An Ecosystem Approach to Management of Seamounts in the Southern Indian Ocean

Volume 1 – Overview of Seamount Ecosystems and Biodiversity

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This paper is to be read in conjunction with two others: one on threats to seamount ecosystems (Volume 2) and one on a legal and instituional gap analysis (Volume 3).

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Cover photos: Front: Unidentified octopus, South West Indian Ocean, R/V Fridtjof Nansen Cruise, Nov-Dec 2009. Back: Chaunacidae – Sea toads, South West Indian Ocean, R/V Fridtjof Nansen Cruise, Nov-Dec 2009.

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I. GENERAL: ABOUT SEAMOUNT ECOSYSTEMS

Seamounts are topographic rises of the seabed with a limited extent across the summit. Originally this definition held that seamounts had an elevation of ≥1,000 m and that they were intraplate features, reflecting a contrasting geological origin to those associated with mid-ocean ridges and other settings (Staudigel *et al.,* 2010). However, smaller submarine knolls (elevation 500-1,000 m) and hills (elevation >500 m) share many of the environmental characteristics of larger features, and given that the size distribution of such elevations are continuous, the term seamount is used interchangeably for most features >100 m in elevation (Wessel, 2007; Staudigel *et al.,* 2010). Large seamounts usually originate as volcanoes, although some, such as Atlantis Bank in the South West Indian Ocean, are formed by tectonic uplift, or even from serpentinite mud (e.g., Fryer *et al.,* 1992). Most large seamounts are associated with intraplate hotspots, mid-ocean ridges or island arcs. There may be up to 100,000-200,000 large seamounts in the oceans, with perhaps >25 million (with a range of error of 8-80 million) with an elevation ≥100 m (Wessel, 2007; Wessel *et al.,* 2010). Most seamounts are located in the Pacific Ocean, with lower numbers in the Indian, Atlantic, Arctic and Southern Oceans (Wessel, 2007). Overall this adds up to a globally significant area of habitat with an estimate of nearly 10 million km^2, comparable with tropical humid forest, temperate broad-leafed forest or all the world's wetlands (Etnoyer *et al.,* 2010).

There is evidence that seamounts form hotspots of biological activity in the oceans. Over large geographic scales ocean predators appear to be associated with seamounts and other features. Tuna, billfish, sharks, cetaceans, pinnipeds, turtles and seabirds may all be associated with seamounts, and high biomass and abundance of such predators have been observed in the vicinity of seamounts (Holland and Grubs, 2007; Kaschner, 2007; Litvinov, 2007; Santos *et al.,* 2007; Thompson, 2007). This is thought to be because of enhanced levels of prey or feeding opportunities for these species. Seamounts may also act as 'navigational waypoints' for oceanic species that undergo large-scale annual or ontogenetic migrations (e.g., Holland and Grubs, 2007) and for some species of catadromous and demersal fish are important as spawning sites (e.g., Pankhurst *et al.,* 1987; Boehlert and Sasaki, 1988; Pankhurst, 1988; Tsukamoto *et al.,* 2003; Tsukamoto, 2006).

To date (July 2010), 798 species of fish have been listed as occurring at seamounts (Morato *et al.,* 2004). Deep-sea fisheries target a relatively small fraction of these that aggregate around seamounts. Most of these species have been identified as forming a specific guild of robust-bodied demersal fish species, generally characterized by a strong swimming ability, high food consumption and energy expenditure, and low rates of growth and productivity (e.g., Koslow *et al.,* 2000). These species include orange roughy *(Hoplostethus atlanticus),* pelagic armourhead (*Pseudopentaceros wheeleri; Pseudopentaceros richardsoni*), rockfish (*Sebastes* spp., *Helicolenus* spp.), oreos (Oreosomatidae), cardinal fish (*Epigonus* spp.) roundnose grenadier (*Coryphaenoides rupestris*), Patagonian toothfish (*Dissostichus eleginoides*) and alfonsinos (*Beryx splendens, Beryx decadactylus*). These fish are specifically associated with seamounts, although they also occur on continental slopes and the slopes of oceanic islands.

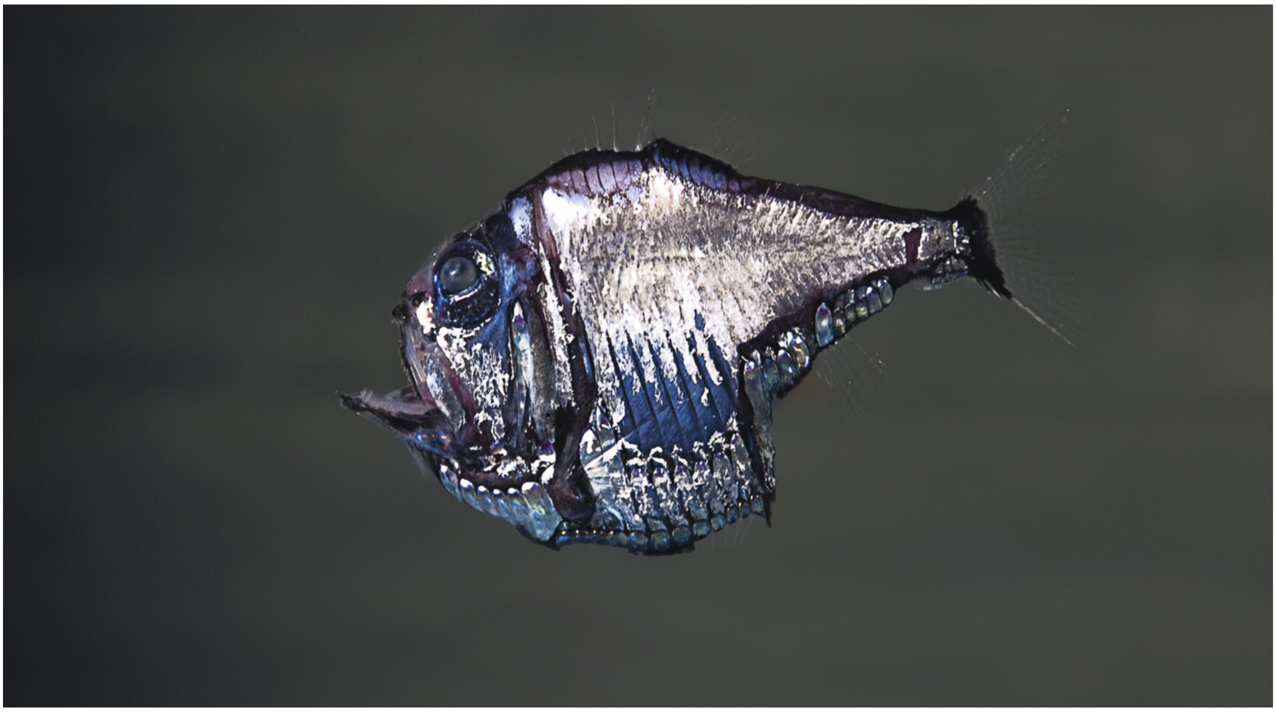
Why seamounts host abundant populations of fish and other pelagic and aquatic predators is still uncertain. Early observations suggested that chlorophyll concentrations may be higher above seamounts than in non-seamount locations (Bezrukov and Natarov, 1976; Lophukin, 1986; Boehlert and Genin, 1987; Dower *et al.,* 1992; Mouriño *et al.,* 2001). This gave some support to a hypothesis of enhanced primary productivity above seamounts, resulting from nutrient enrichment of the euphotic zone by localized upwelling induced by current-topography interactions, especially the formation of Taylor columns. Seamounts may also be associated with turbulent mixing caused by internal or baroclinic waves that can also induce upwelling of nutrients (Kunze and Sanford, 1997; Toole *et al.,* 1997). However, it has been argued more recently that evidence for enhancement of primary production, beyond sporadic and temporary blooms of phytoplankton, are lacking (Genin and Dower, 2007; Clark *et al.,* 2010). Although such phenomena may enhance patchiness of phytoplankton downstream of seamounts, they are unlikely to significantly enhance the productivity of the seamounts themselves.

It is now recognized that several other physical processes associated with seamounts may enhance productivity or food supply in their vicinity. These include tidal rectification (generation of mean residual currents by tidal flow), flow acceleration and the formation of internal waves, and can enhance vertical mixing around a seamount, causing upwelling of nutrient-rich deep water and enhancement of primary production (White *et al.,* 2007; Lavelle and Mohn, 2010). The water above a seamount may become stabilized by high-density stratification, promoting productivity (Comeau *et al.,* 1995). Seamounts may also interact with eddies shed from frontal zones, or Meddies, lenses of warm salty water released from the Mediterranean into the colder waters of the Atlantic which can interact with seamounts. Eddies have been observed to interact to different degrees with seamounts, sometimes moving around them, sometimes becoming trapped over them or being split by them. During such interactions eddies can be dissipated to different degrees and also significantly alter the physical structure of the waters above the summit and flanks of a seamount (Bashmachnikov *et al.,* 2009; Lavelle and Mohn, 2010). At the largest scales, chains of seamounts can significantly alter or steer large ocean currents (Lavelle and Mohn, 2010).

Another source of enhanced production at seamounts is the advection of phytoplankton, zooplankton, larger organisms, particulate organic material and nutrients from the far-field into the sphere of influence of a seamount (Genin and Dower, 2007; White *et al.,* 2007). In such cases, enclosed or semi-enclosed circulation patterns over seamounts may retain material advected into the vicinity of a seamount or produced over it (White *et al.,* 2007). Asymetric flow acceleration over a seamount flank or summit may also enhance horizontal fluxes of organic material (White *et al.,* 2007).

Several studies indicate that seamounts may also trap the diurnally migrating layers of plankton and micronekton (Rogers, 1994; Genin and Dower, 2007; Porteiro and Sutton, 2007). These layers, known as the deep-scattering layer (DSL) because it is seen as a layer of acoustic reflectivity in echosounders, undergo migrations towards the surface at dusk and then back down into deeper waters at dawn. During the night the DSL may be advected over a seamount and at dawn, when the organisms descend, their passage is obstructed by the raised topography and they are preyed on by fish and other planktivores living on the seamount (Genin and Dower, 2007). The DSL may be enhanced by organisms that are associated with the seabed on the seamount but which undertake migrations into the water column to feed at night (Boehlert and Seki, 1984; Vereshaka, 1995). Evidence that the DSL is an important food source for seamount-resident or visiting species of predators has been observed through analyses of stomach contents for demersal and pelagic species (Genin *et al.,* 1988; Seki and Somerton, 1994; Fock *et al.,* 2002; Holland and Grubbs, 2007). Acoustic surveys have also shown seamount associated fish ‘intercepting’ the DSL as it moves downwards at dawn (Isaacs and Schwartzlose, 1965; reviewed in Genin and Dower, 2007; Porteiro and Sutton, 2007).

Seamounts differ in their size, shape, elevation, summit depth, and oceanographic and climatic setting, the latter varying with latitude (Rowden *et al.,* 2005). They are often exposed to strong water flow because of the interactions of impinging currents and tides with elevated topography, and as a result of this and the steep and irregular profiles they may present, hard substrata are more common than on continental slopes and abyssal plains (Rogers, 1994). However, sediment-covered environments also occur on seamounts, especially on the flat summits of guyots and banks (Clark *et al.,* 2010). As a result of strong current flow, the predominant benthic communities on seamounts are suspension feeding (Samedi *et al.,* 2007). On hard substrata, frequently observed epilithic organisms include corals (Scleractinia, Octocorallia, Antipatharia, Zoantharia, Stylasterida), actiniarians, hydroids, sponges, ascidians and crinoids (Genin *et al.,* 1986; Boehlert and Genin, 1987; Rogers *et al.,* 1994; Samedi *et al.,* 2007; McClain *et al.,* 2009).



Hatchetfish (*Argyropelecus acuelatus*). © IUCN/Sarah Gotheil

These organisms may structure the ecosystems by forming reefs (Scleractinia) or dense gardens (Scleractinia; Octocorallia; Antipatharia; Stylasterida) associated with other species of sessile and mobile organisms such as molluscs, crustaceans and echinoderms (Samedi *et al.,* 2007; Althaus *et al.,* 2009). In some cases these biogenic habitats, such as cold-water coral reefs, can be extensive and are occupied by a distinctive and diverse fauna (De Forges *et al.,* 2000; Koslow *et al.,* 2001; O'Hara *et al.,* 2008; Althaus *et al.,* 2009). Observations indicate that soft substrata may be inhabited by both epibenthic megafauna, such as sea pens (Pennatulacea), hexactinellid sponges and xenophyophores (Rogers, 1994). Presence of epibenthic megafauna on soft substrata can also influence the diversity of other species. A variety of animals have been found living in or on the tests of xenophyophores and they can also enhance the diversity and abundance of species living in the sediment beneath (Gooday, 1984; Levin *et al.,* 1986; Levin and Thomas, 1988).

For both hard and soft substrata, exposure to current is important in determination of the local distribution of fauna. Epilithic species favour locations with a higher exposure to current at a variety of spatial scales. Thus the abundance of suspension feeders on hard substrata may be higher on seamount peaks and along the rims of summits, on terraces or basalt dykes, whilst at smaller spatial scales, abundance is higher on pinnacles and knobs of rock or on vertical rock walls (Tunnicliffe *et al.,* 1985; Genin *et al.,* 1986; Moskalev and Galkin, 1986; Grigg *et al.,* 1987). Areas with a greater exposure to current probably also receive greater supplies of suspended food particles and perhaps larvae, whilst substrata are less likely to become inundated with sediment (Rogers, 1994). For soft substrata, current directly influences the grain-size of sediments, and infaunal densities have been observed to be inversely proportional to coarseness of sediment (Levin and Thomas, 1989).

Depth is also a major determinant of community composition on seamounts. Shallow seamounts, where the summit lies within the euphotic zone, may host communities of macroalgae including kelps and coralline encrusting algae (e.g., Bowie Seamount, NE Pacific, McDaniel *et al.,* 2003; Vema Seamount, SE Atlantic, Simpson and Heydorn, 1965; Walter's Shoal, western Indian

Ocean, Colette and Parin, 1991) or, in the tropics, reef-forming corals. Analyses of the composition of communities beneath the euphotic zone show that the taxa present and community composition vary significantly with depth (Rogers *et al.,* 2007; Samedi *et al.,* 2007). This is a result of changes in environmental parameters such as temperature, pressure, oxygen concentration and food supply with increasing depth (Clark *et al.,* 2010).

Seamount communities tend to reflect the local species pool (Hall-Spencer *et al.,* 2007; Samedi *et al.,* 2007; Thoma *et al.,* 2009) and can display normal patterns of latitudinal species turnover from the tropics to sub-polar regions as other marine ecosystems (O'Hara, 2007). Although there have been claims of high levels of endemism in seamount fauna from some regions of the world (Parin *et al.,* 1997; De Forges *et al.,* 2000; Stocks and Hart, 2007) these are difficult to evaluate because of the lack of sampling of non-seamount deep-sea habitats within regions. Contradictory evidence to high levels of endemism include studies that have identified that seamounts represent a 'sub-sample' of regional fauna (see above), and evidence of widespread haplotypes in organisms such as corals and fish (e.g., Martin *et al.,* 1992; Sedberry *et al.,* 1996; Horau and Borsa, 2000; Smith *et al.,* 2004) have been cited as supporting long-distance dispersal of species that live on or around seamounts (McClain *et al.,* 2009). However, genetic studies have only been undertaken on a limited subset of seamounts and taxa; interpretation of genetic data can be complicated by historical influences on populations; and there are studies that provide evidence of genetic differentiation between populations located between seamounts, and between seamounts and islands or the continental margin (reviewed in Clark *et al.,* 2010). Sampling of seamounts at larger geographic scales is extremely uneven (e.g., Rogers *et al.,* 2007; Stocks and Hart, 2007), making attempts to estimate the geographic range of seamount-associated species difficult to ascertain. Regardless of levels of endemism, it is clear that seamount communities are different in composition to those of nearby slopes of continents and oceanic islands (Samedi *et al.,* 2006; Hall-Spencer *et al.,* 2007; McClain *et al.,* 2009). Taxa that are rarely observed or which occur as scattered individuals may be abundant on seamounts, raising the possibility that seamounts may act as source populations for some taxa within regions (McClain *et al.,* 2009). Such findings not only complicate the relationship between sampling effort on seamount and non-seamount localities and estimates of levels of seamount endemism, but also make interpretation of the conservation value of seamounts markedly different to one based solely on the presence of endemic species (McClain *et al.,* 2009).

Left, a scorpionfish (Scorpaenidae sp.) and, right, splendid alfonsino (*Beryx splendens*).
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II. SPECIFIC: THE SOUTHERN INDIAN OCEAN AND ITS SEAMOUNTS

The Indian Ocean is the world's third largest ocean, stretching 9,600 km from the Bay of Bengal to Antarctica and 7,600 km from Africa to Australia (Demopoulos *et al.,* 2003). It is a globally important region for marine capture fisheries, representing more than 10% of global catches according to the latest FAO figures (as of July 2010, FAO, 2009). Within this region, the western Indian Ocean is notable for recent increases in fish catches (FAO, 2009). However, it is also the region of the world where the highest proportions of exploited fish stocks are of unknown or uncertain status (Kimani *et al.,* 2009), reflecting problems of fisheries management and ocean governance in the region. Artisanal fisheries in the Indian Ocean are critical for the livelihoods and food security of the populations of coastal States in the region, particularly island nations such as the Seychelles. The offshore fisheries of the western Indian Ocean are rich but countries within the region have been unable to develop the infrastructure to exploit these fisheries. As a result they have allowed the distant-water fishing fleets of developed countries to access fish resources through multilateral or bilateral agreements (Kimani *et al.,* 2009). This situation is promoted by the subsidies received by foreign distant-water fleets which give them a competitive advantage over local fishing fleets (Kimani *et al.,* 2009).

Unlike other oceans of the world, the Indian Ocean was explored relatively little during the 'heroic age' of deep-sea exploration. It was only during the Indian Ocean Expedition of 1962-1965 that deep-sea areas were extensively sampled. Since that time deep-sea research in the Indian Ocean has largely focused on the Arabian Sea, and in general the deep-sea ecosystems of the rest of the region remain poorly explored (Banse, 1994; Ingole and Koslow, 2005). Although the geology of seamounts in the Indian Ocean has been explored extensively, the seamount fauna inhabiting the region is poorly known (Rogers *et al.,* 2007). There is an urgent requirement to explore these ecosystems to complete the picture of the biodiversity and productivity associated with the Indian Ocean (Demopoulos *et al.,* 2003). Until now the main source of information on the biology of these seamounts have been scientific/fisheries reports of past Soviet expeditions related to exploratory fishing which are focused on fish populating the ridges of the Indian Ocean (Romanov, 2003). Here, current knowledge on seamounts in the Indian Ocean is summarized with respect to geology and particular ecology.

The Indian Ocean hosts fewer seamounts than the Atlantic and Pacific Oceans (Kitchingham *et al.,* 2007). Many seamounts are associated with ridges or originate at ridges (spreading centres) even though they are located within the ocean basins of the Indian Ocean (e.g., Central Indian Ocean Basin; Mukhodpadhyay *et al.,* 2002; Das *et al.,* 2007). Several ridges form significant ranges of seamounts, including the Carlsberg Ridge, Madagascar Ridge, Central Indian Ridge, South West Indian Ocean Ridge, Chagos-Laccadives Ridge, the 85° East Ridge (Afanasy-Nikitin Seamount; Krishna, 2003), the Ninety-East Ridge, the South East Indian Ridge, the Broken Ridge and the East Indiaman Ridge. Several of these ridges are aseismic and may be associated with hot-spots (e.g., Chagos-Laccadive Ridge and the Réunion Hotspot; Ashalatha *et al.,* 1991; Henstock & Thompson, 2004) and several of them are extremely long. Uplifted areas of the seafloor are a special feature of the Indian Ocean and include areas such as the Aghulas Plateau and the Mascarene Plateau (Gershanovich and Dubinets, 1991). Most seamounts in the Indian Ocean are deep (>3,000m) and most are located north of 55°S and west of 80°E (Gershanovich and Dubinets, 1991).

Whilst little is known about the biology associated with seamounts in the Indian Ocean, studies have indicated that they exert an important influence on water circulation in the region. For example, the water circulation of the upper layers of the Southern Indian Ocean is dominated by a Sub-Tropical Anticyclonic Gyre which is mainly located in the western half of the ocean (Demopolous *et al.,* 2003; Sultan *et al.,* 2007). The eastern extension of the gyre is mainly blocked by the South-East Indian Ocean Ridge, although some water penetrates further east to be blocked by the Ninety-East Ridge. Topographic constraints exerted by the Madagascar and South West Indian Ocean Ridges force the separation of three small anticyclonic cells within the Sub-Tropical Anticyclonic Gyre: two to the east of the

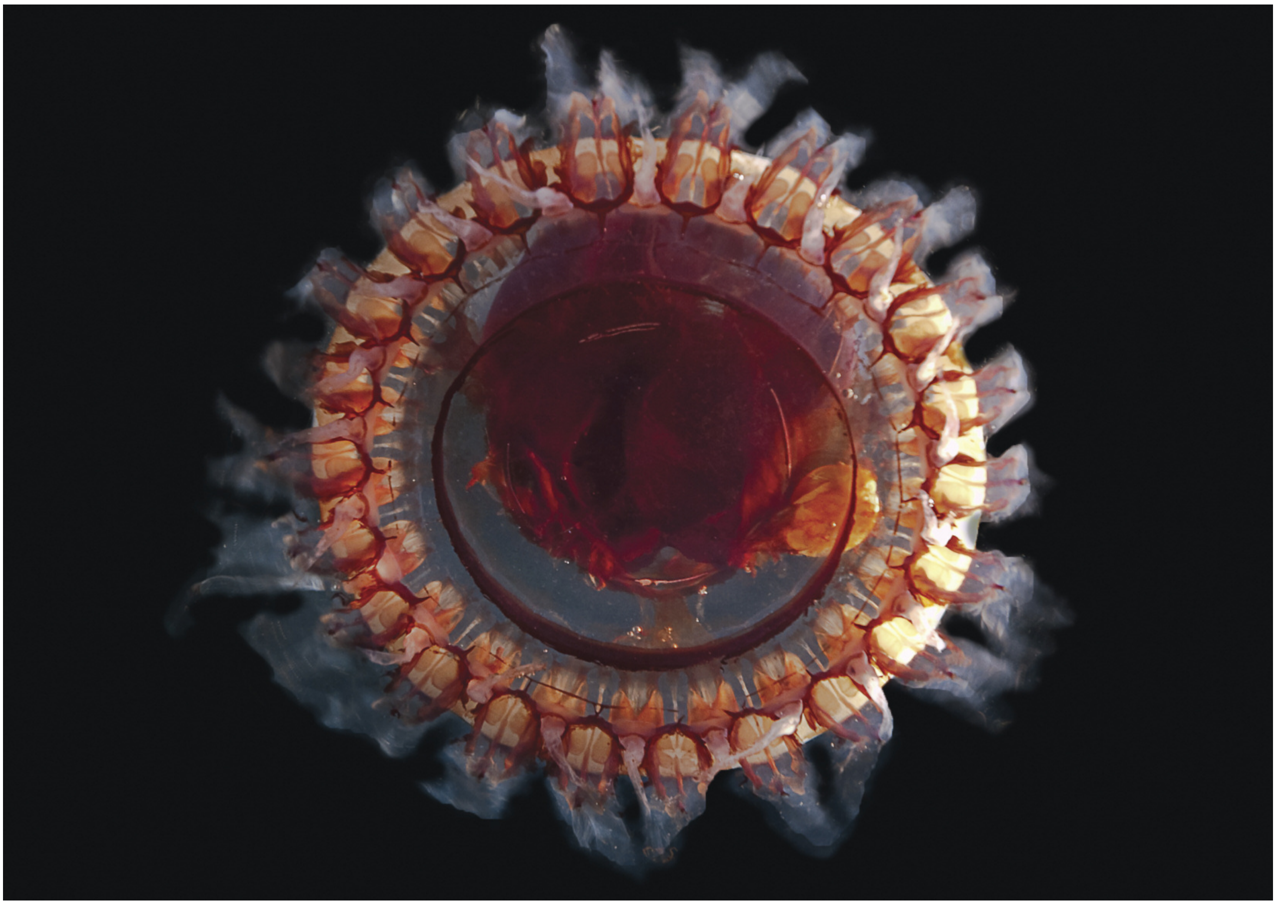
Madagascar Ridge and one between the Madagascar Ridge and South Africa (Sultan *et al.,* 2007). This also holds true for deeper circulation as well. For example, between 2,000 and 3,500 m depth, modified North Atlantic Deep Water (NADW) flows into the southwestern Indian Ocean (McDonagh *et al.,* 2008) along the African continental slope, up through the Mozambique Channel and also around the southern South West Indian Ocean Ridge and Del Cano Rise (Van Aken *et al.,* 2004). In the northwestern part of the region the NADW flows up along the eastern slope of the Madagascar Ridge and then on over the Madagascar Ridge at about 35°S. Deeper still, the flow of Antarctic Bottom Water into the Indian Ocean is controlled by the South West Indian Ocean Ridge. The main flow, from the Enderby Basin into the Aghulas Basin, is over a saddle in the ridge between 20°E and 30°E, probably via deep channels (>4,000m depth) in the ridge (Boswell and Smythe-Wright, 2002). This water continues to flow northwards through the gap between the Aghulas Plateau and South West Indian Ocean Ridge and then onto the Mozambique Channel. Another branch crosses the ridge at 35-36°S through the Prince Edward Fracture Zone, whilst a third branch passes along the southern flank of the Del Cano Rise (Boswell and Smythe-Wright, 2002). At smaller scales, ridges within the Indian Ocean are associated with internal wave formation, and possibly the formation of eddies and localized upwelling (e.g., Konyaev *et al.,* 1995; Morozov and Vlasenko, 1996; Romanov, 2003). However, studies on mesoscale to microscale oceanography associated with seamounts in the Indian Ocean remain few.

A. Biology of seamounts in the Indian Ocean

Data on the diversity of biological communities of the Southern Indian Ocean are sparse. More studies have been undertaken on Walter's Shoal than other seamounts, probably because the region is closer to land than other areas and because of interests in commercial fisheries in the region. The shoal was sampled during the Indian Ocean expedition in 1964 by the *R/V Anton Bruun* and subsequently by the *Vityaz*. These collections included a new endemic sub-species of crinoid, *Comanthus wahlbergi tenuibrachia* (Clark, 1972), prevalent in the shallow waters of the shoal (Collette and Parin, 1991), and several crustaceans including an endemic species of alpheid shrimp (*Alpheus waltervadi*; Kensley, 1981) and an endemic isopod (*Jaeropsis waltervadi;* Kensley, 1975). Recently, an endemic species of rock lobster, *Palinurus barbarae*, has been described from the shoals following the landing of the species from commercial fishing vessels (Groeneveld *et al.,* 2006). Collette and Parin (1991) described the fish fauna from ~400 m depth to the surface on the shoal (summit depth approx. 15 m) and identified 20 species of which several were potentially endemic, undescribed species; several were widespread temperate or sub-tropical species and several were Indo-Pacific reef-associated species. Biogeographic affinities of elements of the shallow fish fauna with Gough Island, Tristan da Cunha and St Pauls and Amsterdam Islands (West Wind Drift Islands) were identified, particularly in the occurrence of species such as *Helicolenus mouchezi, Trachurus longimannus* and *Serranus novemcinctus* (Collette and Parin, 1991). Others (*Acantholatris monodactylus, Lepidoperca coatsii, Nelabrichthys ornatus*) are found in Australia and New Zealand. *Helicolenus mouchezi* and possibly several other species from Walter's Shoal also occur on the South West Indian Ocean Ridge. The implication here is that the Sub-Tropical Anticyclonic Gyre and Antarctic Circumpolar Current and/or other westerly flowing currents have assisted in transoceanic dispersal of these species, with islands and seamounts acting as stepping stones. Russian exploration of the Madagascar Ridge in the search of fisheries resources identified: dories (Oreosomatidae), sharks, *Alepocephalus* sp., *Beryx* sp., Macrouridae, Moridae, *Plagiogeneion rubiginosum, Polyprion americanus, Polyprion oxygeneios, Pseudopentaceros richardsoni,* scabbard fish, Scorpaenidae, *Trachurus longimannus*, tuna, Uranoscopidae.

Vereshchaka (1995) summarized several investigations on the macroplankton occurring on slopes and seamounts in the Indian Ocean. The paper lists a large number of taxa as occurring on Walter's Shoal including: Mysidacea – *Gnathophausia ingens, G. gracilis, Siriella thompsoni, Euchaetomera typica, E.*

glythidophthalmica, Metamblyops macrops; Euphausiacea – *Thysanopoda monacantha, T. tricuspidata, T. aequalis, T. obtusifrons, T. pectinata, T. orientalis, T. egregia, Nematobrachion flexipes, N. boopis, Euphausia recurva, E. diomedeae, E. mutica, E.similis, E. spinifera, E. hemigibba, E. paragibba, E. pseudogibba, Thysanoessa gregaria, Nematoscelis megalops, N. microps, N. atlantica, N. gracilis, N. tenella, Stylocheiron carinatum, S. affine, S. suhmi, S. longicorne, S. elongatum, S. abbreviatum, S. maximum;* Decapoda – *Funchalia villosa, Gennadas parvus, G. propinquus, G. scutatus, G. bouvieri, G. incertas, G. tinnayrei, G. gilchristi, Sergestes corniculum, S. disjunctus, S. atlanticus, S. sargassi, S. pectinatus, S. armatus, S. orientalis, Sergia prehensilis, Sergia scintillans, Sergia splendens, Sergia grandis, Sergia laminata, Lucifer typus, Pasiphaea natalensis, Acanthephyra quadrispinosa, Notostomus elegans, Oplophorus spinosus, O. Novaezelandiaea, Systellaspis debilis, S. guillei, Stylopandalus richardi;* Larvae – *Penaeus* sp., *Solenocera* sp., *Gennadas* sp., *Sergestes* sp., *Acanthephyra* sp., Palaemoninae, Pontoniinae, Pandalidae, Nematocarcinidae, *Lysmata* sp., *Alpheus* sp., *Pontophilus* sp., *Stenopus* sp., *Panulirus* sp., *Jasus* sp., *Scyllarides* sp., Paguridae, *Galathea* sp., *Callianassa* sp., *Homola* sp., Dromiidae, *Albunea* sp., Cancridae, Majidae, Calappidae, Brachyura, *Amphionides reynaudi.* These animals fall into two distinct groups: species that were associated mainly with the water column and decrease in numbers towards the seabed; and those that are associated with the seabed. The latter group falls into several categories, including: animals that are found near the seabed at night but disappear by day, presumably because they migrate to benthic habitats during daylight hours; animals found well above the seabed by day and which descend to the seabed by day; and larval animals which are found mainly over areas of seabed inhabited by adults (Vereshchaka, 1995).



Atolla jellyfish (*Atolla wyvillei*). © IUCN/Sarah Gotheil

Investigations of high-seas areas of the Indian Ocean for fish resources were undertaken by Soviet research vessels and exploratory fishing vessels from the 1960s to 1998. Whilst detailed information is not available data on the fish species present on the South West Indian Ocean Ridge have been published. The following species were identified as being present: *Alepocephalus* spp., *Antimora rostrata, Beryx splendens, Beryx decadactylus, Centrolophus niger,* Chauliodontidae, *Dissostichus eleginoides, Electrona carlsbergi, Epigonus* spp., Gonostomatidae, *Helicolenus mouchezi, Hyperoglyphe antarctica, Lepidopus caudatus, Macrourus carinatus,* Myctophidae, *Nemadactylus macropterus, Neocyttus rhomboidalis, Notothenia squamifrons, Plageogeneion rubiginosum, Polyprion americanus, Polyprion oxygeneios, Promethichthys prometheus, Pseudopentaceros richardsoni,* rays, *Ruvettus pretiosus, Schedophilus huttoni, Schedophilus maculatus, Schedophilus velaini,* sharks, *Trachurus longimannus* (Romanov, 2003). A more extensive species list is given in Romanov (2003) but this list is for all the seamounts sampled in the Indian Ocean from 1969-1998. It was noted that seamounts on the South West Indian Ocean Ridge showed a marked variation in the fish present. For example, pelagic armourhead, *Pseudopentaceros richardsoni,* was only caught in commercial quantities on Seamount 690 (Romanov, 2003), which corresponds in position to Atlantis Seamount. The species has also been found on Sapmer Seamount (López-Abellán *et al.,* 2008). Some of the species listed are exclusively Antarctic/Sub-Antarctic and so probably occur further south than the seamounts sampled on the present expedition.

As with invertebrates and fish, knowledge of the distribution of aquatic predators, including cetaceans and birds in the region, is sparse. There have been sightings of concentrations of humpback whales in the vicinity of Walter's Shoal (e.g., Collette and Parin, 1991; Shotton, 2006), suggesting that it may be an important migratory area between high-latitude feeding grounds and low-latitude breeding grounds off Madagascar. There are reports of pilot whales, humpback whales and sperm whales in the areas of deep-water fishing in the Southern Indian Ocean, although it is not clear where these were (Shotton, 2006).

Shotton (2006) reports that sightings of birds are rare in the areas of fishing and these were rarely seen north of 35°S. White-chinned petrels (*Procellaria aequinoctialis*) had been reported as occurring in areas of deep-water fishing, and cape pigeons (*Daption capense*) and sooty shearwaters (*Puffinus griseus*) were reported as being observed from fishing vessels (Shotton, 2006). Bird observations taken from a cruise between La Réunion, Crozet, Kerguelen, St. Paul, Amsterdam Islands, and Perth, Western Australia identified 51 species of birds from over 15,000 sightings (Hyrenbach *et al.,* 2007). During this cruise the density of birds increased significantly across the sub-tropical convergence, from 2.4 birds/km^2 in sub-tropical waters to 23.8 birds/km^2 in sub-Antarctic waters. The taxonomic composition of birds also differed markedly in the three areas, with prions (*Pachyptila* spp.) accounting for 57% of all sub-Antarctic birds, wedge-tailed shearwater (*Puffinus pacificus*) accounting for 46% of all sub-tropical birds, and Indian Ocean yellow-nosed albatross (*Thallasarche carteri*) accounting for 32% of all birds in the sub-tropical convergence zone (Hyrenbach *et al.,* 2007). Given that this cruise transited part of the South West Indian Ocean Ridge, it would seem likely that significant numbers of seabirds are present in the vicinity of the seamounts, particularly in the more southerly areas.

Hydrothermal vents have been located on ridges in the Indian Ocean. The first were observed on the Central Indian Ocean Ridge in 2000 (Hashimoto *et al.,* 2001; Van Dover *et al.,* 2001). This site comprised a fauna with affinities to western Pacific hydrothermal vent fields but with the addition of shrimps, *Rimicaris karei*, closely related to the visually dominant species, *Rimicaris exoculata,* at some Atlantic hydrothermal vents (Watabe and Hashimoto, 2002; Komai *et al.,* 2007; Komai and Segonzac, 2008). Vent plumes were first identified along the South West Indian Ocean Ridge in 1997 (German *et al.,* 1998) but the first vent has only just been discovered using an autonomous underwater vehicle (Tao *et al.,* 2007). The site has not been sampled but comprises black smokers, sulphide edifices and a fauna comprising stalked barnacles, anemones and gastropods. Hydrothermal vents are of current interest for mineral extraction and it is likely that possibilities for mining these sites will be explored in the future (see below).

B. Deep-sea fisheries on seamounts in the Indian Ocean

The development of deep-sea fisheries in the high-seas regions of the Indian Ocean was undertaken by distant-water fleets of developed countries, particularly the USSR, whose distant-water fishing fleet in the early 1970s was the largest in the world (Romanov, 2003). Exploratory fishing on the South West Indian Ocean Ridge, the Mozambique Ridge and the Madagascar Ridge began in the 1970s by the Soviet fleet, and associated research institutions, with commercial trawling beginning in the early 1980s (Romanov, 2003; Clark *et al.,* 2007). These fisheries targeted redbait (*Emmelichthys nitidus*) and rubyfish (*Plagiogeneion rubiginosus*) with catches peaking in about 1980 and then decreasing in the mid-1980s (Clark *et al.,* 2007). Fishing then switched to alfonsino (*Beryx splendens*) in the 1990s as new seamounts were exploited. Some exploratory trawling was also carried out on the Madagascar Ridge and South West Indian Ocean Ridge by French vessels in the 1970s and 1980s, targeting in particular Walter's Shoals and Sapmer Bank (Collette and Parin, 1991).

In the late 1990s, a new fishery developed on the South West Indian Ocean Ridge, with trawlers targeting deep-water species such as orange roughy (Hoplostethus atlanticus), black cardinal fish (*Epigonus telescopus*), southern boarfish (*Pseudopentaceros richardsoni*), oreo (Oreosomatidae) and alfonsino (Clark *et al.,* 2007). This fishery rapidly expanded, with estimated catches of orange roughy being in the region of 10,000 tonnes, but the fishery rapidly collapsed. Fishing then shifted to the Madagascar Plateau, Mozambique Ridge and Mid-Indian Ocean Ridge, targeting alfonsino and rubyfish (Clark *et al.,* 2007).

Fishing continues along the South West Indian Ocean Ridge, mainly targeting orange roughy and alfonsino. Recent fishing has also taken place on the Broken Ridge (eastern Indian Ocean), 90 East Ridge, possibly the Central Indian Ridge, the Mozambique Ridge and Plateau and Walter's Shoal (western Indian Ocean), where a deep-water fishery for lobster (*Palinurus barbarae*) has developed (Bensch *et al.,* 2008). The banks around Mauritius within the Exclusive Economic Zone (EEZ) and high-seas portions of the Saya da Malha Bank have been targeted by fisheries for *Lutjanus* spp. and lethrinid fish (SWIOFC, 2009). There are also reports of unregulated fishing using gill-nets (which target sharks) in areas of the Southern Indian Ocean such as Walter's Shoal (Shotton, 2006). The Southern Indian Ocean Fishers' Association (SIODFA) report that their vessels undertake approximately 2,000 deep-water trawl tows per year in the entire Indian Ocean. By-catch of fish from SIODFA fishing operations in the region are reported to be small, especially when fishing below 500 m depth (Shotton, 2006). As with New Zealand vessels operating in the southern Pacific Ocean, tow times have been reported to be typically short in the region, with a duration of 10-15 minutes (Shotton, 2006), reflecting the highly targeted nature of roughy and alfonsino fisheries on seamounts.

Currently (as of July 2010), there is little or no information available for the assessment of the impacts of deep-sea fishing in high-seas areas of the Indian Ocean on populations of target or by-catch species. Reporting of data is complicated by issues of commercial confidentiality in fisheries where individual stocks may be located across a wide area (e.g., the South West Indian Ocean Ridge). At present, new fisheries are developing in the region with no apparent assessment of resource size or appropriate exploitation levels to ensure sustainability of fisheries.

C. Management of deep-water fisheries on the high seas of the Indian Ocean

At present there are two main agreements that exist for the Southern Indian Ocean, the Southwest Indian Ocean Fisheries Commission (SWIOFC), which was opened in 2004 to promote sustainable utilization of marine living resources. This agreement was signed by Comoros, France, Kenya, Madagascar, Mauritius, Mozambique, the Seychelles, Somalia and Tanzania. SWIOFC is focused on shallow-water fisheries but some States are investigating new fisheries for deep-water species within their EEZs (e.g., Mauritius or Mauritian dependencies on the Nazareth and St Brandon Banks; SWIOFC, 2009). In 2006, the South Indian Ocean Fisheries Agreement (SIOFA) was opened and signatories so far include Australia, the Comoros, France, Kenya, Madagascar, Mozambique, Mauritius, New Zealand, Seychelles and the European Community. However, the latter agreement, which forms the basis of a regional fisheries management organization (RFMO), has not yet entered into force (as of July 2010). This delay in the implementation of the SIOFA agreement, and the concern it raised amongst several of the deep-water fishing companies in the area, brought about the formation, in 2006, of SIODFA. The association's objectives are to promote technical, research and conservation activities that will furnish a future RFMO with the necessary data required for management of deep-water fisheries in the region (Shotton, 2006).

At present the only initiative protecting vulnerable marine ecosystems in the high-seas region of the Indian Ocean is the unilateral declaration by SIODFA of Benthic Protected Areas (BPAs). The companies that belong to SIODFA have voluntarily closed these areas to bottom-fishing or mid-water trawling (Shotton, 2006). The BPAs were selected on the basis of a number of criteria, including:

- representivity of seabed type (e.g., seamount, slope edge);
- fishing history;
- level of pre-existing knowledge on an area of geology, bathymetry and biology;
- protection of benthic communities; and
- protection of areas of special scientific interest (e.g., geological features of Atlantis Bank).

Squid (*Histioteuthis* sp.).
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Using these criteria, ten areas were protected in the Indian Ocean on the basis of the knowledge gathered from various sources by the members of the association, as well as the research and data gathered during fishing operations by vessel masters. These sites include a number of seamount, knoll, ridge and other topographic features that in some cases are known or suspected to host Vulnerable Marine Ecosystems (VMEs), as well as populations of commercial and non-commercial fish species.

At present little is understood about the representivity of the BPAs or whether they offer protection from bottom-fishing, as non-members of SIODFA are under no legal obligation to avoid fishing these areas.

III. KNOWLEDGE GAPS

In general terms many aspects of our understanding of seamounts remain poor. The seafloor of the oceans is not mapped to a sufficient resolution to determine the position, size and shape of the majority of seamounts, particularly those <1,000 m in elevation. Knowledge on interactions between seamounts and the ocean is based on a few observational 'case studies' and modeling of idealized seamount and flow configurations (Lavelle and Mohn, 2010). Likewise, studies of pelagic and benthic communities on seamounts remain limited, with only a few hundred seamounts having been sampled at all (Samedi *et al.,* 2007) and only few of these having been sampled extensively. With such a lack of observations, generalization about any aspect of the biology of seamounts is extremely difficult.

As well as very limited sampling effort, seamount studies are also subject to significant bias in a number of aspects. For example, few low-latitude seamounts have been studied as most research has concentrated on mid-latitude seamounts close to the coastlines of developed States (e.g., NE Atlantic or SW Pacific; Rogers *et al.,* 2007). Knowledge of seamounts is particularly poor for some regions, especially the Indian Ocean, parts of the Pacific and the Southern Ocean. Studies on seamount fauna have focused on large organisms obtained in dredges or bottom trawls, or those easily viewed from towed cameras or submersibles.

Despite these limitations, a general picture of the potential interactions of seamounts with the ocean, and there importance to marine ecosystems, has developed, especially over the last 20 years. To further this understanding, particularly in the context of management of seamount ecosystems, the following areas require further research effort at the present time:

- Meter – 100 km scale current-seamount interactions, particularly in relation to tidally-driven effects;
- Linkages between current-seamount interactions and seamount food webs;
- Resolution of the importance of upwelling, vertical mixing, retention and resuspension on primary production;
- The basis of seamount food webs, particularly bentho-pelagic coupling;
- Factors influencing the seamount-scale distribution of benthic organisms;
- The importance of seamount ecosystems to the surrounding ocean, especially to visitors such as aquatic predators;
- Connectivity of seamount populations, and distributional geographic ranges of seamount species;
- The differences (and similarities) of seamount and non-seamount communities, including consideration of ecosystem structure and endemism;
- Life histories of seamount species;
- The nature of the association between commercially targeted species and the seamount ecosystem;
- Recovery of seamount ecosystems following human-induced impacts; and
- Long-term implications of climate change to seamount communities.

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