and fishes such as liparids and macrourids (Jamieson et al., 2009; Fujii et al., 2010).

Because of their extreme depth, trenches have not been subject to commercial activity, such as fishing, mining, or energy extraction. However, they have been subject to dumping, such as of pharmaceuticals in the Puerto Rico trench (Ramirez-Llodra et al., 2011).

2. Documented anthropogenic impacts on the deep ocean including their history (as appropriate) on a regional basis.

2.1 Fishing

A few deep-water artisanal hook and line fisheries around islands and seamounts maintained steady landings with few environmental impacts for decades to centuries (e.g. oilfish in the South Pacific and black scabbardfish around Madeira (Koslow 2007; Silva and Pinho, 2007). Modern large-scale fisheries on seamounts, ridges, and other features with abrupt topographies were initiated after World War II, fostered by technological developments and distant-water industrial fishing. Gillnets, longlines, and both pelagic and bottom trawls are the primary gears (Gianni, 2004; Clark et al., 2007; Bensch et al., 2009). Bottom trawls have had greatest impact, affecting both targeted and non-targeted species including associated benthic communities (Koslow et al., 2001; Clark and Koslow, 2007; Clark and Rowden, 2009). These fisheries have occurred in all oceans except the Arctic.

The first Pacific seamount-associated fisheries were for pelagic species, such as albacore, that aggregated over seamounts in the North Pacific. From 1967 to 1989, a demersal seamount trawl fishery targeting aggregations of pelagic armorhead on the Emperor Seamount chain landed about 800,000 tons of armorhead along with about 80,000 t of alfonsino (Clark et al., 2007). These stocks were depleted and have still not recovered (NPFC, 2014).

Two species of red coral (*Corallium* spp.) were also depleted sequentially from the Emperor seamounts by a tangle-net fishery between 1965 and 1990 (Clark and Koslow 2007; Koslow, 2007).

Since the mid-1970s, trawl fisheries expanded to seamounts and plateaus in the South Pacific, predominantly for orange roughy and oreos, but also for alfonsino, black cardinalfish, and other species (Clark et al., 2007). A series of these stocks underwent boom-and-bust cycles, mostly in the space of 5 – 10 years and many have not recovered (Clark et al., 2007). Both pelagic and demersal fisheries also occurred on seamounts and ridges in the southeast Pacific, the East Pacific Rise, the Nazca and Sala-y-Gomez Ridges,

and the Chilean Rise. Catches were not large nor were they sustainable (Clark et al., 2007).

In the Southern Ocean, seamounts were fished for nototheniids between 1974 and 1991. In the 1990s, the ridges, plateaus, and seamounts around remote sub-Antarctic islands came to be heavily fished for Patagonian toothfish with trawls and longlines. Initially much illegal, unreported and unregulated (IUU) fishing occurred but has declined significantly since 1996 (Agnew et al., 2009).

Large-scale industrial deep-water fisheries in the North Atlantic date to the development of redfish fisheries in the 1950s using both midwater and demersal trawls over the mid-Atlantic Ridge and on some plateaus. Redfish catches peaked at almost 400,000 tons in the 1950s and have declined considerably but several continue to support some harvest (Koslow et al., 2000; ICES, 2013). Fisheries for roundnose grenadier and Greenland halibut first developed on the upper continental slopes of the Northwest Atlantic in the late 1960s, peaking at over 80,000 tons in 1971 and then rapidly declined and moved to the mid-Atlantic Ridge and Rockall-Hatton Bank in 1973 (Troyanovsky and Lisovsky, 1995; Clark et al., 2007). Several other species have been exploited from the seamounts and ridges of the North Atlantic, including alfonsino, orange roughy, deep-water sharks, ling, blue ling, black cardinalfish, tusk, deep-water crabs and shrimp, and others (Clark et al., 2007; Bensch et al., 2009). From the latter half of the 1990s onwards, declines in catch per unit effort (CPUE) indicated that most targeted North Atlantic deep-water fisheries were overfished and some severely depleted (Koslow et al., 2000; Large et al., 2003; Large and Bergstad, 2005; Devine et al., 2006; Bensch et al., 2009; Rogers and Gianni, 2010).

In 2003, the International Council for the Exploration of the Sea (ICES) deemed that most deep-water stocks “were probably outside safe biological limits.” In the last decade fisheries on seamounts and ridges in the Atlantic have declined significantly due to a combination of declining fish populations, significantly altered socioeconomic conditions, and increased regulation by national governments and Regional Fisheries Management Organizations (RFMOs).

Retrospective analyses based on research vessel surveys also indicated that several target and non-target species in the Northwest Atlantic had declined by >90 per cent between 1978 and 1994 (Devine et al., 2006). Many fishery restrictions were implemented and recent survey data indicate biomass levels have stabilized in most surveyed areas (Neat and Burns, 2010). However, recovery for deep-water species with low productive capacity will probably take decades or longer (Baker et al. 2009; Neat and Burns, 2010).

Seamount fisheries in the South Atlantic have been undertaken at a smaller scale than in the North Atlantic. However, there have been seamount fisheries targeting orange roughy, alfonsino, cardinal fish, armorhead, Patagonian toothfish and deep-sea red crab, and some continue to the present day (Rogers and Gianni, 2010; www.seafo.org).

Exploratory trawl fishing on seamounts in the Indian Ocean began in the 1970s targeting shallow-water redbait and rubyfish on the Southwest Indian Ocean Ridge, the Mozambique Ridge and the Madagascar Ridge (Romanov, 2003; Clark et al., 2007) and continued into the mid-1980s. In the late 1990s, trawlers working on the Southwest Indian Ocean Ridge targeted deep-water species, such as orange roughy, black cardinalfish, pelagic armorhead, oreosomatids and alfonsino (Clark et al., 2007), but the fishery rapidly collapsed (Gianni, 2004). Fishing has shifted to the many ridges, seamounts and plateaus targeting a variety of species of deep-sea fish and crustaceans (Clark et al., 2007; Bensch et al., 2009; SWIOFC, 2009).

Overall, deep-water demersal fisheries over the continental slope, ridges, seamounts, and plateaus have landed between 800,000 and 1,000,000 t per annum from the mid-1960s to 1990s (Koslow et al., 2000) and annual landings on the order of 100,000 t since about 1990 (Clark et al., 2007; Watson et al., 2007). The vast majority of seamount-associated demersal fisheries have proven unsustainable, undergoing a boom-and-bust cycle that has usually lasted less than 10 years. Many of the stocks have vulnerable life histories and are small, remote, and difficult to monitor and manage effectively (Koslow, 2007). However, during the last 10-15 years many States and intergovernmental organizations have recognized the need for enhanced management action to protect vulnerable marine species and habitats to facilitate the recovery of depleted stocks.

2.2 *Fishing impacts on seamount benthic habitats*

Energetic seamount habitats that support substantial fish aggregations also often host diverse, productive benthic habitats dominated by corals, sponges, and associated fauna (Rogers et al., 2007; Samadi et al., 2007). Demersal trawling on seamounts generally removes benthic habitat as by-catch along with the target species or destroys it converting reefs and other structure-forming species to rubble. See chapter 11 for more details on the nature of these impacts. The United Nations General Assembly has been looking into the impact of bottom trawling (e.g. resolutions 61/105, 64/72 and 66/68),¹ although no global assessment has been carried out on the extent of benthic impacts. The documented widespread extent of deep-water trawl fisheries has led to pervasive concern for the conservation of fragile benthic habitats. Moreover, on seamounts where trawling has been discontinued, little regeneration is observed even after five to 10 years (Althaus et al., 2009; Williams et al., 2010) and recovery may require centuries to millennia. Because of the close correspondence between the productivity and diversity of seamount benthic habitats, there are likely few diverse seamount habitats within the vertical range of bottom-trawl fishing that remain pristine, and many have been denuded, their coral and sponge habitats reduced to rubble.

Examples of measures taken by regional fisheries management organizations and arrangements (RFMO/As) to avoid or mitigate fishing impacts on benthic habitats include:

¹ Reports of the Secretary-General on this issue have been issued as A/61/154, A/64/305 and A/66/307.

- Both the North Atlantic Fisheries Organization (NAFO) and North East Atlantic Fisheries Commission (NEAFC) in the North Atlantic set quotas for deep-sea stocks based on scientific assessments, and have identified and closed to fishing areas that meet the Food and Agricultural Organization of the United Nations (FAO) criteria for vulnerable marine ecosystems.
- The Southeast Atlantic Fisheries Organization (SEAFO) has closed selected ridge sections and seamounts to fishing, restricted fisheries to certain subareas, and introduced catch quotas (TACs) for the fishes and deep-water crab targeted on seamounts.
- States which participated in the negotiations for the establishment of the North Pacific Fisheries Commission have established interim measures for fisheries management and are working towards stock assessments to modify fishing effort to sustainable levels (Rogers & Gianni, 2010; NPFC, 2014).
- The South Pacific Regional Fisheries Management Organization has called for interim conservation measures, including freezing of the fishing footprint and catch based on historical patterns of fishing which have been implemented by some States (SPRFMO, 2014). Efforts are underway by some member States to map vulnerable marine ecosystems and to assess fisheries data in order to estimate stock biomass and sustainable levels of exploitation (SPRFMO, 2014).
- The Commission for the Conservation of Antarctic Marine Living Resources banned bottom trawl fishing; has restricted remaining fishing opportunities to previously licensed fishing areas or exploratory areas and species specific catch quotas (or total allowable catches (TACs)); and is implementing spatial measures to prevent adverse impacts on bottom-associated vulnerable marine communities.
- The Southern Indian Ocean Deep-sea Fishers Association declared a number of seamounts in the Southern Indian Ocean as voluntary closed areas to fishing although levels of compliance amongst non-members are unknown. With the ratification in 2012 of the Southern Indian Ocean Fisheries Agreement (SIOFA), a new regional fisheries management arrangement for the region is expected to lead to better data collection and regulation of seamount fisheries.

While these actions are progressive, their effectiveness in ensuring the sustainability of exploitation of populations or recovery of vulnerable species and communities is not yet clear (see sections 4-6 below). Indeed whether full closures will result in recovery of vulnerable communities to a former state or a shift to some less desirable community state remains uncertain given current knowledge.

2.3 *Pollution*

The deep sea was once considered as being too remote from the point sources of industrial pollution for pollution to be a significant issue. However, key contaminants of

concern, including mercury and many halogenated hydrocarbons (e.g., DDT, PCBs, and many other pesticides, herbicides, and industrial chemicals) are volatile and enter the ocean predominantly through the atmosphere. These are discussed in Chapter 20. As noted there, concentrations of persistent organic pollutants in deep-sea-dwelling fish may be an order of magnitude higher than in surface-dwelling fish, and the deep sea has been described as one of the ultimate global sinks for such contaminants. Butyl tin, an antifoulant that causes imposex in mollusks, is reported in elevated concentrations in deep-sea organisms, particularly in the vicinity of shipping lanes (Takahashi et al., 1997), and microplastics are now widely reported in deep-sea sediments (van Cauwenberghe et al., 2013).

2.4 *Climate change, including acidification and deoxygenation*

Predicted shoaling in the depth of calcium carbonate saturation horizons will expose large areas of seamount, ridge, plateau and slope habitat to undersaturated waters (Guinotte et al., 2006). Recent reviews and meta-analyses of the impacts of ocean acidification summarize the present understanding of its effects on cold-water corals (e.g. Wicks and Roberts, 2012), although to date no experimental studies have focused on seamount species. Studies have highlighted the ability of live cold-water corals to maintain calcification at reduced pH (Maier et al., 2009; Form and Riebesell 2012) but synergistic effects with increasing temperature and longer-term effects on resource allocation and reproduction remain unknown. It is becoming clear that deep-water ecosystems may experience more natural variability in carbonate chemistry than was previously supposed (Findlay et al., 2013; Findlay et al., 2014) and that calcareous species can persist even in under-saturated conditions on Tasmanian seamounts (Thresher et al., 2011). However, undersaturated waters will be corrosive to dead coral skeletons that provide structural habitat for many other species, a factor potentially explaining the limited scleractinian coral reef framework on the Hebrides Terrace Seamount (Henry et al., 2014). Increased carbon dioxide and reduced pH may also directly affect marine organisms' physiology, growth, and behaviour (Wicks and Roberts, 2012). It is thus necessary to understand their ecosystem-level impacts, such as the effects of acidification on bioerosion of deep-water corals (Wisshak et al., 2012).

Global climate models predict that oxygen concentrations will decline in the deep ocean due to decreased ventilation (a warmer ocean will be a more stratified ocean) and decreased oxygen solubility at warmer temperatures (Sarmiento et al., 1998; Matear and Hirst, 2003; Shaffer et al., 2009). Over the past 20 years, oxygen concentrations have declined in regions around the North Pacific Ocean and the tropical Indian, Atlantic and Pacific Oceans which have pronounced OMZs, with concomitant horizontal and vertical expansion of these OMZs (Whitney et al. 2007, Bograd et al., 2008; Stramma et al., 2008; Keeling et al., 2010). Benthic communities are dramatically affected where OMZs impinge on seamounts, ridges or continental margins, with greatly reduced biomass and biodiversity (Wishner et al., 1990; Levin 2003; Stramma et al., 2010). Deoxygenation may also affect deepwater benthic organisms indirectly through habitat

loss and declining food availability. Midwater fishes, the primary food of many deepwater squid and fish species, including orange roughy, declined ~60 per cent during recent periods of low-oxygen availability in the California Current (Koslow et al., 2011). Palaeoceanographic studies have pointed to the significance of perturbations in oxygen concentration in controlling deep coral occurrence in the Eastern Mediterranean (Fink et al. 2012) and on seamounts (Thiagarajan et al., 2013). Most major marine mass extinction events in the geological past are associated with anoxia and acidification (Harnik et al., 2012).

2.5 *Mining*

There is the possibility of future mining of cobalt-rich ferromanganese crusts on the bare volcanic rock of seamounts, ridges and plateaus found particularly on seamounts within the exclusive economic zones of island States in the western equatorial Pacific (Rona, 2003; see Chapter 23). Significant differences have been found in the communities inhabiting cobalt-crust-hosting seamounts in the northern Pacific and seamounts outside of the cobalt-rich zone (Schlacher et al., 2013). These differences are not related to species richness but more to the relative abundance of species and community composition in the cobalt-crust rich areas versus non-cobalt rich areas. A high level of heterogeneity amongst the seamounts in terms of their biological communities within the region was also found. Thus, although it is suggested that mining operations will severely affect a small percentage of available seamount area (Hein et al., 2010), predicting the impacts of such activities will be complicated and precautionary spatial management of mining activities based on scientific information will be required.

2.6 *Dumping*

Although in the past dumping has been a significant issue in the deep sea (Thiel, 2003), it has not been a major issue for most of the habitats treated here, except trenches. Pharmaceutical dumping was permitted in the Puerto Rico Trench from 1973-78, with some 378,000 tons dumped. Impact was noted on the microbial community and invertebrates, and the dumping was halted in early 1980s (reviewed in Ramirez-Llodra et al., 2010). Dumping of radioactive waste in trenches was banned in the 1990s (see Chapter 24).

3. Social and economic considerations, including capacity-building needs.

To date, deep-water fisheries comprise the primary documented direct contribution of seamounts, ridges, canyons, and plateaus to human social and economic wellbeing. Estimating this contribution is challenging, and it is certain that other ecosystem

services are provided by these ecosystems that have not been specifically identified or in any way valued.

Deep-water fisheries exploiting resources associated with seamounts, ridges, and plateaus are a relatively minor component of global fisheries, comprising about 1 per cent of total annual landings (Koslow et al., 2000; Gianni, 2004; Clark et al., 2007; Watson et al., 2007; Bensch et al., 2009; Sumaila et al., 2010). High-seas bottom-trawl fisheries are carried out predominantly by a few developed countries of Asia, Oceania and Europe: Australia, Denmark (Faroe Islands), Estonia, France, Iceland, Japan, Latvia, Lithuania, New Zealand, Republic of Korea, Russian Federation, Spain and Ukraine (Gianni 2004; Sumaila et al., 2010). These fisheries account for about 2 per cent of the total landings and about 3 per cent of the landed value for these countries' fisheries. Total subsidies (fuel and non-fuel) for the high-seas bottom-trawl fisheries are estimated to be about 25 per cent of their value and substantially more than their net profit (Sumaila et al., 2010). Gianni (2004) estimated that high-seas bottom trawling occupied the equivalent of 100-200 vessels full time out of a total of 3.1 million fishing vessels worldwide.

Deep-water trawling affects the sedentary species on the continental shelf of countries, which can extend beyond 200 nautical miles. Many of these are developing countries which may need capacity-building in this regard (Gianni 2004). Fisheries associated with seamounts and other submarine topographic features are exceptionally difficult to manage sustainably. Capacity-building is desirable in the areas of stock assessment and sustainable management where such fisheries occur around developing States. This may require investment in international infrastructure (e.g. fisheries research vessels) that is often unavailable to developing States as well as investment at a national level (e.g. fisheries research laboratories and scientists, fisheries ministries). An example of the former is the Nansen Programme that has operated around the Africa Coast and in the Indian Ocean for several decades.

If mining of seamounts proceeds, multi-sectoral management will be needed, in particular the need to balance mining and fishery interests with those of conservation. Within areas under national jurisdiction, the agencies that manage mineral resources generally have no authority to manage the exploitation of living marine resources. The same is true of the International Seabed Authority with regard to the "Area".

4. Management and conservation of the habitat and its resources.

Several scientific reviews of deep-water fisheries over seamounts, ridges, and other abrupt topographies in deep waters have called attention to serious deficiencies in their management and conservation (Koslow et al., 2000; Koslow, 2007 (Chapter 10); Clark et al., 2007; Clark 2009; Rogers and Gianni 2010; Norse et al., 2012). Key contributing factors include the life-history characteristics of many exploited and bycatch species: extreme longevity, late maturity, slow growth, and infrequent recruitment events.

These characteristics lead to low productivity and high vulnerability to over-exploitation. Low productivity in itself promotes unsustainable harvest practices based on economic incentives to liquidate a relatively unprofitable resource (Clark, 1973). In addition, many of the stocks are small and aggregated predominantly over isolated features, such as seamounts, making the populations highly vulnerable to serial depletion. The fisheries are carried out predominantly with bottom trawls, which are severely destructive to the fishes' associated benthic habitats, which are often dominated by structure-forming taxa such as corals and sponges.

Deep-sea fisheries within the EEZs of coastal States are in a varied state including depleted, overfished and sustainably fished at the present time (e.g. ICES, 2014). Low-productivity deep-sea species have tended to fall into the former two categories. Management of deep-water fisheries on the high seas, where many of the stocks occur, is more complicated and difficult. To address this situation, the United Nations General Assembly adopted resolutions 61/105, 64/72 and 66/68 in 2006, 2009 and 2011, respectively, calling on RFMOs and States to manage high-seas deep-water fisheries sustainably through the application of the precautionary approach to fisheries management, and in 2008 the FAO Guidelines for the management of deep-sea fisheries on the high seas were adopted (FAO, 2009; Norse et al., 2012). These resolutions of the General Assembly recommended that impact assessments be carried out prior to the development of new fisheries and steps taken, such as setting aside reserves, or eliminating damaging forms of fishing from sensitive areas, to ensure the conservation of vulnerable habitat. This approach should be adopted prior to mining development as well.

Because of deep-water fishing impacts on sensitive benthic habitats, many States and RFMOs have set aside portions of such habitats as marine reserves or bottom-fishing closures in the Atlantic and North and South Pacific Oceans (e.g. NAFO, NEAFC and SEAFO; Clark and Dunn, 2012). In general, many of the areas that were protected or are planned to be protected through area-based management tools by States and by RFMOs are located in areas remote from where commercial activities occur or are expected to fail to protect those species, communities and habitats most threatened (Devillers et al., 2014). Given the difficulties of surveying deep-water habitats, predictive habitat models may prove useful to identify areas that might be designated for protective measures to meet conservation goals (Taranto et al., 2012; Yesson et al., 2012) as recently put forward in SPRFMO (SPRFMO, 2014).

However, Rogers and Gianni (2010) have provided examples of inadequate implementation of the FAO Guidelines. The need to review the efficacy of conservation measures has been underlined (e.g., the details of move-on rules: Auster et al., 2011). In 2013 and 2014 several RFMOs revised their relevant management measures. Reports on actions taken by States and RFMOs in response to United Nations General Assembly resolutions 64/72 and 66/68 are due to be reviewed by the General Assembly in 2016. We believe this is likely to be the case for many deep-water marine reserves, although this issue has not been specifically addressed for the deep sea.

5. Integrated assessment of the status of the habitat. Cross-cutting and emergent conclusions.

The development of deep-water fisheries, particularly those carried out across wide areas with bottom trawls over seamounts, ridges, canyons and plateaus at upper bathyal depths, have been one of the most transformative human impacts affecting such areas of the global ocean in the latter half of the twentieth century (Ramirez-Llodra et al., 2011). Impacts appear to have been greatest on shallow seamounts, because the depth, biological and physical conditions (e.g. accelerated current flows) support fish resources that can easily be targeted. However, a continuum of physical conditions and biological communities is found on these types of features. All of these communities have been subject to deep-water fisheries and their impacts.

The vast majority of deep-water fisheries have been carried out unsustainably, or at least without satisfactory assessments of impacts and sustainability. This has led to the serial depletion of dozens of stocks from about a dozen species commercially harvested from these habitats. Severe impacts have been reported for by-catch species, including other fishes and benthic invertebrates from the diverse coral and sponge communities found on these communities. The extent of benthic impacts has been described for local fishing grounds but has not been assessed globally; however, if the impacts of these regional studies are generalized, we can extrapolate that fishing, and in particular deep-water trawling, has caused severe, widespread, long-term destruction of these environments globally. The time scale for recovery of deep-water reef habitats is unknown but has been estimated to be on the order of centuries to millennia. Although progress has been made toward sustainable management and conservation of fish stocks and associated diverse, vulnerable benthic communities, numerous studies show that progress to date has not been adequate, with fisheries often closed or limited only after severe depletion has already occurred.

Extractive industries, such as mining and oil and gas development, are generally required to carry out baseline monitoring and assess their environmental impacts prior to development. The General Assembly has called upon States to strengthen the procedures for carrying out assessments on the impacts of bottom fishing activities on vulnerable marine ecosystems and to make the assessments publicly available; not all are currently available. Deep-water fishing has until recently been permitted to proceed in areas of highly diverse and vulnerable ecosystems without consideration of environmental impacts (despite the known, highly destructive impacts of these activities). There is an urgent need, even at this late date, for baseline monitoring of seamount habitats in regions of ongoing and potential fishing activity, and in areas set aside for protection. It is critical that relevant scientific expertise is engaged to develop representative networks of marine protected areas, which may then require the development of conservation measures, such as banning of destructive fishing methods. Reviews of existing conservation measures could address whether conservation and

management objectives are met. Devillers et al. (2014) consider that high-seas MPAs must address conservation needs and not be merely designated in areas remote from commercial interests.

The impacts of pollution and climate change, including deoxygenation and acidification, remain poorly understood but are potentially severe. There is an urgent need for research to examine how these factors may potentially influence deep-water benthic communities.

Mining of cobalt-rich ferromanganese crusts from these habitats has been mooted but remains uncertain. Mining would remove all benthic organisms where crust is removed and potentially affect a larger area through sediment mobilization. The environmental impact of mining operations would need to be considered carefully, considering the impacts on regional fisheries and benthic communities, and consideration given to setting aside areas for conservation.

6. Gaps in scientific knowledge.

Since 2000, scientific interest in the ecology of seamounts, ridges, and other sensitive submarine benthic habitats has burgeoned. The development of deep-water fisheries and the need to understand and manage these fisheries and their environmental impacts stimulated this interest, with support from international programmes like the Census of Marine Life. However, these habitats are vast, as well as difficult and expensive to study and the research to date has been largely exploratory. Even after more than a decade of scientific activity, it is apparent that these habitats still remain relatively poorly known. Only a few hundred of the $10^5 - 10^7$ seamounts have been sampled, and the rate of discovery of new species still has not levelled off.

Predictive habitat models have recently been developed to indicate where such habitats are likely to occur, but no one has attempted to assess their present status or the global impact of deep-water trawling, and it is doubtful that the data exist to do so. These models remain largely untested; it is urgently necessary to ground-truth them. Furthermore, knowledge of deep pelagic ecosystems is especially poor (Webb et al., 2010) and the ecological interactions between the geological features considered here and the overlying water column comprise a substantial gap.

Deep-sea ecosystems associated with seamounts, ridges, and other topographic features are now and will increasingly be subjected to multiple stressors from habitat disturbance, pollutants, climate change, acidification and deoxygenation. Studies to date on these impacts have been limited and considered in isolation. The scientific understanding of how these stressors may interact to affect marine ecosystems remains particularly poorly developed. For example, the widespread destruction of deep-water benthic communities due to trawling has presumably reduced their ecological and evolutionary resilience as a result of reduced reproductive potential and loss of genetic

diversity and ecological connectivity. The synergistic influence of these factors is unknown at present.

Although it is heartening that some seamounts, ridges and other sensitive marine habitats are being protected by fishing closures, Marine Protected Areas and other actions, little scientific understanding of the efficacy of actions implemented to date and few studies to assess this exist. The connectivity between these habitats remains largely unknown, as are the factors that influence colonization, species succession, resilience and variability. Comparative studies of seamount, canyon, and continental margin habitats seem to indicate that many species are shared (but see Richer de Forges et al., 2000); however, community structure differs markedly and the factors influencing such differences remain unknown (McClain et al., 2009). Our starting point in attempting to understand and manage these habitats is, to paraphrase Socrates, that we know almost nothing.

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