
current

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DEEP-SEA CORALS

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CURRENT LOG *The least-explored forests on Earth aren't in rain-drenched Amazonia or the lofty Himalayas; they're in the oceans' depths. These deep-sea "forests" of gorgonian corals and reefs of stony corals were nearly unknown to science just a few years ago. But now scientists are finding that some of the sea's most biologically diverse ecosystems are coral communities occurring far below depths where people used to think that corals dwell. Indeed, the deep sea is home to thousands of coral species. Most are tiny, solitary cup corals. But some deep-sea bamboo coral colonies can reach 33 feet tall, and several kinds of deep-sea stony corals can form miles-long structurally complex reef ecosystems with hundreds of associated animal species. These deep-sea forests and reefs are the most exciting new marine discoveries since scientists first laid eyes on hydrothermal vents in 1977.*

Some deep-sea corals cling to outcroppings on continental slopes, the steep margins of the continents. Others coat the crests and shoulders of thousands of seamounts, mysterious, mainly extinct undersea volcanoes. One thing is clear: the scientific exploration of deep-sea corals and their associated sponges, fishes, and other species has scarcely begun.

Sadly, just as scientists are making exciting new discoveries around the world, we are finding places where corals had thrived until years or even months ago that are now fields of rubble or rocks shorn bare of corals and other life. Off Tasmania and Norway, Nova Scotia, and Florida, we are seeing places where somebody arrived before the scientists: trawlers that dragged the seafloor for orange roughy, cod, redfish, or rock shrimp. In doing so, they ripped gorgonians from the seabed and smashed glass-fragile stony corals to smithereens.

Marine Conservation Biology Institute (MCBI) has worked for years by bringing scientists together to document the distribution and value of deep-sea corals and the impact of trawling on them. We've studied their potential as sources of pharmaceuticals and mapped their distributions. And we've worked to secure protection of our nation's deep-sea coral ecosystems.

Our staff scientists and policy experts recently celebrated when the North Pacific Fishery Management Council—with some nudging from Oceana, The Ocean Conservancy, and the Alaska Marine Conservation Council—declared a huge area surrounding Alaska's Aleutian Islands off-limits to bottom trawling, barring the most destructive fishing method from the most vulnerable deep-sea ecosystems. I commend the scientists, conservationists, commercial fishermen, and government officials who made this happen, and hope that this sets a new standard, demonstrating that some ecosystems are so important to biodiversity and fisheries that we will all work together to protect them.

ELLIOTT A. NORSE, PH.D. is President of MCBI, a nonprofit science and conservation organization headquartered in Redmond, Washington. He is also President of the Marine Section of the Society for Conservation Biology and a Pew Fellow in Marine Conservation.

LANCE E. MORGAN, PH.D. is Chief Scientist for MCBI and Affiliate Assistant Professor at the School of Marine Affairs at the University of Washington.

MARGARET PIZER was Research Assistant at MCBI and is currently Editorial Associate at *Conservation in Practice* Magazine. She received her master's degree in Biology from Duke University, where she studied larval development and evolution in echinoderms.

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WHAT ARE DEEP-SEA CORALS?

BY LANCE E. MORGAN

THIS ISSUE OF CURRENT INTRODUCES YOU TO DEEP-SEA CORALS. *The articles highlight recent research from the U.S. and Europe, primarily aimed at exploring and understanding ecosystems that were literally below the sonar screens of many scientists and agencies just a decade ago. Who knew there were coral reefs in Norway, coral gardens in Alaska, and undiscovered species of corals to be found just miles from Los Angeles, California? These very long-lived animals may provide us with untold medical benefits and also serve as harbingers of climate change, but they are currently threatened by destructive fishing practices. Thanks to the wonderful work of the National Oceanic and Atmospheric Administration's (NOAA's) Office of Ocean Exploration (OE), a number of activities are included in this issue that examine exploration of the deep sea from the safe confines of the classroom.*

Few people have difficulty conjuring up images of tropical coral reefs, colorful fishes, vibrant anemones, and gently waving sea fans. At the same time, for many, the deep sea brings up images of sand ripples, mud plains, and boulder fields. But nothing could be further from the truth. Recent technological advances have provided marine scientists with unprecedented opportunities to study the seafloor beyond the limited depths accessible by conventional SCUBA.

What we have found is striking. We now know the majority of coral species live in the colder, darker depths, some of these deep-sea corals are similar to shallow water corals in appearance, and they are important to marine biological diversity and fisheries. Throughout the world's oceans, a wave of ocean exploration is bringing back photographs and video of amazing coral gardens, extensive reefs, and Christmas tree corals. Although not strictly comparable, the deep-sea coral (*Lophelia pertusa*) reefs of the European continental margin, stretching from Norway around the British Isles and south to Spain and Portugal at roughly 4,500 km in length, extends over a much larger linear distance than the Great Barrier Reef of Australia (2,000 km long). Based on the work of our European colleagues, we also know that the *Lophelia* reefs in the dark, cold waters of the northeast Atlantic are home to over 1,300 species of fish and invertebrates, a number that will undoubtedly continue to grow with ongoing research (Freiwald and Roberts, 2005).

Moreover, marine scientists have observed large numbers of commercially important but increasingly uncommon groupers, rockfishes, and other deep-sea fishes among the sheltering structures of some deep-sea corals. And because of their longevity, some deep-sea corals can serve as archives of past climate conditions that are important to understanding global climate change. In short, based on current knowledge, deep-sea coral communities appear to be as important to the biodiversity of the oceans and the sustainability of fisheries as their better recognized cousins in shallow tropical seas.

DEFINING DEEP-SEA CORALS

While we understand the concept of a tropical coral reef, it is not intuitively obvious how to generalize about the diverse taxa that constitute deep-sea corals. Some authors describe them as cold-water corals, while others describe them as azooxanthellate (meaning that, lacking symbiotic algae, they must satisfy all their nutritional requirements by the direct intake of food, unlike their tropical relatives). In truth, nothing about deep-sea corals can be said to be exclusive to them. Close relatives of deep-sea corals can be found in shallow waters (less than 10 m) and in warm tropical waters. Though deep-sea corals are primarily azooxanthellate, so are shallow water octocorals, hydrocorals, and black corals. Finally, just to confuse things further, deep-sea corals are an evolutionarily diverse group that contain scleractinians (stony corals, what we typically consider the corals of tropical coral reefs), octocorals (gorgonians, sea fans, and sea pens), and hydrocorals (lace corals, stylasterids, and fire corals). In reality, corals represent a continuum of closely related species in both the shallow and deep sea, and only our limited ability to peer into the deeper depths of the ocean can be blamed for our parochial view of corals as shallow-water reef-formers.

Deep-sea corals include members of several major taxonomic groups within the phylum Cnidaria: hydrocorals (Stylasteridae), black corals (Antipatharia), true or stony corals (Scleractinia), sea fans (Gorgonacea), soft corals (Alcyonacea), sea pens (Pennatulacea), and stoloniferans (Stolonifera), as well as a few others. Gorgonians, alcyonaceans, pennatulaceans, and stoloniferans belong to the subclass Alcyonaria and are collectively referred to as octocorals. They are ahermatypic or non-reef building corals, but many are structure forming. The degree to which they provide structure depends on their maximum size, growth form, fine-scale intraspecific distribution, and interaction with other structure-forming invertebrates. Only members of the scleractinia actually form "reefs" and only a few species, most notably *Lophelia pertusa*, do so in the deep sea.

MAJOR TAXA OF DEEP-SEA CORALS

Hydrocorals (Class Hydrozoa, Order Stylasterina)

Hydrocorals, or lace corals, form erect or encrusting calcareous colonies and require exposed, hard substrate for attachment. Most are important structure-forming corals. Some erect species, most notably *Stylaster cancellatus*, may grow to almost one meter in height and are often patchily distributed. Hydrocorals, particularly *S. campylecus*, are a major structural component of Aleutian Island coral gardens (discussed by Stone in this issue). The California hydrocoral (*S. californicus*) often forms extensive beds in the southern California bight, and others are common structure formers in the waters off Florida.

Black Corals (Class Anthozoa, Order Antipatharia)

Black corals are important structure-forming corals. They are locally abundant, patchily distributed, and a few species, such as *Antipathes dendrochristos*, can grow to almost three meters in height (see Yoklavich and Love, this issue). Black corals are also harvested for the commercial jewelry trade in Hawaii, the only current commercial harvest of corals in U.S. waters. Black corals are found throughout U.S. waters from the shallow depths of Hawaii to the deep slopes of the Atlantic and Pacific continental margins.

Stony Corals (Class Anthozoa, Order Scleractinia)

There are many species of stony coral in the U.S. north Pacific. Most are solitary cup corals; however, in the U.S. Atlantic, *Lophelia pertusa* and *Oculina varicosa* form large reefs. The largest colonies develop into bioherms, consolidating broken coral and sediment into a hard carbonate structure. These corals continue to grow and expand as a colony for decades to many centuries. They require exposed, hard substrate for attachment. Articles by Roberts and Freiwald, and Reed and Ross, both in this issue, discuss recent research and findings concerning these coral reefs in European and U.S. waters respectively. These deep-sea coral reef builders provide important structural habitat for many macro-invertebrates and commercially important fishes.

Gorgonians (Class Anthozoa, Order Gorgonacea)

Sea fans or gorgonians are important structure-forming corals. They are widespread throughout the oceans, including seamounts, and require exposed, hard substrate for attachment. Gorgonians are often locally abundant and patchily distributed, and several species grow to massive size. *Primnoa pacificum* attains a height of seven meters in Alaskan waters, while other *Primnoa* species reach heights of several meters in many parts of the world. Another large gorgonian (*Paragorgia arborea*) can measure two meters high and wide, and its New Zealand



Coral forests in the Aleutian Islands, Alaska.

cousin may reach 10 m in height. Many other gorgonians such as bamboo corals (Family Isididae) grow to over one meter high. Gorgonians form both single- and multi-species assemblages. Several gorgonians are now prized as precious corals, including the red coral (*Corallium rubrum*), which was also valued in ancient Greece.

True Soft Corals (Class Anthozoa, Order Alcyonacea)

True soft corals can form encrusting colonies or can stand erect. One species (*Anthomastus Ritterii*) may reach 20 cm in height. They require exposed, hard substrate for attachment, are locally abundant, and have a patchy distribution. This group is known throughout the U.S., but is not particularly species diverse.

Pennatulaceans (Class Anthozoa, Order Pennatulacea)

Pennatulaceans, or sea pens, are uniquely adapted to living exclusively in soft-sediment areas. They burrow and anchor in soft sediment by means of peristaltic contractions against the hydrostatic pressure of the peduncle. Unlike other corals, they are sessile rather than sedentary and are capable of reburial if excavated from the sediment. Sea pens may form extensive groves in some areas.

EXPLORING THE DEEP

Deep-sea corals are now known from all the world's oceans. Marine scientists have discovered deep-sea corals in 41 countries so far including Japan, Spain, Seychelles, New Zealand, Mauritania, Canada, Australia, Colombia, Brazil, Norway, Angola, Russia, Sweden, United Kingdom, Ireland, and the United States of America. This exploration depends on access to research submarines and remotely operated vehicles suitable for studying the deep sea. Although this technology is limited to relatively few institutions and agencies and time at sea is expensive, scientific investigation is burgeoning. In his article in this issue, McDonough discusses U.S. efforts to continue exploring the deep sea and its myriad seamounts, cold seeps, and submarine canyons for new discoveries of ocean life.

Among the more fascinating areas for exploration are seamounts, with their untold diversity of deep-sea corals. In recent years, cruises to previously unexplored seamounts in the Tasman and Coral Seas recorded over 850 species of macro- and mega-fauna. Cruises to seamounts in the Gulf of Alaska, Northwestern Hawaiian Islands, and New England have all brought back many new species of deep-sea corals, including some with incredible morphologies. Because seamounts are essentially undersea islands, many seamount species are endemics—species that occur nowhere else—and are therefore exceptionally vulnerable to extinction.

DEEP-SEA CORALS UNDER THREAT

It is increasingly clear that deep-sea corals usually inhabit places where natural disturbance is rare, and where growth

and reproduction appear to be exceedingly slow. Deep-sea corals may live for centuries, making them and the myriad species that depend on them extremely slow to recover from disturbance. Unfortunately, just as scientists have begun to understand the diversity, importance, and vulnerability of deep-sea coral communities, humans have developed technologies that have the potential to profoundly threaten them. There is reason for concern about deep-sea oil and gas development, deep-sea mining, and changes to the deep ocean from global warming, but, at present, the greatest human threat to deep-sea coral communities is bottom trawling. Trawlers are vessels that drag large, heavily weighted nets across the seafloor to catch fishes and shrimps. Scientific studies around the world have shown that trawling is devastating to deep-sea corals. As trawlers become more technologically sophisticated, and as fishes disappear from shallower areas, trawling is increasingly occurring at depths exceeding 1,000 m. In 2004, 1,036 scientists released a public statement calling on the nations of the world to protect deep-sea coral ecosystems. However, without the informed participation of the public in this debate, action to protect these corals will languish. The articles and activities gathered together in this issue provide an introduction to these important, but poorly known communities.

LANCE E. MORGAN, Ph.D. is Chief Scientist for Marine Conservation Biology Institute (MCBI). He is lead author of the first rigorous, quantitative comparison of the ecological damage caused by commercial fishing methods in the U.S., *Shifting Gears*, and an author of *Occurrences of Habitat-forming Deep-sea Corals in the Northeast Pacific Ocean*.

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FOR MORE RESOURCES:

The text and signatories of the Scientists' Deep-Sea Coral Statement can be viewed at:

http://www.mcbi.org/DSC_statement/sign.htm

PHOTO CREDIT:

Page 3: Courtesy of NOAA Fisheries, photo by Alberto Lindner

THE SEARCH FOR DEEP-SEA CORALS - ESTABLISHING A FOUNDATION FOR RESEARCH AND MANAGEMENT

BY JOHN McDONOUGH

RIGOROUS EXPLORATION AND RESEARCH *has begun to search for, map, and study deep-sea coral communities in a systematic way. Recent expeditions have yielded exciting findings, including the discovery of new species of corals and coral-associated invertebrates. Much work remains to be done, and exploration will continue to play a crucial role in providing scientists, natural resource managers, and educators with the first records and descriptions about deep-sea coral ecosystems.*

THE NEED FOR EXPLORATION

Until the last few decades, the majority of information on deep-sea corals and their habitat was based on observations made by the commercial fishing industry. For example, while trawling around seamounts and other submerged high-relief areas, fishermen often would collect unique specimens of deep-sea corals, including scleractinians (stony corals), gorgonians (soft branching corals), and antipatharians (black corals). Although these observations were not made in a systematic manner, the evidence suggested that deep-sea corals could be found in all of the world's oceans, and they could form an array of habitats from fairly monotypic reef-like structures dominated by a single or few species, to diverse communities populated by multiple species from several families. Quite often these communities also exhibited a rich array of sponge, crustacean, mollusk, and fish species.

More rigorous exploration and research have recently begun to search for, map, and study deep-sea coral communities in a systematic way, and have demonstrated that these corals are fragile, long-lived, slow-growing, and extremely susceptible to physical disturbance. In fact, it is unknown whether these species are capable of repopulating a given area if they are destroyed. Furthermore, despite an increase in exploration and research, next to nothing is known about deep-sea coral distribution, population dynamics and ecology, or about how deep-sea corals function in providing habitat for other species. As fisheries and other human activities, such as oil and gas exploration, expand into deeper waters, the need for deep-sea coral exploration and research is growing more critical.

EXPLORATION – A WORKING DEFINITION

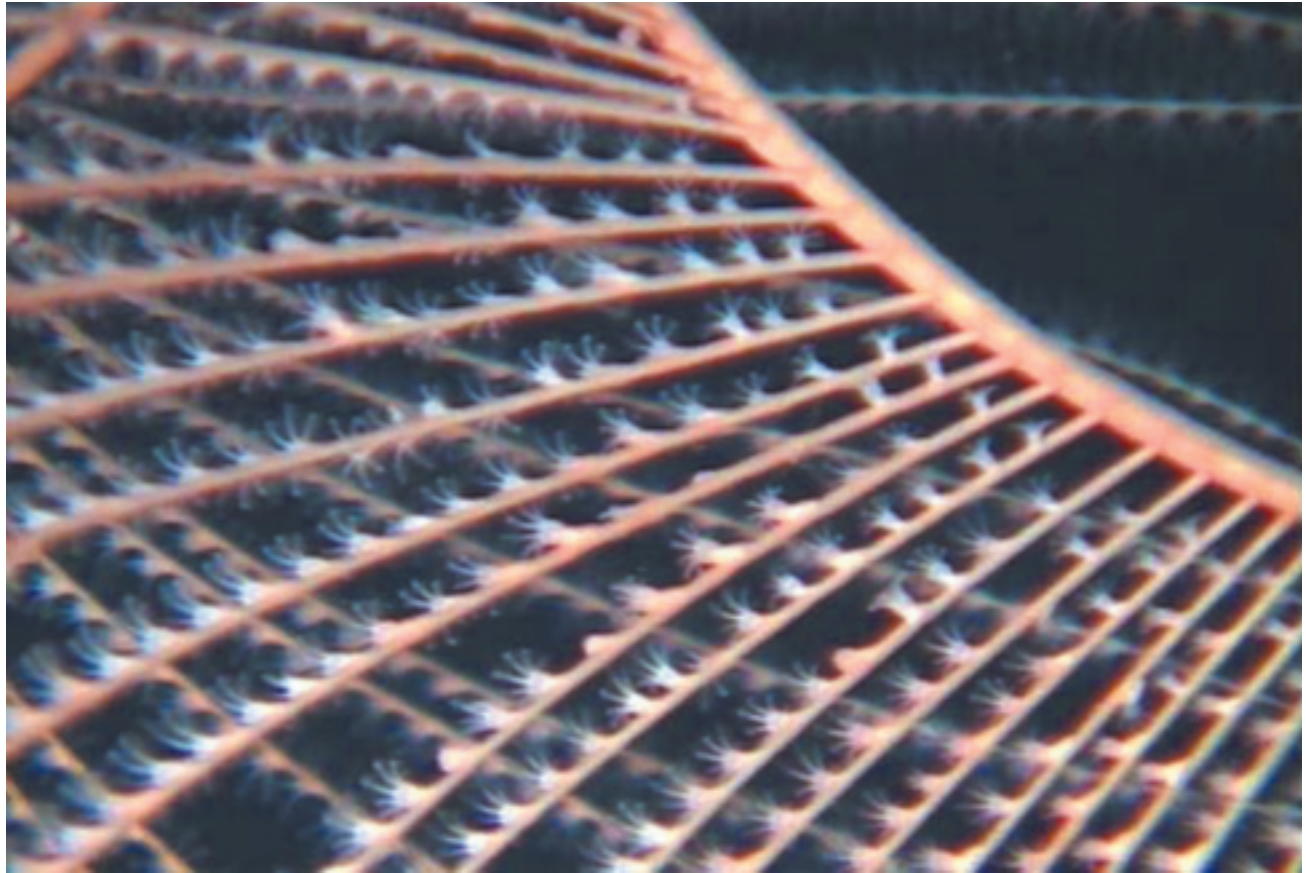
Exploration can be defined as the first foray into an unknown or poorly known area for the purpose of describing what is there. Exploration is distinguished from hypothesis-driven research in that it applies the principles of the geographer to describe the basic set of conditions governing a given area. Specifically, exploration provides a comprehensive description of an area's geology, geomorphology, biology, oceanography, ecology, and

human activities. In contrast, research is traditionally based on developing and testing more process-oriented hypotheses involving the systematic collection and analysis of data, and often includes monitoring conditions over time.

Exploring the world's oceans, especially areas that may contain deep-sea coral habitat, requires specialized equipment. Explorers often use mapping instruments such as side-scan sonar, multi-beam sonar, or laser line scan technology to image and map the seafloor. Mapping efforts may include covering large areas to identify features—such as shelf-edge and slope topographic highs, submerged canyons, and seamounts—that might support deep-sea corals, or mapping small pre-determined targets at extremely high resolution to distinguish differences in bottom substrate or habitat type. Ocean explorers also use human-occupied submersibles or remotely operated vehicles (ROVs) outfitted with arrays of sophisticated cameras and lights to gather video and still images of deep-sea coral habitat and associated species. This information is often invaluable for identifying species and understanding and describing their behavior and interactions. Submersibles and ROVs also provide explorers with a means of collecting discrete samples of rocks, sediment, corals, fishes, and invertebrates to further describe the area they are investigating. Finally, explorers collect water samples and information on oceanographic conditions to help describe the environment supporting the development of deep-sea coral habitats.

THE VALUE OF EXPLORATION

Exploration provides a foundation of information from which hypotheses can be generated and tested. Under certain conditions, exploration may also provide information used for making effective management decisions. In the case of deep-sea corals, the information derived from exploration is used to describe the species and community structure within a given area, the status of the system in terms of health (especially when compared to a known system), as well as the effects of human activities like physical destruction from trawl gear. This body of information is used to organize research and monitoring efforts. For example, the results of exploration



A close-up of *Iridogorgia* coral found on Manning Seamount during the "Mountains in the Sea 2003" expedition.

activities are used very effectively to help establish the *Oculina* Habitat Area of Particular Concern (HAPC) off the east coast of Florida. The information collected through these expeditions is also used to guide further exploration into other areas that may exhibit similar conditions.

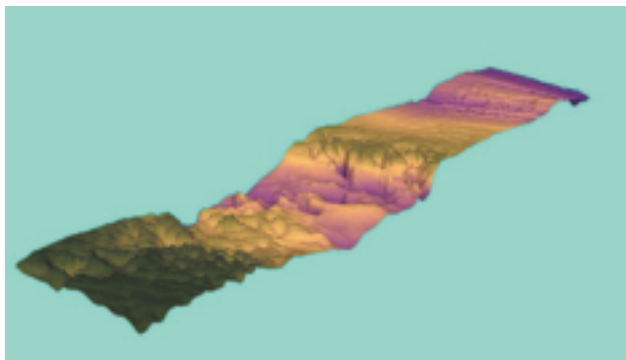
EXAMPLES OF RECENT DEEP-SEA CORAL EXPEDITIONS

From the earliest efforts to assess historical fisheries bycatch statistics to the most recent expeditions using the latest technology, there is a long history of exploration related to deep-sea coral habitats. These include the efforts of scientists and technicians from a wide variety of public and private institutions, all striving to learn more about these unique and fragile systems.

In June 2000, a U.S. panel of ocean scientists, explorers, and educators convened to create a National Strategy for Ocean Exploration. Their final report, *Discovering Earth's Final Frontier: A U.S. Strategy for Ocean Exploration*, provided a vision for undertaking new activities in ocean exploration. As recommended in the report, the National Oceanic and Atmospheric Administration (NOAA) renewed its commitment

through its Office of Ocean Exploration (OE), and created new partnerships with public, private, and academic ocean exploration programs throughout the community of ocean science. The mission of the NOAA OE Program is to search and investigate the world's oceans for the purpose of discovery and for the advancement of knowledge of the oceans' physical, chemical and biological environments, processes, characteristics, and resources. Specifically, the office was created to provide a focus for gathering information on unknown and poorly known ocean areas, including areas containing deep-sea corals.

Since 2000, OE and its partner office, the NOAA Undersea Research Program (NURP), have supported a total of 48 exploration projects that have provided information to further both research and management. These include projects using well-known assets, such as the *Alvin*, the *Johnson-Sea-Link*, and the *Pisces IV* and *V* submersibles, to focus on locating and characterizing deep-sea coral habitats and investigating their biology and ecology. The following provides a brief description of some of these projects.



Scientists use high-resolution maps such as this image of the Charleston Bump off the coast of South Carolina to identify areas that might support deep-sea coral communities.

Northwest Hawaiian Islands: Sixteen expeditions have been undertaken focusing on a range of issues from mapping the distribution of deep-sea coral habitats found in submerged canyons to collecting samples for genetic analysis in order to determine potential links between discrete populations. Several of these projects have focused on determining how species, such as monk seals, may use these areas for foraging (see Morgan, this issue, for more). All of this information is available to help NOAA and the state of Hawaii in efforts to designate this region as a National Marine Sanctuary.

New England: Thirteen expeditions have explored deep-sea coral habitats found on the New England Seamounts and investigated similar communities found in the canyons that deeply incise the continental shelf. Much of this work has involved mapping and the collection of visual imagery to quantify discrete habitat areas and to investigate community associations and dynamics. This information is critical for supporting efforts to reduce the negative effect of certain types of fishing practices, such as bottom trawling and bottom traps.

South Atlantic Bight: Eleven expeditions focusing on deep-sea coral reefs and bioherms comprised of species such as *Lophelia pertusa* and *Oculina varicosa* were conducted over the past several years. These efforts have included mapping, using side-scan sonar and multi-beam sonar to accurately plot the locations of individual reefs, as well as describing food-web relationships and energy flow within coral ecosystems. This information has been particularly useful for the continued protection of the *Oculina* Banks as a Habitat Area of Particular Concern (HAPC), as well as in support of efforts of the South Atlantic Fisheries Management Council to identify a network of marine protected areas (MPAs) that will protect and maintain sustainable stocks of commercially important fish species.

Gulf of Alaska: While NOAA Fisheries has been conducting and supporting many deep-sea coral research projects in the Aleutian Islands that have provided information useful for the establishment of HAPCs, the OE and NURP programs have supported eight expeditions to investigate and characterize

deep-sea coral communities found in association with the seamounts in the Gulf of Alaska. This cutting-edge work has involved interdisciplinary teams of scientists, including geologists, biologists, and ecologists who have been establishing a foundation of information that will guide future exploration, research, and management (see Tsao and Morgan, this issue, for more).

Gulf of Mexico: Five expeditions have searched for deep-sea corals from Pulley's Ridge, north of the Dry Tortugas, to deepwater relict salt domes in the Northern Gulf. These expeditions have collected images and samples from some very unique sites using ROVs, and have provided information that will be built upon by the Minerals Management Service (MMS) to help guide and manage oil and gas exploration and development in the region.

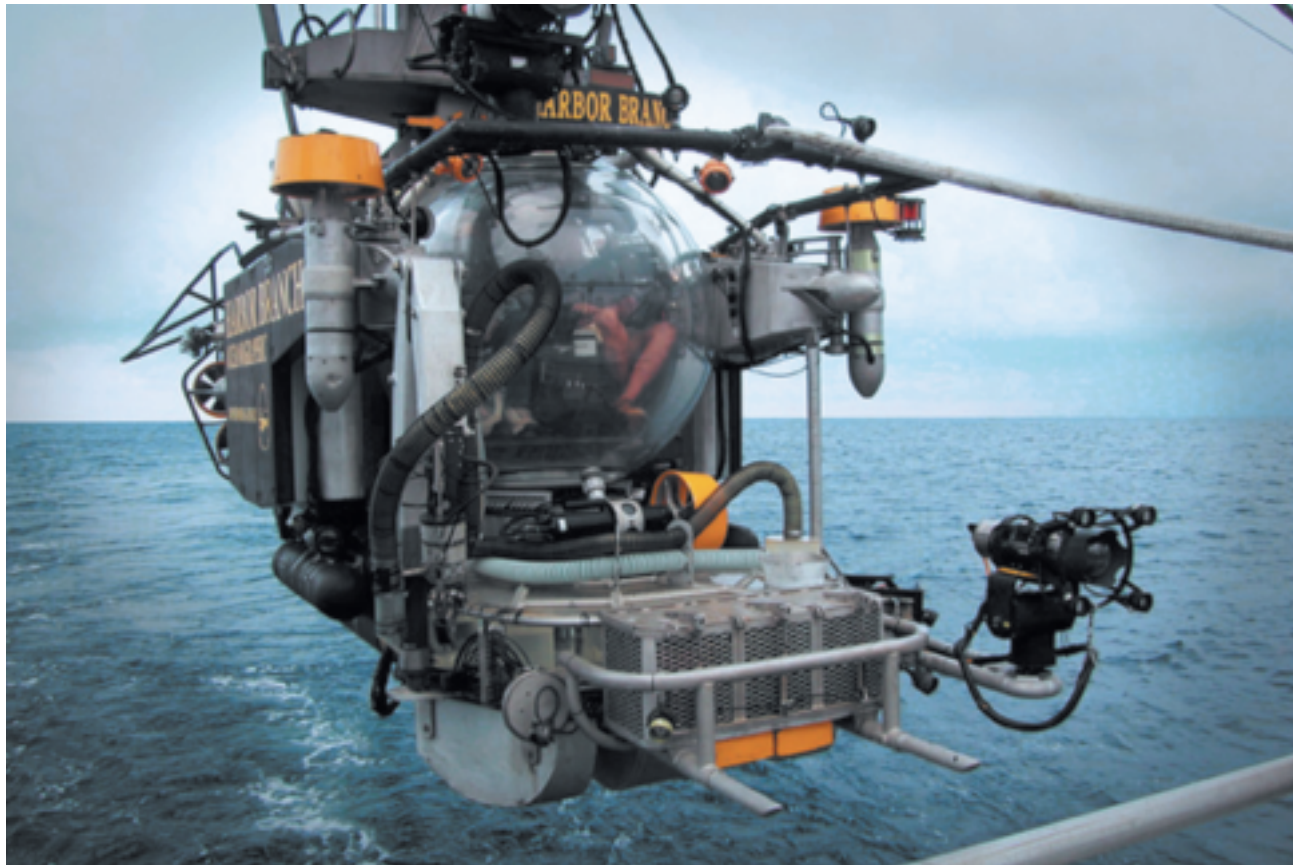
CONCLUSION—FUTURE EXPLORATION

The recent report by the U.S. Commission on Ocean Policy, *An Ocean Blueprint for the 21st Century*, recommends that NOAA serve as the lead agency for managing deep-sea coral communities, and acknowledges that NOAA should continue to work with states and academic institutions to expand exploration and research on deep-sea corals for the purposes of effective management. Much work remains to be done since so little is known about deep-sea coral habitats, and exploration will continue to play a crucial role in providing scientists, natural resource managers, and educators with the first records and descriptions about these systems. Ocean explorers will be called upon to provide a framework and foundation of information that will fill existing gaps in our knowledge and set the stage for refined research, management, and monitoring.

JOHN McDONOUGH joined the NOAA Office of Ocean Exploration in January 2003 as the expedition's coordinator. He served as a physical scientist with NOAA's National Ocean Service from 1989 to 2002, where he developed data and geographic information systems related to coastal and marine environments, and applied that information to help prepare management plans for MPAs. During that time, he was also the project manager for large-scale undersea research expeditions using a variety of tools and techniques, including manned and unmanned submersibles.

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- U.S. Department of Commerce and the National Oceanic and Atmospheric Administration (2003). *Summary, Deep-Sea Corals Workshop: International Planning and Collaboration*



Human occupied submersibles such as the *Johnson-Sea-Link* (owned and operated by the Harbor Branch Oceanographic Institution) allow scientists to explore deep-sea coral communities.

Workshop for the Gulf of Mexico and the North Atlantic Ocean. Galway, Ireland, January 16-17, 2003. NOAA Technical Memorandum NMFS-SPO-60. 51 pp.

U.S. Department of Commerce and the National Oceanic and Atmospheric Administration (2000). *Discovering Earth's Final Frontier: A U.S. Strategy for Ocean Exploration*. Report of the President's Panel on Ocean Exploration. 61 pp.

FOR MORE RESOURCES:

NOAA Ocean Explorer:
<http://oceanexplorer.noaa.gov/>

NOAA Undersea Research Program (NURP):
<http://www.nurp.noaa.gov/>

U.S. Commission on Ocean Policy:
<http://www.oceancommission.gov/>

NOAA Ocean Exploration Panel Report, *Discovering Earth's Final Frontier: A U.S. Strategy for Ocean Exploration*:
http://oceanservice.noaa.gov/websites/retiredsites/supp_oceanpanel.html

PHOTO CREDITS:

Page 6: Courtesy of Woods Hole Oceanographic Institution

Page 7: Courtesy of Phil Weinbach, South Carolina Department of Natural Resources

Page 8: Courtesy of Art Howard, NAPRO Communications Raleigh, North Carolina

CORALS THAT LIVE ON MOUNTAINTOPS

BY FAN TSAO AND LANCE E. MORGAN

IN RECENT YEARS, scientists, with backing from the National Oceanic and Atmospheric Administration's (NOAA's) Office of Ocean Exploration (OE) program, have begun to investigate underwater mountains called seamounts. A variety of diverse deep-sea corals have been discovered living at great depths. Despite this wave of exploration, only a small fraction of seamounts have been visited by scientists, though it is likely that most shallow seamounts (those with summits less than 1,000 m below the ocean surface) have already been commercially fished.

Numerous extinct and active volcanoes stand thousands of meters tall on the seafloor in U.S. waters. From New England to Alaska, scientists dive beneath the sea to explore seamounts, often finding diverse communities of deep-sea corals growing on the summits and slopes of these undersea mountains. Living with these deep-sea corals are fishes and invertebrates deriving benefits from the corals' three-dimensional structures.

A seamount is defined as an underwater mountain rising more than 1,000 m above the surrounding seafloor. Deep-sea corals live on seamounts because underwater currents flow faster above seamounts, sweeping away sediment and revealing rocky outcrops for the corals to settle and grow on (Stone et al., 2004), and delivering food particles for deep-sea corals to eat. Because rocky seafloor is rare and productivity is limited in the deep sea, seamounts are an ideal place for filter-feeding animals like deep-sea corals to live (Genin et al., 1986). The distribution of deep-sea corals on seamounts also suggests the importance of water currents. Deep-sea corals tend to concentrate on the tops of sharply peaked seamounts as opposed to the slopes, but on seamounts with flat tops, corals reside along the perimeter of the flat top—in both cases, where currents are the strongest (Genin et al., 1986; De Vogeleare et al., 2005). Currents may carry more coral larvae to seamounts allowing greater colonization of seamounts than of the surrounding seafloor (Genin et al., 1986). In addition, under certain environmental conditions, currents above seamounts can develop into a gyre, or circular eddy, that traps larvae and prevents them from drifting away from the seamount.

Because of these unique characteristics and the rarity of seamounts in the deep sea, many have very high levels of endemism (species unique to one area of the world). In one study of seamounts located in the Tasman and Coral Seas, researchers found 850 new species (Richer de Forges et al., 2000): 42 percent more than were discovered in the past 125 years of seamount research combined. Moreover, 34

percent of these species were potential endemics. Another study determined that 16 to 33 percent of the 300 fish and invertebrate species found on seamounts south of Tasmania were restricted to seamount environments (Koslow et al., 2000). Commercially valuable fishes aggregate around seamounts (e.g., orange roughy [*Hoplostethus atlanticus*] and pelagic armorhead [*Pseudopentaceros wheeleri*]), but their low productivities and long life histories make them incredibly vulnerable to overfishing, and the type of fishing gear used—bottom trawls—results in damage to delicate structures such as deep-sea corals (Morato et al., 2004; Koslow et al., 2001). Many other species, including pelagic fishes, seabirds, and marine mammals, often concentrate above seamounts.

Below we highlight some of the recent explorations of seamounts off the east and west coasts of the U.S. and in the Gulf of Alaska and Hawaii that have yielded exciting discoveries of deep-sea coral communities and a better understanding of the close relationship between corals and seamounts.

NEW ENGLAND SEAMOUNT CHAIN

The 1,500 km long New England Seamount Chain consists of extinct volcanoes stretching from offshore Cape Cod to halfway across the western Atlantic. The bases of these seamounts are 5,000 m deep, but their tops reach depths of 1,500 m. Recent research cruises revealed an astonishing diversity of life on these unique seamount habitats and a high abundance of deep-sea corals. In 2003, researchers onboard the deep-diving submersible *Alvin* photographed and collected seamount fauna on Bear, Kelvin, and Manning Seamounts. In 2004, scientists used remotely operated vehicles (ROVs) equipped with robotic claws to survey the same seamounts in addition to Balanus and Retriever Seamounts. The ROVs took thousands of high-resolution digital images (Figure 1), and the claws collected boxes of selected specimens. They also brought to the surface some fossil corals for climate researchers to study. Scientists reported 24 coral species between the depths of 2,200 and 1,100 m, including ubiquitous bubblegum

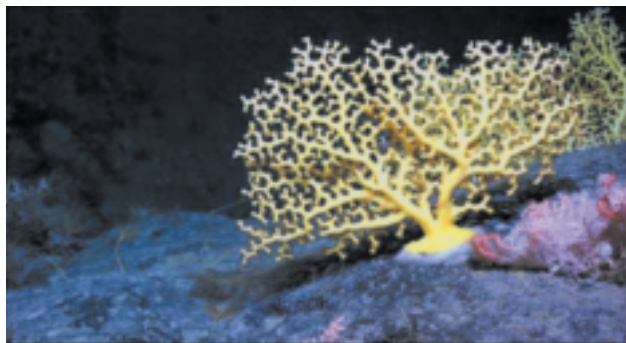


Figure 1. This stunning yellow *Enallopsammia* stony coral with pink *Candidella* is teeming with brittle stars on Manning Seamount. Image taken by researchers on the NOAA "Mountains in the Sea 2004" cruise.

corals (*Paragorgia* spp.) and two-meter tall whip corals (*Lepidisis* spp.). Balanus Seamount, explored in 2004, has a forest of whip corals reaching heights of four meters. Fish eggs, from a not yet identified species, were attached to *Metallorgorgia* branches, indicating that deep-sea corals may be important nursery grounds for fish. Marine biologists also found bioluminescent bamboo corals (*Keratoisis* spp.) that emitted blue-green light when disturbed.

DAVIDSON SEAMOUNT

Davidson Seamount is a massive seamount 120 km southwest of Monterey, California. Its large base occupies a 40 km by 10 km area at a depth of 3,650 m. The 2,400 m tall seamount is marked by dense ridges. In 2002, scientists conducted 90 hours of surveys on the seamount over the course of six ROV dives. Deep-sea corals were distributed from almost 3,000 m deep to the seamount top. Deep-sea coral forests were concentrated on the high-relief ridges near the top, where bubblegum corals grow to two meters tall and two meters wide. This cruise also observed soft mushroom corals (*Anthomastus* spp.), black corals (*Antipatharia* spp.), and pink corals (*Corallium* spp.). Almost all of the corals had associated fauna, ranging from polychaete worms, basket stars, octopuses, to thornyhead fish (De Voogeleare et al., 2005).

GULF OF ALASKA SEAMOUNTS

The 2004 Gulf of Alaska research cruise visited five seamounts in the Kodiak-Bowie Seamount Chain with 18 submersible dives down to a depth of 2,700 m. Like other seamount cruises, this one revealed deep-sea coral species new to science. Scientists found high levels of deep-sea coral diversity as well as a high diversity of associated fishes and invertebrates. The most abundant corals are red-tree (Primnoids), bubblegum, bamboo (Isidids), and black corals. Beside collecting corals with the submersible's arms and visually documenting the coral habitats, scientists also used a slurp gun to vacuum animals from the corals and bring them to the surface in order to further analyze the composition of the deep-sea coral ecosystem. They found that crabs, brittle

stars, and shrimps are common associates of the corals. Certain species are found only on corals and nowhere else on the seabed, such as the galatheid crab (*Gastroptychus iaspus*) and the unbranched basket star (*Asteronyx* spp.). Species assemblages in coral habitat vary with depth, but researchers suspect these species associate with corals for three reasons: 1) suspension feeders climb on corals to elevate themselves off the seafloor for faster current flow, which carries more food; 2) small crustaceans use coral structures as refuge from predators; and 3) some species such as sea stars and sea spiders feed on corals directly.

HAWAIIAN RIDGE - EMPEROR SEAMOUNTS

This chain of islands and seamounts extends some 6,000 km from a submerged active volcano just southwest of the island of Hawaii to the Aleutian Trench off Alaska. The Hawaiian islands themselves are not seamounts—yet. But as they subside into the north Pacific they will become seamounts in coming millennia. Scientists have explored small sections of this chain and found intriguing animals such as deep-sea corals, including valuable precious corals belonging to three families: gold coral (Parazoanthidae; Figure 2), red or pink coral (Corallidae), and bamboo coral (Isididae). Another taxon, black coral (Antipathidae), is collected at shallower depths and polished into jewelry. Perhaps the most significant fact about the Emperor Seamount chain is the history of exploitation of fishes in this region prior to scientific discovery. The pelagic armorhead fishery began in 1968 when Russian fishermen began fishing the summits and upper slopes of seamounts in the southern Emperor Seamounts. By 1975, the combined Russian and Japanese catch totaled approximately one million tons of fish. In 1978, the U.S. began regulating this fishery on the Hancock Seamounts, which are within the U.S. EEZ in the northernmost section of the Northwestern Hawaiian Islands. However, management was too late in coming, and in 1986, a fishing moratorium was put in place after the fishery collapsed. In 2004, even after an 18-year moratorium, fish populations show no evidence of recovering.

There are an estimated 15,000 to 100,000 seamounts in the world, yet only a small percentage have been explored. There is reason to believe that more wonders of the deep sea are waiting to be discovered, but these ecosystems are fragile and under growing threat from bottom-trawl fishing. Conservation organizations are currently advocating at the United Nations for a moratorium on high-seas bottom trawling to protect seamounts, but as yet there is little or no protection in international waters for these unique ecosystems and species. In the U.S., Davidson Seamount was set aside from trawling recently, and some protection from bottom fishing has been accorded the Gulf of Alaska Seamounts by the North Pacific Fishery Management Council. These are laudable steps to protect seamounts and to conserve the deep-sea corals and other species that inhabit these places.



Figure 2. A large galathea crab on gold coral on Cross Seamount in Hawaii. Image taken by researchers on the NOAA "Deep-Sea Precious Corals" cruise in 2004.

FAN TSAO is Conservation Scientist at Marine Conservation Biology Institute (MCBI). She received her master's degree in Marine Affairs from the University of Washington, where she studied the natural and social sciences pertaining to marine conservation.

LANCE E. MORGAN, PH.D. is Chief Scientist for Marine Conservation Biology Institute (MCBI).

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FOR MORE RESOURCES:

Seamounts Online:

<http://seamounts.sdsc.edu/>

Davidson Seamount:

<http://oceanexplorer.noaa.gov/explorations/02davidson/davidson.html>

Gulf of Alaska Seamounts:

<http://oceanexplorer.noaa.gov/explorations/04alaska/welcome.html>

New England Seamounts:

<http://oceanexplorer.noaa.gov/explorations/04mountains/welcome.html>

Northwestern Hawaiian Island Seamounts:

<http://oceanexplorer.noaa.gov/explorations/02hawaii/welcome.html>

PHOTO CREDITS:

Page 10: Courtesy of NOAA and Researchers on the "Mountains in the Sea 2004" Cruise

Page 11: Courtesy of Amy Baco-Taylor; Thomas Shirley; Pilots T. Kerby and M. Cremer; and NOAA

Did You Know?

During the first year of the orange roughy fishery on South Tasman Rise seamounts off Australia, an estimated 1.6 tons of coral were caught as bycatch by fisherman per hour of fishing, resulting in a total bycatch of 10,000 tons of coral that year.

THE INTERTWINED FATES OF PRECIOUS CORALS AND MONK SEALS

BY LANCE E. MORGAN

SCIENTISTS EMPLOY A NUMBER OF HIGH-TECH TOOLS to explore the deep sea in search of corals, but none is more exotic than the Hawaiian monk seal! By placing satellite tags on monk seals (*Monachus schauinslandii*) Frank Parrish and colleagues studied the diving patterns of foraging seals from French Frigate Shoals (FFS) in the Northwestern Hawaiian Islands. Movement patterns of 30 seals identified only two locations where seals frequented deep depths (greater than 300 m). Using manned submersibles, the scientists surveyed these locations and precious coral beds were found at both. The success at locating coral beds by following the seals contrasts with 11 earlier submarine surveys done by Hawaii Undersea Research Laboratory in 1984 around FFS atoll, which did not find any coral beds. The conclusion was clear: monk seals specifically targeted deep-sea coral beds and led scientists to them.

This serendipitous discovery came as a result of efforts to understand and protect endangered monk seals. The Northwestern Hawaiian Island ecosystem is home to what some consider to be the last viable population of monk seals (Caribbean monk seals are extinct and Mediterranean monk seals are critically endangered, the population is probably less than 400 individuals), and this population has been declining since the 1950s. The Hawaiian monk seal was designated as endangered under the Endangered Species Act of 1976, and current monk seal numbers are only 60 percent of what they were in the late 1950s. There is no evidence to indicate that the population will begin growing in the near future, and plans for commercial harvest of precious coral (gorgonians that are polished into jewelry) near monk seal colonies have raised concern over impacts to seal populations.

These solitary animals may have been so named for their lonely "monk-like" existence, but the Hawaiian name "*ilio-holo-kai*," has a much more colorful translation: "the dog that runs in the sea." They are often found alone making it difficult for researchers to learn what they need to know about the seals' biology in order to enhance their recovery. At FFS, where the largest island population of monk seals is found, scientists have observed poor survivorship and emaciation of young and mature seals over the past decade, prompting the suggestion that prey availability at the atoll may have declined and seals are starving. Certainly, declines in key prey species such as lobster have occurred due to fishing.

Although the state of Hawaii and the National Oceanic and Atmospheric Administration (NOAA) Fisheries actively manage the harvest of several species of precious corals, including black corals (*Antipathes* spp.), red and pink corals (*Corallium* spp.), and gold corals (*Gerardia* spp.; see Figure 2 on page 11), the occurrence of precious coral beds is patchy and the distribution of the beds is poorly known. Fish are attracted to and shelter within the beds, including some species of eels that commonly associate with the largest deep-sea corals. Seals may be seeking out coral beds to feed on resident fish, thus improving their feeding success and justifying the energetic investment of deep foraging. With ages of corals ranging to potentially hundreds of years, harvest of large coral colonies could alter habitat for

decades and perhaps make prey less accessible to foraging seals. Managers and industry have worked together to amend harvest regulations to protect the seals' forage habitat. A ban on the use of nonselective harvest gear and the preservation of some identified coral stands were some of the regulations proposed to maintain the seal's access to its forage base. Thus, the fates of endangered monk seals and precious corals are intertwined, as there is hope that protecting the corals will benefit the seals and vice versa.

LANCE E. MORGAN, PH.D. is Chief Scientist for Marine Conservation Biology Institute (MCBI).

FURTHER READING

Parrish F. A., K. Abernathy, G.J. Marshall and B.M. Buhleier (2002), "Hawaiian Monk Seals (*Monachus schauinslandii*) Foraging in Deep-Water Coral Beds." *Marine Mammal Science* 18(1):244-258.

PHOTO CREDIT:

Page 12: Courtesy of Jennifer Palmer, NMFS (MMP #848-1335), USFW



A monk seal pup in Hawaii.

ACTIVITY: LEAVING HOME

FOCUS

Dispersal of benthic invertebrate larvae

GRADE LEVEL

5-6 (Life Science)

FOCUS QUESTION

How can scientists study dispersal mechanisms of invertebrate larvae in the marine environment, and what is the importance of these mechanisms to benthic invertebrate populations?

LEARNING OBJECTIVES

Students will be able to explain the meaning of “larval dispersal” and “larval retention.”

Students will be able to explain the importance of larval dispersal and larval retention to populations of organisms in the marine environment.

Given data on recruitment of organisms to artificial substrates, students will be able to draw inferences about larval dispersal in these species.

MATERIALS

- Copies of “Recruitment to Artificial Substrates Near Bear Seamount,” one copy for each student or student group (see pages 16-17 for a copy)

AUDIO/VISUAL MATERIALS

None

TEACHING TIME

One 45-minute class period

SEATING ARRANGEMENT

Classroom style or groups of 3-4 students

MAXIMUM NUMBER OF STUDENTS

30

KEY WORDS

Seamount	Larval dispersal
New England Seamounts	Larval retention
Endemic	Recruitment

BACKGROUND INFORMATION

Seamounts are undersea mountains that rise from the ocean floor, often with heights of 3,000 m (10,000 ft) or more. Compared to the surrounding ocean waters, seamounts have

high biological productivity, and provide habitats for a variety of plant, animal, and microbial species. Seamounts are formed by volcanic processes, either as isolated peaks or as chains that may be thousands of miles long. In the Atlantic Ocean, the New England Seamounts form a chain of more than 30 peaks that begins on the southern side of George’s Bank near the coast of New England and extends 1,600 km to the southeast. Some of the peaks are more than 4,000 m above the deep-sea floor—similar to the heights of major peaks in the Alps.

While several of the New England Seamounts were visited by geologists in 1974, until recently there has been little biological exploration of these habitats. Preliminary investigations in 2002 found numerous invertebrates, including cephalopods, crustaceans, and more than a hundred other species in 10 different phyla. These investigations also found more than 100 species of fishes, some of which are commercially important. Several species were previously unknown to science. In the summer of 2003, a team of scientists, educators, artists, and oceanographers participated in a cruise on the R/V *Atlantis* to explore some of these seamounts. The submersible *Alvin* was used to visit areas whose depths ranged from 1,100 m to 2,200 m. Photographic images as well as samples of living organisms were collected.

Biological communities in the vicinity of seamounts are important for several reasons. High biological productivity has been documented in seamount communities, and these communities are directly associated with important commercial fisheries. Unfortunately, some of these fisheries cause severe damage to seamount habitats through the use of commercial fishing trawls. Scientists at the First International Symposium on Deep-Sea Corals (August, 2000) warned that more than half of the world’s deep-sea coral reefs have been destroyed. Ironically, some scientists believe that destruction of deep-sea corals by bottom trawlers is responsible for the decline of major fisheries such as cod. Besides their importance to commercial fisheries, seamount communities are likely to contain significant numbers of species that may provide drugs that can directly benefit human beings (see Maxwell, this issue, for more).

Because seamounts are relatively isolated from each other, they can vary greatly in their biodiversity (the number of different species present) and may also have a high degree of endemism (species endemic to seamounts are species that are only found around seamounts). Biodiversity and endemism are both affected by the reproductive strategy used by benthic seamount species. Most benthic marine invertebrates produce free-swimming or floating planktonic larvae that can be carried for many miles by ocean currents until the larvae settle to the bottom and change (metamorphose) into juvenile animals that usually resemble adults of the species. The advantage

of a longer larval phase is it allows for greater dispersal, which gives the species a wider geographic range. On the other hand, although species with shorter larval stages do not have the advantage of broad dispersal, they are more likely to remain in favorable local environments. Some species do not have a free larval stage at all, but brood their larvae inside the adult animal or in egg cases until metamorphosis.

Other forces may also tend to keep larvae from drifting away. Eddies known as Taylor columns can effectively trap larvae that would otherwise be carried away [see the "Extensions" section for website to access "Round and Round" lesson plan of the 2003 Mountains in the Sea Expedition for more information on Taylor columns].

To protect seamount communities, it is essential to understand the reproductive strategies used by benthic seamount species. This is one of the focal points of the Ocean Exploration 2004 Mountains in the Sea Expedition. During the 2003 expedition, scientists deployed blocks of basalt rock within an aggregation of deep-water corals on the Manning Seamount and at a location approximately 50 m outside the aggregation. These blocks provide artificial surfaces on which larval corals may settle. These blocks were recovered during the 2004 expedition and examined for young corals to obtain some insight on the distances coral larvae are transported from parent colonies. In this activity, students will analyze data from a similar experiment, and draw inferences about the reproductive strategy of species that are found on the artificial surfaces.

LEARNING PROCEDURE

1. Explain that seamounts are the remains of underwater volcanoes, and that they are islands of productivity compared to the surrounding environment. Although seamounts have not been extensively explored, expeditions to seamounts often report many species new to science and many that appear to be endemic to a particular group of seamounts. Point out that seamounts are relatively isolated, and explain the meaning of endemic species.

Discuss ways in which planktonic larvae may affect the distribution of species, and ask students to infer advantages and disadvantages that might be associated with a long or short larval phase. Introduce the terms "larval dispersal" (scattering larvae away from parent animals) and "larval retention" (keeping larvae close to the parent animals). Ask students what other factors might affect transport of planktonic larvae. Tell students that scientists refer to the process in which new individuals enter a community as recruitment, and that their assignment is to analyze data on recruitment of several species to artificial substrates, and draw inferences about the reproductive strategies used by these species.

2. Provide each student or student group with a copy of "Recruitment to Artificial Substrates Near Bear Seamount."

Note that these are simulated data, since the actual experiment at Manning Seamount has not been completed.

Have each student or student group summarize the data from the artificial substrates:

- a. Count the number of individuals of each species recruited to each plate.
 - b. Calculate the mean number of individuals of each species recruited for each of the five distances from the benthic community.
 - c. Graph the mean number of individuals of each species recruited (y-axis) as a function of distance from the benthic community (x-axis).
3. Lead a discussion of students' results. Students should realize that larvae of *Metallogorgia* corals were recruited to plates 30 m - 100 m from the benthic community, and this suggests that larval retention may be an important part of the reproductive strategy for these corals. More larvae of *Acanthogorgia*, on the other hand, were recruited to plates 200 m from the benthic community, suggesting that dispersal may be an important part of reproductive strategy of these corals, though they were still relatively close to the parent animals. Very few larvae of *Paragorgia* were recruited to any of the artificial surfaces. This may suggest that dispersal is the primary reproductive strategy for these corals, but there are several other possible explanations as well: perhaps these corals didn't produce as many larvae as the other two genera, or maybe the larvae of *Paragorgia* simply didn't like the artificial surfaces and settled elsewhere. Ask students what sort of experiments they could design to get a better picture of the reproductive strategy of *Paragorgia*.

THE BRIDGE CONNECTION

An interactive activity involving crustacean larvae:
<http://www.vims.edu/bridge/crustacean.html>

THE "ME" CONNECTION

Have students write a short essay in which they imagine they are a coral larva, state whether they would like to have a reproductive strategy that emphasized dispersal or retention, and explain the reasoning behind their choice.

CONNECTIONS TO OTHER SUBJECTS

English/Language Arts, Physical Science

EVALUATION

Data summaries and group discussions offer opportunities for evaluation.

EXTENSIONS

Have students visit <http://oceanexplorer.noaa.gov> to find out more about the 2004 Mountains in the Sea Expedition, and about opportunities for real-time interaction with scientists on current Ocean Exploration expeditions.

RESOURCES

Seamounts website sponsored by the National Science Foundation:

<http://seamounts.edsc.edu/main.html>

Brink, K. H. 1995. Tidal and Lower Frequency Currents Above Fieberling Guyot. *J. of Geophysical Research*, 100:10,817-10,832; and Mullineaux, L. S. and S. W. Mills. 1997. A test of the larval retention hypothesis in seamount-generated flows. *Deep-Sea Research* 44:745-770. A technical journal article about larval dispersal on a seamount

NATIONAL SCIENCE EDUCATION STANDARDS

Content Standard A: Science As Inquiry

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

Content Standard B: Physical Science

- Motions and forces

Content Standard C: Life Science

- Populations and ecosystems
- Diversity and adaptations of organisms

Content Standard F: Science in Personal and Social Perspectives

- Populations, resources, and environments

FOR MORE INFORMATION

Paula Keener-Chavis, National Education Coordinator/Marine Biologist
NOAA Office of Exploration
2234 South Hobson Avenue
Charleston, SC 29405-2413
843.740.1338
843.740.1329 (fax)
paula.keener-chavis@noaa.gov

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STUDENT HANDOUT

Recruitment to Artificial Substrates Near Bear Seamount

These diagrams illustrate young corals that were found on a series of artificial substrates deployed for one year in the vicinity of Bear Seamount. The artificial substrates were flat plates of basalt rock measuring 20 cm x 20 cm. The plates were distributed at different distances from a benthic community containing three genera of deep-water corals: *Metallogorgia*, *Acanthogorgia*, and *Paragorgia*

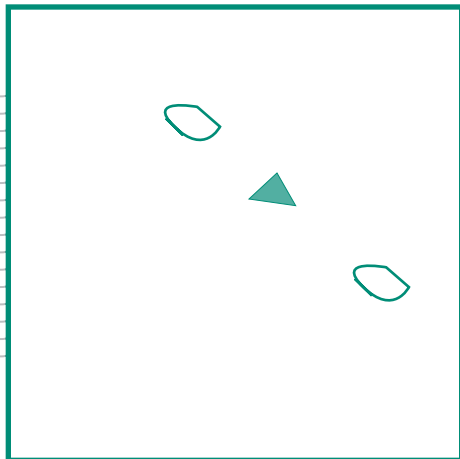


Plate #3241
Distance from benthic community: 3 m

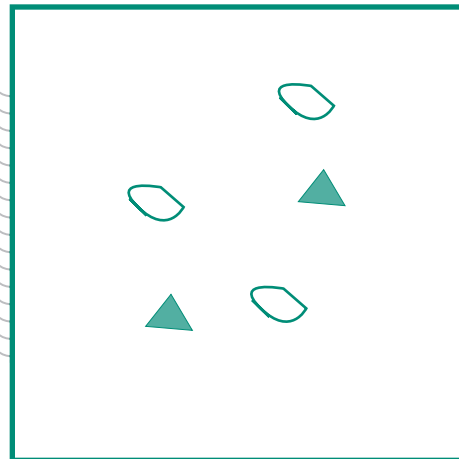


Plate #3242
Distance from benthic community: 3 m

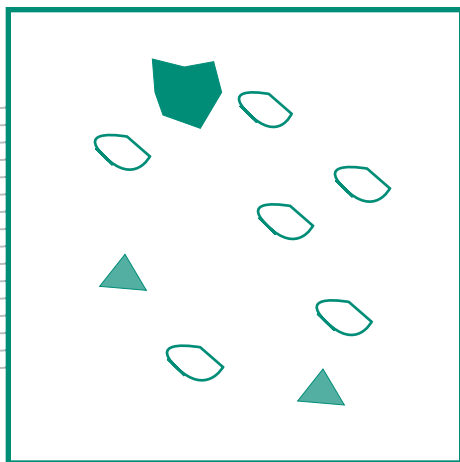


Plate #3243
Distance from benthic community: 30 m

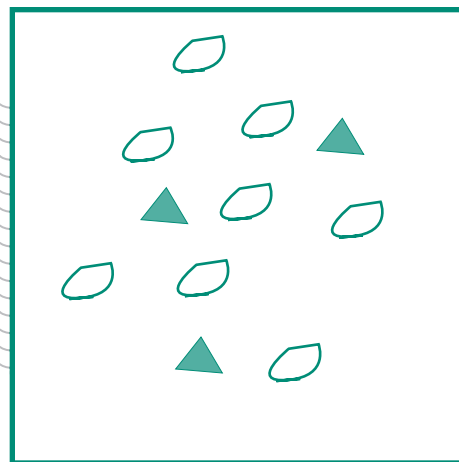


Plate #3244
Distance from benthic community: 30 m

Key

 <i>Metallogorgia</i>	 <i>Acanthogorgia</i>	 <i>Paragorgia</i>
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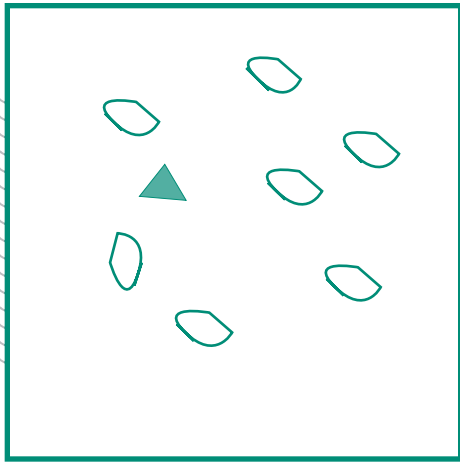


Plate #3245
Distance from benthic community: 100 m

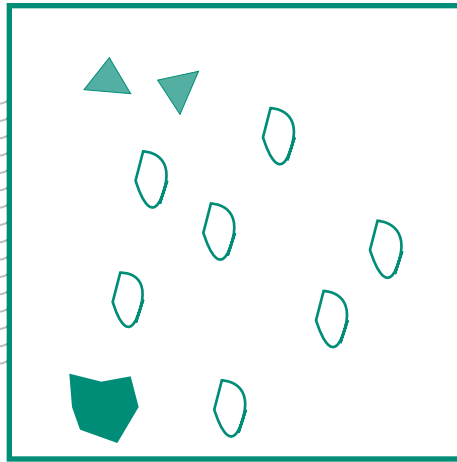


Plate #3246
Distance from benthic community: 100 m

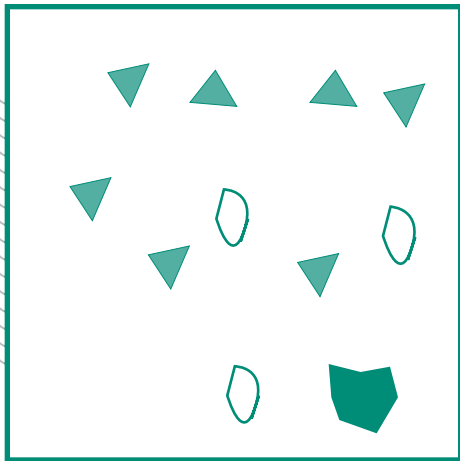


Plate #3247
Distance from benthic community: 200 m

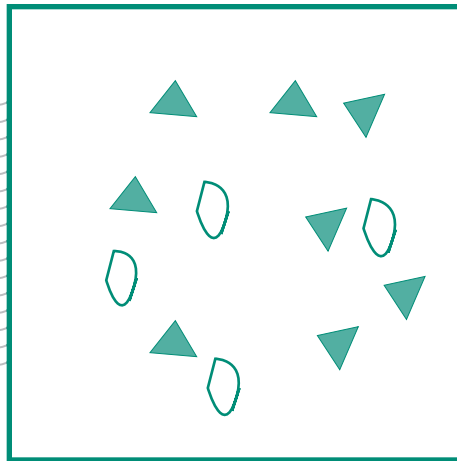


Plate #3248
Distance from benthic community: 200 m

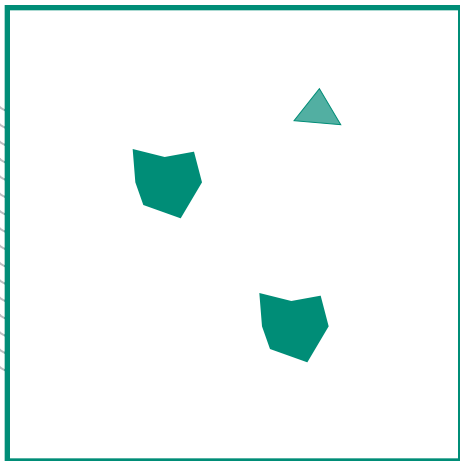


Plate #3249
Distance from benthic community: 500 m

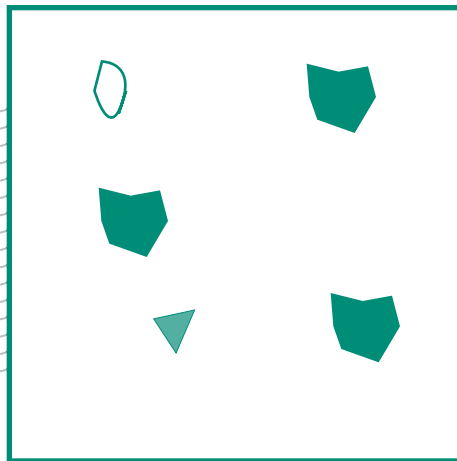


Plate #3250
Distance from benthic community: 500 m

EXPLORING DEEP-SEA CORAL HABITAT ON THE EDGE —ALASKA'S ALEUTIAN ISLANDS

BY ROBERT P. STONE

INSPIRED BY DIVERSE CORAL BYCATCH SPECIMENS collected during commercial fisheries in the Aleutian Islands of Alaska, fisheries researchers launched a three-year quest to see firsthand the seafloor that was yielding such a bounty of corals. Scientists knew that working in one of the most remote places on Earth would be challenging, but armed with a durable manned submersible and a deep diving remotely operated vehicle (ROV), they discovered some of the most spectacular cold-water coral habitat ever seen. Although findings from this research are only now coming to light, fisheries managers recently took a major step to protect coral habitat by planning to close more than 75,000 km² of the area's fishing grounds to bottom trawling.

The first biological expeditions to the Aleutian Islands more than a century ago returned with a diverse collection of coral fauna. Benthic ecologists, however, paid little attention to this region of Alaska until they became intrigued by more recent collections of deep-sea corals. Corals are widespread on the continental shelf and slope throughout Alaska, but there is strong evidence that a significant shift in coral abundance and species diversity occurs west of the Alaska Peninsula (Heifetz et al., in press). When scientists examined collected coral specimens, they realized the Aleutian Islands might harbor the highest diversity of cold-water corals in the world and that at least 25 species or subspecies of hydrocorals and gorgonians were endemic (Heifetz et al., in press).

The National Marine Fisheries Service (NMFS, also known as NOAA Fisheries) estimates that more than 81 metric tons of coral is removed from the seafloor each year by commercial fishing activities in Alaska (NMFS, 2004). More than 90 percent of this coral bycatch occurs in the Aleutian Islands and Bering Sea. Studies of coral specimens collected as bycatch during the golden king crab fishery in the Aleutian Islands have prompted major taxonomic revisions and the publication of a field guide to assist fishery observers with onboard coral identifications (Wing and Barnard, 2004). The bycatch data clearly indicated

to scientists that there is a significant interaction between coral habitat and fisheries using bottom-contact gear.

Until recently, scientists' limited knowledge about deep-sea corals in the Aleutian Islands was based almost entirely on fisheries bycatch data. Bycatch data provide useful information at the large scale of existing fisheries, but don't answer questions about how corals are integrated into the overall seafloor landscape. How are corals distributed relative to depth and existing fisheries? Are there reserves of deep-sea corals in areas and at depths where fisheries do not presently occur? Are commercially targeted species of fish and crab associated with coral habitat? Scientists seek answers to these basic questions so as to develop effective measures for minimizing adverse effects of fishing activities on this fragile habitat—actions that are required under the essential fish habitat provision of the Magnuson-Stevens Fishery Conservation and Management Act.

THE ALEUTIAN ISLANDS—A REFUGE FOR DEEP-SEA CORALS?

The Aleutian Archipelago spans more than 1,900 km and extends from the Alaska Peninsula to the Kamchatka Peninsula in Russia (Figure 1). The archipelago is supported by the Aleutian Ridge that forms the boundary between the deep North Pacific Ocean and the shallower Bering Sea. Strong tidal currents through island passes exchange water and nutrients between the two water bodies. The Aleutian Ridge is a volcanic arc that was formed along zones of convergence between the North American Plate and other oceanic plates, and is the site of more than 20 active volcanoes and frequent earthquake activity. This combination of unique geological and oceanographic features provides three ingredients essential for deep-sea corals: exposed rock substrate, plankton- and nutrient-rich waters, and strong currents.

The geographical remoteness of the Aleutian Islands provided a *de facto* haven for deep-sea corals until fisheries fully developed there in the 1960s. The Aleutian Islands and the

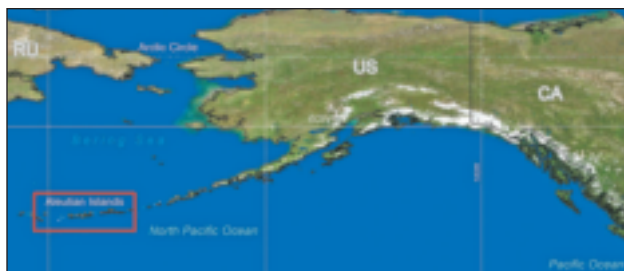


Figure 1. Map of the North Pacific Ocean and the Aleutian Island Archipelago. The coral study area is located in the central Aleutian Islands (see red box in map).



Figure 2. Deep-sea gorgonians and demosponges are two common groups found in coral gardens in the Aleutian Islands.

neighboring Bering Sea now support some of the largest groundfish fisheries in the world. Major fisheries using four types of bottom-contact gear currently exist and continue to proliferate to deeper waters and more remote areas—a trend that is worldwide. Non-pelagic trawl fisheries target many species such as walleye pollock (*Theragra chalcogramma*), Pacific cod (*Gadus macrocephalus*), Atka mackerel (*Pleurogrammus monopterygius*), and rockfish (*Sebastes* spp.). Longline fisheries target Pacific cod, sablefish (*Anoplopoma fimbria*), Pacific halibut (*Hippoglossus stenolepis*), and other species of flatfish. Pot fisheries target Pacific cod, sablefish, and golden king crabs (*Lithodes aequispinus*). These fisheries are distributed at depths from 27 m to about 1,000 m, but most effort occurs at depths shallower than 200 m.

ALEUTIAN CORALS—FIRST GLIMPSES IN 2002

NMFS scientists first visited the Aleutian Islands specifically to study coral habitat in 2002. They chose the central Aleutian Islands as the study site because they believed that coral distribution, coral diversity, and fishing effort there were most representative of the entire archipelago. But also important was the fact that the Port of Adak, a major U.S. naval port until the mid-1990s, offers one of the few protected areas from which to mobilize submersible operations and to retreat when rough seas and strong tidal currents preclude safe operations.

Scientists used the submersible *Delta* to collect video footage of the seafloor along 25 transects throughout the Andreanof Islands and on Petrel Bank in the Bering Sea (Figure 1). The *Delta* is capable of diving to depths of 367 m. During the first expedition, scientists confirmed that corals are widespread, diverse, and abundant in some areas (Stone, in preparation). Corals were present on all transects and at depths between 27 and 363 m, but were most abundant at depths between 100 and 200 m. Coral abundance (1.23 colonies per m²) far exceeded that reported for other high-latitude ecosystems. Six major taxonomic groups of corals were present, but gorgonians and hydrocorals were the most abundant and diverse coral groups.

Scientists observed high-density coral gardens (3.85 colonies per m²), a previously undocumented habitat feature in the North Pacific Ocean, at seven locations in the study area (Figure 2). Although not true coral reefs and comprising only azooxanthellate (i.e., not containing symbiotic algae) corals, the gardens are similar in structural complexity to tropical reefs, sharing several important characteristics, including underlying support by a rigid framework, positive topographic relief, and high taxonomic diversity. Hydrocorals are a major structural component of the gardens and are often encrusted with sponges and stoloniferans. The platform they form provides an elevated feeding station for many species of sedentary and sessile invertebrates.



Figure 3. The submersible *Delta* was used to examine coral habitat at depths less than 367 meters.

Altogether, the vertical relief provided by the dense aggregation of invertebrates may exceed several meters.

The first submersible observations also provided important insights into habitat requirements of corals, fish and invertebrate associations with corals, and into fishery interactions with deep-sea corals. Slope and offshore pinnacle habitats characterized by exposed bedrock, boulders, and cobbles generally supported the highest abundances of coral and fish. Overall, 84 percent of the commercially important fish and crabs were associated with corals and other sedentary structure-providing invertebrates. Disturbance to the seafloor from bottom-contact fishing gear was widespread—about 39 percent of the seafloor on transects had been disturbed. In total, 8.5 percent of the corals, mostly hydrocorals and gorgonians, were damaged.

DEEPER EXPLORATION IN 2003 TO 2004

Scientists from NMFS, Alaska Department of Fish and Game, the University of Alaska, and several other institutions returned to the central Aleutian Islands in 2003 and 2004 with the *Delta* (Figure 3), the deep diving remotely operated vehicle *Jason II* (Figure 4), and a rigorous study design that allowed for extrapolating findings on coral distribution to other areas of the Aleutians. The objective was to document coral habitat at 17 sites, chosen systematically, between Sequam Pass (174°W longitude) and Petrel Bank (180° longitude). Geologists mapped the seafloor at each site using multi-beam bathymetry and backscatter data, and then constructed habitat maps detailing substrate types and geological features. Video transects were selected to cover a broad depth range (between 30 and 3,000 m) and multiple habitat types at each site. The *Delta* was used to document coral habitat in areas less than 365 m deep, while the *Jason II* was used to document coral habitat in deeper waters—to almost 3,000 m and well below the depth of current fishing activities. The *Jason II*, owned and operated by the Woods

Hole Oceanographic Institution (WHOI), is capable of diving to a depth of 6,500 m.

Scientists are currently analyzing hundreds of hours of video footage collected during the 2003 to 2004 cruises. First, corals are identified and enumerated, and then for each coral, the depth, substrate type, seafloor roughness, seafloor slope, and percent coverage and vertical relief of other invertebrates are recorded. Researchers will model coral density using these variables—the models will ultimately be used to predict where corals are located throughout the Aleutian Islands based on known geographic features, depth, and substrate types.

Observations made during the deepwater *Jason II* cruise confirmed the presence of corals to depths of at least 3,000 m and showed that corals were most abundant and diverse in areas of exposed bedrock (Figure 5). Gradual changes in coral density, diversity, and species composition were evident at approximately 1,400 m, 800 m, and 400 m, with density and diversity increasing in magnitude from deep to shallow water. All seven major groups of corals found in Alaskan waters (hydrocorals, black corals, stony corals, gorgonians, true soft corals, pennatulaceans, and stoloniferans) were observed in deepwater areas. Contrary to expectations, scientists discovered that soft-bottom areas were not devoid of corals, but rather were colonized in some areas by extensive groves of sea pens and the gorgonian (*Radicipes*), which resembles “pigtailed.”

CONSERVATION AND MANAGEMENT

Recent emphasis on managing fisheries with an ecosystem approach, and protecting essential fish habitat, has sparked worldwide interest in the conservation of deep-sea corals. There is clear evidence worldwide, and now including the Aleutian Islands, that deep-sea corals are an important component of benthic ecosystems, but are also fragile and easily damaged by contact with fishing gear. Many species of



Figure 4. The remotely operated vehicle, *Jason II* was used to examine coral habitat at depths between 367 and 3000 meters.



Figure 5. Most deep-sea corals in the Aleutian Islands are located in areas of exposed bedrock. In this photo, a shortspine thornyhead (*Sebastolobus alascanus*) and a golden king crab (*Lithodes aequispina*) rest on a bedrock ledge colonized by hydrocorals and gorgonians at a depth of 727 meters.

fish and invertebrates, especially juveniles, use coral habitat as refuge and focal areas for other important life processes. The North Pacific Fisheries Management Council took a major precautionary step in 2005 when they closed more than 75,000 km² of the fishing grounds in the Aleutian Islands to bottom trawling. Six additional areas totaling 377 km², where coral gardens were discovered during the first *Delta* survey, were closed to all bottom-contact fishing gear. These closures are the result of several years of pioneering research in a remote part of the globe, compromise between stakeholders who share the area's benthic resources, and the foresight of fisheries managers in preserving a unique ocean habitat (see Frame and Gillelan, this issue, for more).

ROBERT P. STONE is a fishery research biologist at the National Marine Fisheries Service's Auke Bay Laboratory in Juneau, Alaska. He has studied seafloor habitat in Alaska for the past 20 years and has recently led four research cruises to the Aleutian Islands to study deep-sea corals.

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FOR MORE RESOURCES:

Alaska Fisheries Science Center:

<http://www.afsc.noaa.gov/abl/MarFish/geareffects.htm>

Exploring Corals of the Aleutian Seas:

<http://www.alaskascienceoutreach.com/coralsite/index.html>

Voyage to the Aleutian Islands: Understanding Alaska's Deep Sea Frontiers:

http://www.oar.noaa.gov/spotlite/spot_aleutian.html

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Page 20 (top): Courtesy of Patrick Malecha

Page 20 (bottom): Courtesy of Sean Rooney

DEEP-SEA CORALS ARE LONG-LIVED HISTORIANS

BY FAN TSAO

UNDERWATER "CORAL FORESTS" *have more in common with ancient terrestrial forests than you might think. Red-tree coral (*Primnoa resedaeformis*) colonies that now offer refuge for fishes in Alaskan waters began to grow when Emily Dickinson and Walt Whitman were writing poems, and before Theodore Roosevelt became President more than 100 years ago (Andrews et al., 2002). The oldest known deep-water corals, gold corals (*Gerardia* spp.) growing off Florida, can live up to 1,800 years, making them older than most trees other than giant sequoias and bristlecone pines (Druffel et al., 1995). Living in a low-temperature and low-disturbance environment, all deep-sea corals are slow growing and long lived. Even those that don't survive for millennia can live to two, five, even 10 times the human lifespan. In coral reefs along the Southeastern U.S., *Lophelia pertusa* that began growing 700 years ago still thrive at the top of the reef, while dead coral rubble nearby is more than 20,000 years old.*

The rate at which individual corals and their colonies grow depends on a variety of factors, including food supply. The same species can grow at different rates in different locations. The red-tree coral in Alaska, for instance, grows about two centimeters per year, about 10 times as fast as the same species in the Atlantic (Andrews et al., 2002). At this rate, it still took one colony in Alaska 112 years to reach a height of two meters. Growth rate also varies from one species to another. The growth rate of *Desmophyllum cristagalli*, a scleractinian coral, ranges from 0.1 to 3.1 mm/year (Cheng et al., 2000), and *Oculina varicosa* and *L. pertusa* both extend approximately 1.6 cm each year (Reed, 2002).

Like trees, deep-sea corals form growth rings. The pattern of these concentric bands is affected by the coral's physiological rhythm, food supply, sediment influx, and other factors. The generation of growth rings tends to have an annual pattern (Figure 1), but some corals also form sub-annual bands. Counting the rings under a scanning electron microscope is one of the methods used to determine the age of a coral. Other methods include: analyzing the ratios of stable isotopes of such elements as carbon and oxygen, examining the amount of radioactive carbon in the coral, and assessing the ratio of radioactive isotopes of lead, thorium, uranium, or radium in the coral specimen. Scientists generally use a combination of these techniques to age the specimen and validate the age. Depending on the characteristics of the coral, some techniques work better than others. For example, the growth ring counting method is more suitable for dating bamboo coral than other gorgonian corals because bamboo coral has low organic content and hence does not interact with the fixatives used in this method, and this yields a clearer result (Sanchez, 2004).

Over the long life of a coral, its growth pattern also records information on how ocean chemistry and even global climate have changed. Methods to read these archives are still being perfected, but exciting progress has been reported in recent years. Researchers analyzed *D. cristagalli* fossils collected off Newfoundland and found a sudden change in one specimen's isotopic composition over its lifetime as well as a major difference between this specimen and other specimens that lived at different times, but in the same region. This pattern is a signal of a rapid climate change—the initiation of the Younger Dryas cooling event—a mini ice-age which took place 13,000 years ago (Smith et al., 1997). As scientists continue to develop techniques to accurately determine the age and growth rate of deep-sea corals and to interpret the changes in corals throughout their lives, corals will help reconstruct high-resolution time series of growth, temperature, and ocean chemistry at great depths beneath the sea.

FAN TSAO is Conservation Scientist at Marine Conservation Biology Institute (MCBI). She received her master's degree in Marine Affairs from the University of Washington, where she studied the natural and social sciences pertaining to marine conservation.

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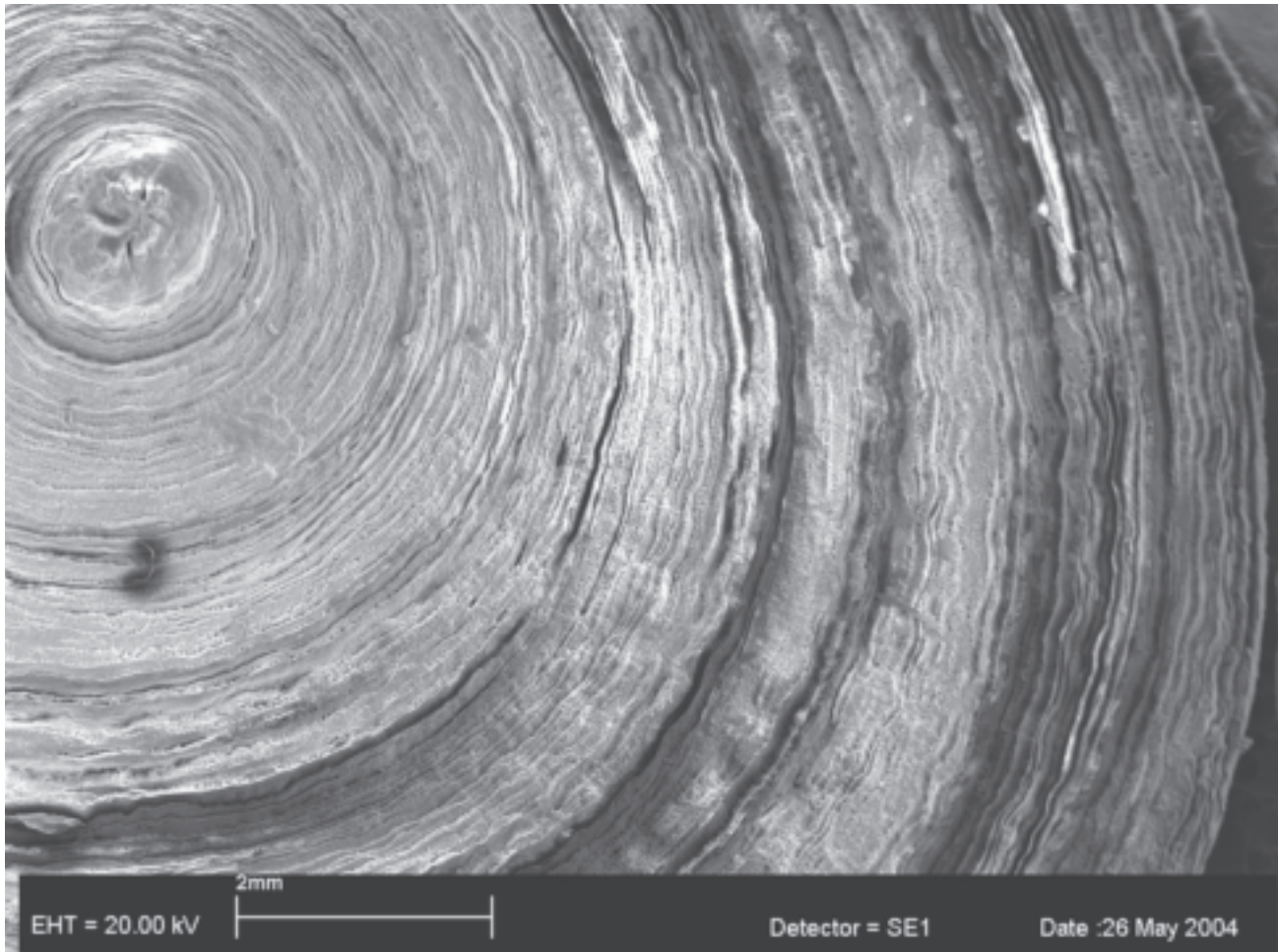


Figure 1. Growth rings of bamboo coral (family Isididae).

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PHOTO CREDIT:

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ACTIVITY: HISTORY'S THERMOMETERS

FOCUS

Paleoclimatological proxies

GRADE LEVEL

9-12 (Physics)

FOCUS QUESTION

How can deep-water corals be used to determine long-term patterns of climate change?

LEARNING OBJECTIVES

Students will be able to explain the concept of paleoclimatological proxies.

Students will learn how oxygen isotope ratios are related to water temperature.

Students will be able to interpret data on oxygen isotope ratios to make inferences about climate and climate change in the geologic past.

ADDITIONAL INFORMATION FOR TEACHERS OF DEAF STUDENTS

In addition to the words listed as Key Words, the following words should be part of the vocabulary list.

Seamounts	Microbial species
Habitats	Deep sea corals
Reefs	Fisheries
Carbonate ions	Oxygen isotopes
Proxies	Rare oxygen isotope
Common oxygen isotope	Delta values
D (x)	Productivity

These words are integral to the unit but will be very difficult to introduce prior to the activity. They are really the material of the lesson. There are no formal signs in American Sign Language for any of these words and many are difficult to lipread. If some of this information has not already been covered in your class, you may need to add an additional class period to teach vocabulary and teach some of the Background Information to the students prior to the activity. Having the vocabulary list on the board as a reference during the lesson will be extremely helpful.

Going to the BRIDGE website before the activity to obtain pictures of corals will be extremely helpful. If you also have pictures of cross-sections of tree trunks showing annual growth rings, you can show both and compare so that the students have a visual connection for the activity.

The "Me" connection activity is excellent to use as an evaluation tool.

MATERIALS

- Copies of "Oxygen Isotope Ratios in Deep-water Coral Samples," enough for each student or student group (see page 26 for a copy)

AUDIO/VISUAL MATERIALS

None

TEACHING TIME

One 45-minute class period

SEATING ARRANGEMENT

Classroom style, or groups of two or three students

MAXIMUM NUMBER OF STUDENTS

No limit, if students work individually

KEY WORDS

Paleoclimatological proxy	Isotope
$\delta^{18}\text{O}$	Deep-water coral

BACKGROUND INFORMATION

Seamounts are undersea mountains that rise from the ocean floor, often with heights of 3,000 m (10,000 feet) or more. Compared to the surrounding ocean waters, seamounts have high biological productivity, and provide habitats for a variety of plant, animal, and microbial species. Numerous seamounts have been discovered in the Gulf of Alaska. Many of these seamounts occur in long chains that parallel the west coast of the U.S. and Canada. One of the longest chains, known as the Axial-Cobb-Eikelberg-Patton chain, is being intensively studied by the Ocean Exploration 2002 Gulf of Alaska Expedition.

Several researchers on the Expedition are studying deep-sea corals. These animals have a hard skeleton like the familiar tropical reef corals, and often form branched shapes resembling trees or fans. Like their warm-water relatives, deep-sea corals form reefs and provide habitat to numerous other species. Besides being important to commercial fisheries, these corals are also of interest to scientists studying the Earth's long-term climate patterns. Deep-sea corals build their skeletons from calcium and carbonate ions that they extract from sea water. Oxygen and oxygen isotopes contained in the carbonate ions, as well as trace metals that are also incorporated into the corals' skeleton, can be used to determine the temperature of the water when the skeleton was formed. Because some corals live for many years (decades or even centuries), their

skeletons contain a natural record of climate variability. Natural recorders are known as proxies, and include tree rings, fossil pollen, and ice cores in addition to corals.

When studying temperature records in proxies, we are usually interested in the ratio of the rare oxygen isotope ^{18}O to the common oxygen isotope ^{16}O . Because the absolute abundance of an isotope is difficult to measure with sufficient accuracy, the isotope ratios in a sample are compared with those in a standard, and the results are expressed as delta values, abbreviated $\delta(x)$ which is found by subtracting the isotopic ratio of the standard from the isotopic ratio of the sample, dividing the result by the ratio of the standard, and multiplying the 1,000 to give a result in parts-per-thousand (‰; also called “parts-per-mille”). Scientists have found that the ratio of oxygen isotopes in carbonate samples is inversely related to the water temperature at which the carbonates were formed, so high ratios of ^{18}O mean lower temperatures. In the simplest case, a temperature change of 4°C corresponds to a $\delta^{18}\text{O}$ of about 1‰.

Ocean temperature changes are known to have significant effects on climate and weather (e.g., El Niño), but these relationships are not generally well-understood. One of the first steps to improving our understanding of these interactions is to document variations that have occurred in the past. Comparing climatic conditions at different times in the past gives important information about rates of climate change. One of the major concerns associated with the prospect of global warming is that this climate change may be happening much more quickly than has been the case in the Earth’s past. If this proves to be true, many organisms and living systems may have difficulty adapting to an unusually rapid rate of change.

LEARNING PROCEDURE

1. Explain that seamounts are the remains of underwater volcanoes, and that they are islands of productivity compared to the surrounding environment. Point out that these undersea mountains can be quite steep, and provide unusual habitats for marine organisms. Discuss the deep-sea corals that are relatively common on seamounts, and be sure that students realize that these animals produce skeletons from calcium carbonate, and continue to grow and add to these skeletons throughout their lives. Explain the concept of climatological proxies, perhaps drawing an analogy to tree rings. Be certain that students understand the concept of isotopes, and explain that the ratio of oxygen isotopes varies with temperature. When oxygen, in both of its isotopic forms, is precipitated in the coral skeleton as calcium carbonate, a record is formed of the temperature at the time of precipitation. Be sure students understand that a temperature change of 4°C corresponds to a $\delta^{18}\text{O}$ of about 1‰.
2. Distribute copies of “Oxygen Isotope Ratios in Deepwater Coral Samples.” Have students or student groups plot these ratios as a function of age ($\delta^{18}\text{O}$ on the y-axis). Ask students to explain their results. They should recognize that corals 1,

3, and 4 grew during a period in which water temperatures were relatively low (as would be the case during periods of glaciation), while corals 2 and 6 grew in warmer conditions.

Coral 5 exhibits significantly different $\delta^{18}\text{O}$ in different portions of its skeleton. Have the students examine the data further to determine that the difference in $\delta^{18}\text{O}$ between two samples only 3 mm apart on the coral skeleton indicates that this coral experienced a rapid cooling of about 6°C in the space of less than 5 years. Discuss how this might have happened. Evidence for such an event has been reported, and interpreted to be linked to a rapid climate shift, the Younger Dryas cooling event which took place 13,000 to 11,700 years ago. Discuss the significance of rapid versus gradual changes to biological communities.

THE BRIDGE CONNECTION

Go to Ocean Science Topics, then Ecology, then Corals for general information about corals:

www.vims.edu/bridge

THE “ME” CONNECTION

Have students write a paragraph on how global climate change would affect their personal lives.

CONNECTIONS TO OTHER SUBJECTS

English/Language Arts, Chemistry, Mathematics, Biology

EVALUATION

If individual evaluations are desired, have students write their interpretations of the data prior to the group discussion.

EXTENSIONS

Have students visit <http://oceanexplorer.noaa.gov> to keep up to date with the latest Gulf of Alaska Expedition discoveries.

RESOURCES

Follow the Gulf of Alaska Expedition daily as documentaries and discoveries are posted each day for your classroom use. A wealth of information can also be found at this site:

<http://oceanexplorer.noaa.gov>

Very readable lecture notes on isotopes in paleoclimatology:

<http://ethomas.web.wesleyan.edu/ees123/>

NOAA site on paleoclimatology, with links to many other resources:

<http://www.ngdc.noaa.gov/paleo>

Science education resources:

<http://www.sciencegems.com>

References on just about everything:

<http://www-sci.lib.uci.edu/HSG/Ref.html>

Smith, J. E., M. J. Risk, H. P. Schwarcz, and T. A. McConnaughey, 1997. Rapid climate change in the North Atlantic during the Younger Dryas recorded by deep-sea corals. *Nature* 386:818-820. (The research paper on which this activity is based)

NATIONAL SCIENCE EDUCATION STANDARDS

Content Standard A: Science as Inquiry

- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

Content Standard B: Physical Science

- Structure of atoms

Content Standard F: Science in Personal and Social Perspectives

- Natural and human-induced hazards

FOR MORE INFORMATION

Paula Keener-Chavis, National Education
Coordinator/Marine Biologist
NOAA Office of Exploration
Hollings Marine Laboratory
331 Fort Johnson Road, Charleston SC 29412
843.762.8818
843.762.8737 (fax)
paula.keener-chavis@noaa.gov

ACKNOWLEDGEMENTS

This lesson plan was produced by Mel Goodwin, Ph.D., The Harmony Project, Charleston, South Carolina for the National Oceanic and Atmospheric Administration. If reproducing this lesson, please cite NOAA as the source, and provide the following URL:
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STUDENT HANDOUT

Oxygen Isotope Ratios in Deep-water Coral Samples

Coral Specimen	$\delta^{18}\text{O}$ (‰)	Age (years)
#1, base of coral	3.8	15,140
#1, 50 mm from base	3.9	
#1, 200 mm from base	4.5	
#1, 400 mm from base	4.1	15,550
#2, base of coral	0.8	3,100
#2, 70 mm from base	0.9	
#2, 220 mm from base	1.1	
#2, 450 mm from base	1.0	3,410
#3, base of coral	4.1	15,400
#3, 100 mm from base	4.3	
#3, 200 mm from base	3.9	
#3, 300 mm from base	4.1	15,695
#4, base of coral	4.5	14,445
#4, 75 mm from base	4.1	
#4, 150 mm from base	3.9	
#4, 300 mm from base	4.0	14,800
#5, base of coral	1.7	13,300
#5, 80 mm from base	1.8	
#5, 85 mm from base	3.3	
#5, 100 mm from base	3.6	13,400
#6, base of coral	1.3	6,400
#6, 100 mm from base	1.5	
#6, 155 mm from base	1.6	
#6, 400 mm from base	1.4	6,675

CHRISTMAS TREE CORALS: A NEW SPECIES DISCOVERED OFF SOUTHERN CALIFORNIA

BY MARY YOKLAVICH AND MILTON LOVE

A NEW SPECIES OF BLACK CORAL was discovered off southern California. The Christmas tree coral (*Antipathes dendrochristos*) was observed from the two-person submersible *Delta* during surveys of benthic fishes on deep rocky banks offshore of Los Angeles. This species forms bushy colonies that grow to three meters in height and width and resemble pink, white, gold, and red-flocked Christmas trees. Christmas tree corals can harbor diverse biological assemblages but were rarely associated with fishes, at least during our daylight surveys. Until our surveys, the occurrence of deep-water black corals off southern California was completely unknown to science. The discovery of the Christmas tree coral clearly demonstrates how much there is yet to learn about marine communities on the seafloor, even along the most populated sections of the west coast.

DISCOVERY

As astonishing as it sounds, colonies of a new species of black coral (Figure 1), sometimes up to 10 feet in height, have managed to grow unnoticed practically in the backyard of the 10 million residents in the greater Los Angeles, California area—until now. We first discovered the Christmas tree coral (*Antipathes dendrochristos*) in 1995 while surveying fishes on deep rocky banks using the two-person submersible *Delta* about 40 miles offshore from Los Angeles. A few specimens and many digital images of the unknown coral were collected in 2002 and recently used to publish a description of this new species (Opresko, 2005).

The Christmas tree coral is a colonial Cnidarian (this phylum includes familiar jellyfishes, sea anemones, sea fans and pens, as well as black corals), in the order Antipatharia and

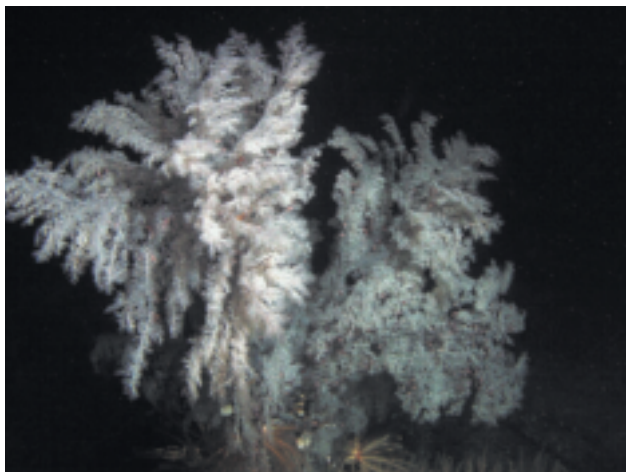


Figure 1. The white color variant of the Christmas tree coral, observed from the manned mini-submersible *Delta* during surveys on rocky banks off southern California in 150 meters water depth.

the genus *Antipathes* (from Latin and Greek, meaning against [anti-] feeling or suffering [pathos]). As fish biologists, we referred to these unknown organisms as “Christmas trees” when encountering them along our surveys. This is because they resembled multicolored, snow-flocked Christmas trees, replete with ornaments of barnacles, worms, shrimps, and crabs. When it came time to choose a scientific name for the new species, it seemed appropriate to call it *A. dendrochristos* (from Greek, meaning tree [dendro-] of Christ [christos]).

DESCRIPTION

Ascending from a substantial hold-fast that is secured to the seafloor, the bushy colonies of the Christmas tree coral are constructed as an upright, rigid black skeleton with multiple branches bearing thorns. While most colonies we have observed are small in height and width (10-50 cm), some have grown to three meters tall. The branchlets of the skeleton are almost completely covered in tiny polyps (Figure 2), which are soft, living organisms that secrete the calcium carbonate skeleton. These polyps are minute (1.0–1.4 mm in diameter), with tiny blunt tentacles arranged in radial symmetry. While most biological aspects of this species are as yet unknown, it has been proposed that the polyps feed at night, preying on planktonic organisms in the surrounding water. The polyps of black corals living around the Hawaiian Islands are known to bioluminesce when disturbed at night; it is unknown whether Christmas tree corals do the same.

These large graceful colonies occur in a variety of colors, including white, golden, pink-orange, red (Figure 3), and red-brown. It is unknown whether these color variants represent one or more species, and we are working with a molecular biologist to determine taxonomic relationships among the different colored colonies. The Christmas tree coral was differentiated from other species of *Antipathes* based on the arrangement, shape, and size of its branches, thorns, and individual polyps. While most



Figure 2. Close-up view of branchlets of the Christmas tree coral, which are completely covered by tiny living polyps.

members of this genus have been found in deep tropical waters, the Christmas tree coral resembles several species found off the southern tip of South America.

Since first noticing the Christmas tree corals, we have observed them living around some islands in the Channel Islands National Marine Sanctuary and on several offshore banks in the southern California Bight (Figure 4). Collectively during the past decade, we have made more than 300 dives (about 500 hours underwater) in the *Delta* mini-submersible on many of the major fishing banks off southern California. Our time underwater has been spent conducting a comprehensive survey of benthic fishes (Love et al., 2003), including over 50 species of rockfishes, along with their seafloor habitats, and associated macro-invertebrates (e.g., feather stars, basketstars, brittlestars, sea pens, sponges, corals, among other forms) at water depths of 25 to 330 m. We have covered a wide range of habitats, from sheer high-relief seamounts to low relief cobble fields and flat mud seafloor. While certainly the largest structure-forming invertebrate in our surveys, the Christmas tree coral is relatively uncommon and represents less than two percent of all macro-invertebrates in our study area (Tissot et al., in press). As many as 135 colonies were found to be narrowly distributed at depths from 90 to 300 m, primarily occurring on rocks, boulders, and cobbles mixed with sand and mud along the continental shelf. The colonies often seem to occur in isolated pairs that are separated at most by a few meters.

Like many other coral species, Christmas tree corals support a diverse biological assemblage. Most organisms associated with them are small and difficult to identify and count without collecting entire colonies. Our assessment of associated fauna, thus far, was based on direct observations from the submersible and accompanying videotapes, and from a few specimens collected serendipitously with pieces of the coral. High densities of stalked barnacles occur throughout the branches of many of the colonies. It appears that these

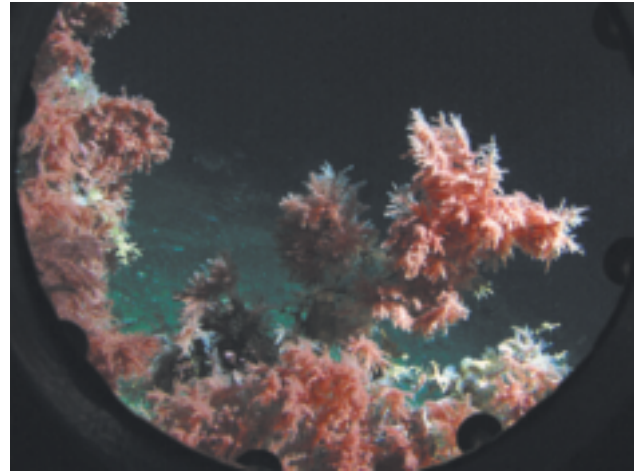


Figure 3. The red color variant of the Christmas tree coral, viewed through the porthole of the mini-submersible *Delta*, at a water depth of 200 meters.

barnacles are overgrown or encrusted by the soft tissue of the coral. A relatively large polychaete worm that resembles the coral polyps also lives among the many branchlets. This worm also is undescribed and likely represents an entirely new genus (personal communication with L. Harris, Los Angeles County Museum of Natural History). Large invertebrates and fishes were rarely associated with the colonies in our surveys (Tissot et al., in press). Only about 15 percent of the colonies harbored organisms such as feather stars (crinoids), sponges, small rockfishes and lingcod, basketstars, and galatheid crabs. Some of the larger colonies displayed evidence of damaged or discolored segments; a few specimens seemed entirely dead. These injured or dead colonies were heavily encrusted by a variety of sessile organisms, such as anemones, hydroids, sponges, bryozoans, and shark egg cases (Figure 5).

FUTURE STUDY

The Christmas tree coral clearly contributes to the diversity, structure, and complexity of seafloor habitats in southern California. Because these organisms could be vulnerable to impacts from at least some fisheries, they may represent habitat areas of particular concern and as such would be protected under the Magnuson Stevens Fishery Conservation and Management Act. However, the association between fishes and these corals remains to be demonstrated. The Christmas tree coral was rarely associated with fishes, at least during the daylight hours of our surveys (Tissot et al., in press). While these corals and many species of rockfishes share the same habitats (i.e., boulders, cobbles, and rocky outcrops at similar water depths), functional relationships between these organisms could not be discerned from videotapes. In addition, beyond the bounds of our surveys, the geographic and bathymetric extents of the distribution of this new species of coral are unknown along the west coast. We hope to pursue more rigorous, quantitative studies, specifically designed to characterize the function of fish and coral associations, as well

as to conduct new surveys of this cold-water coral (and other structure-forming invertebrates) elsewhere off California and northern Baja California to delineate its geographic range.

There is increasing national interest from the science and conservation communities, as well from as the general public, in potential impacts of certain fishing activities on seafloor organisms. Like other species of cold-water corals, the Christmas tree coral likely has a long lifespan (scientists speculate perhaps from 50 to several hundred years), slow growth, a low natural mortality rate, and limited larval dispersal. Corals with this suite of life-history attributes are highly vulnerable to physical disturbance from some heavy fishing gears, and as a result, may take hundreds of years to recover. An overall impression from our surveys in southern California is that the biological components of habitat—that is the structure-forming organisms such as corals, sponges, and other large invertebrates—appear to be flourishing in terms of diversity, density, and size. This seems to be in substantial contrast to perceptions from other areas along the west coast that we have surveyed with the same methods of direct and video observations. This is especially astonishing given that these fairly luxuriant vertical structures are persisting in the

southern California Bight, one of the most heavily used areas of the U.S. coast.

We are now beginning to examine this perceived contrast in a quantitative manner, by analyzing the attributes of these biological communities (i.e., their diversity, densities, and sizes) using our archived video library of underwater surveys and by comparing these attributes among geographic areas having histories of different trawling intensity. Because fishing with various gear types has occurred for decades along most, if not all of the west coast, this issue is difficult to evaluate. However, historically there has been relatively little trawling off southern California, particularly on the deep water banks of our studies, compared to the submarine canyons and rocky banks off central California and further north. Our comparisons of deep-water invertebrate communities along the coast could be very compelling in terms of understanding the impacts of fishing on biogenic components of benthic habitats.

As with deep-dwelling, cold-water corals worldwide, most aspects of the taxonomy, biology, and ecology of the Christmas tree coral remain to be studied. Much of what we know about any of these cold-water corals has come from chance

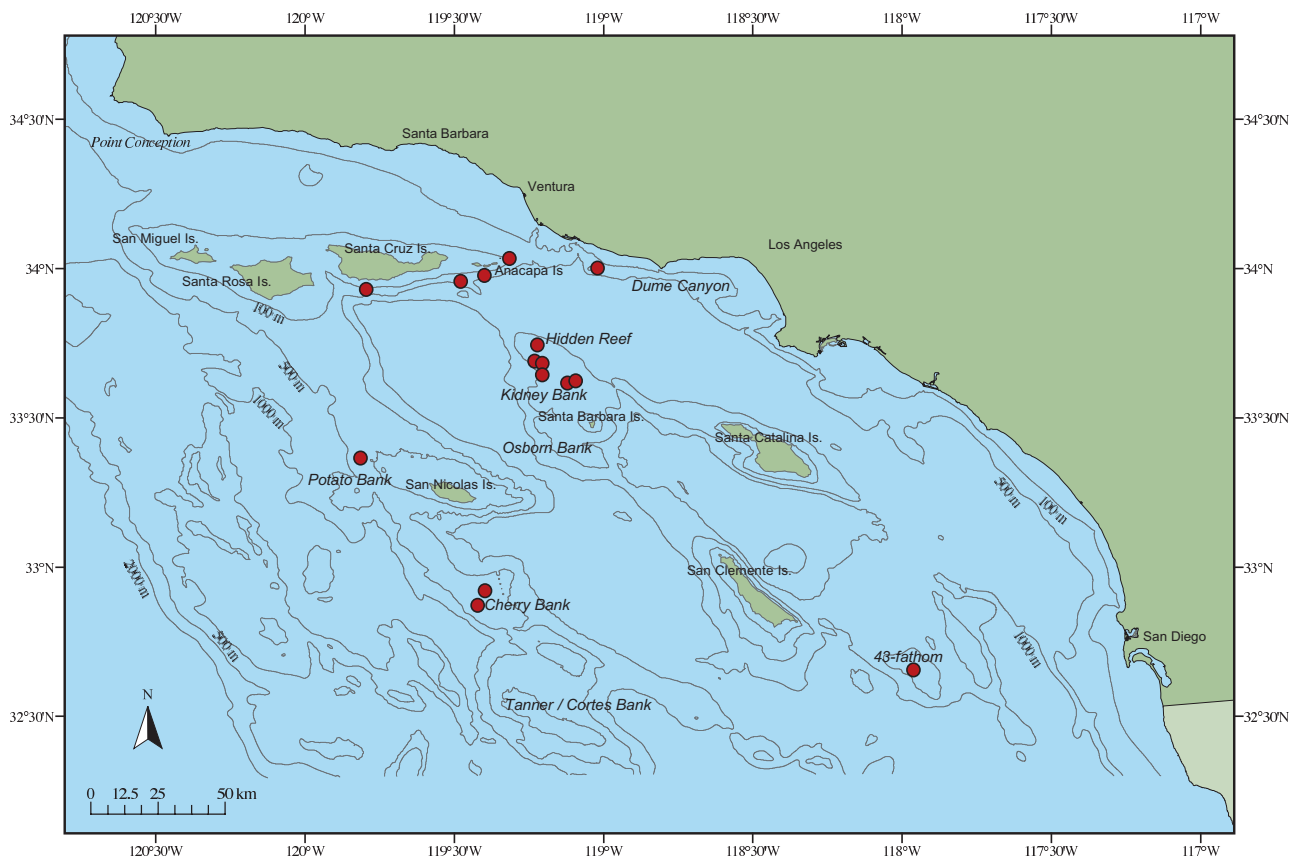


Figure 4. Distribution of Christmas tree coral colonies in southern California assessed from *Delta* mini-submersible during surveys of fishes and habitats on rocky banks.



Figure 5. An example of a dead segment of the Christmas tree coral encrusted with many sessile organisms, including anemones, feather stars, galatheid crab, and shark egg cases.

collections during research cruises or as bycatch of bottom-trawl fisheries. Unfortunately, little information on their natural habitats results from such collections. Recent advances in underwater technologies and the increased availability of observational platforms such as manned submersibles and remotely operated vehicles are providing scientists with new opportunities to assess the distribution and abundance of these corals firsthand and up close in their deep-water habitats. Recent explorations and research studies, such as ours, have resulted in the discovery of several new species of corals, and have given new insight into the ecological associations among these corals and the various biogenic and physical components of their habitat. The level of our understanding is directly related to the amount of time spent observing and exploring these deep environments (see McDonough, this issue, for more).

Until our surveys, the occurrence of deep-water black corals off southern California was completely unknown to science. The discovery of the Christmas tree coral clearly demonstrates how much there is yet to learn about marine communities on the seafloor, even along the most populated sections of the west coast. As we proceed with research on age, growth, resiliency to disturbance, and all aspects of the biology and ecology of this new species, it seems prudent to ensure that protective measures are considered.

ACKNOWLEDGMENTS

We greatly appreciate the contributions of several colleagues associated with this exciting new discovery, particularly D. Opresko, D. Schroeder, M. Nishimoto, L. Snook, C. Wahle, and B. Tissot. This research was partially supported by the National Oceanic and Atmospheric Administration's (NOAA's) National Undersea Research Program, West Coast and Polar Regions Undersea Research Center; David and Lucile Packard Foundation; NOAA Fisheries Office of Habitat Conservation

and Office of Protected Resources; NOAA Marine Protected Area (MPA) Science Center; Biological Resources Division, U. S. Geological Survey; Minerals Management Service; and California Artificial Reef Enhancement Program.

MARY YOKLAVICH leads the Habitat Ecology Team at the NMFS SWFSC Santa Cruz Laboratory. She has conducted research from California to Alaska on a variety of biological topics in marine fisheries. Her innovative research to characterize deep-water habitats and fish assemblages has particular relevance to contemporary resource conservation issues.

MILTON LOVE is a research biologist at the Marine Science Institute, University of California at Santa Barbara. He has conducted research on numerous economically important marine fishes in the northeast Pacific, including over 30 years of work on rockfishes. Milton and Mary are co-authors of the book *The Rockfishes of the Northeast Pacific*, published by University of California Press.

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- Opresko, D.M. (2005). "A New Species of Antipatharian Coral (Cnidaria: Anthozoa: Antipatharia) from the Southern California Bight." *Zootaxa* 852:1-10 (<http://www.mapress.com/zootaxa/content.html>).
- Tissot, B.N., M.M. Yoklavich, M. S. Love, K. York, and M. Amend (in press). "Structure-Forming Invertebrates as Components of Benthic Habitat on Deep Banks off Southern California with Special Reference to Deep-Sea Corals." *Fishery Bulletin*.

FOR MORE RESOURCES:

Photographs of the Christmas Tree Coral:
http://santacruz.nmfs.noaa.gov/ecology_branch/habitat_ecology/black_coral

Video Footage of the Christmas Tree Coral:
<http://www.id.ucsb.edu/lovelab>

PHOTO CREDITS:

Page 27: Courtesy of M. Amend, NOAA NMFS

Page 28 (left): Courtesy of M. Love

Page 28 (right): Courtesy of T. Laidig, NOAA NMFS

Page 29: Map modified from Tissot et al., (in press)

Page 30: Courtesy of D. Schroeder, U.C. Santa Barbara

AN AQUATIC PHARMACY: THE BIOMEDICAL POTENTIAL OF THE DEEP SEA

BY SARA MAXWELL

DEEP-SEA ORGANISMS HAVE UNIQUE ADAPTATIONS *that enable them to survive in cold, dark, and highly pressurized environments. As a result of these unique environments, deep-sea species often produce chemical compounds not found in their shallow-water or tropical counterparts that aid in their defense and survival in the deep sea. Compounds that protect corals and sponges from predation can also protect humans from a variety of ailments such as cancer, Alzheimer's disease, and even pain (Newman and Cragg, 2004).*

Two compounds isolated from deep-sea sponges are in human clinical trials, and several other promising compounds and applications, resulting from research on deep-sea sponges and corals, are in early stages of development:

- **Discodermolide.** Scientists from Harbor Branch Oceanographic Institution isolated discodermolide from the sponge *Discodermia dissolute* found off the coast of the Bahamas in water over 460 feet (140 m) deep. Discodermolide recently completed the early stages of clinical trials and is one of the most exciting compounds to date because it may treat cancers which were resistant to other drugs (Ter Haar et al., 1996).
- **E7389.** This compound comes from the sponge *Lissodendoryx* sp., which lives in New Zealand waters at depths of 330 feet (100 m). E7389 is being tested for the treatment of lung cancer and other cancers and is currently undergoing the early stages of clinical trials (Newman and Cragg, 2004).
- **Dictyostatin-1.** Harbor Branch scientists collected a sponge from the order Lithistida (family Corallistadae) at 1,450 feet (442 m) off the northern coast of Jamaica. Dictyostatin-1 was isolated from this sponge and may be more effective than the very successful anti-cancer drug Taxol (Isbrucher et al., 2003). Harbor Branch researchers are continuing work on this promising substance.
- **Topsentin.** This is one of the only deep-sea compounds that researchers are currently investigating for non-cancer related treatments. Isolated from the sponge *Spongosporites ruetzleri*, which lives at depths of 990-1,980 feet (300-600 m), this compound shows promise as an anti-inflammatory agent to treat arthritis and skin irritations, as well as for the treatment of Alzheimer's disease and to prevent colon cancer (National Research Council, 2002).

- **Bone Grafts.** Doctors have used shallow tropical corals as bone grafts for more than 10 years, but deep-sea species have not been used. Ehrlich and colleagues, however, were recently able to successfully synthesize bone analogs from bamboo corals (family Isididae). Found at depths of more than 3,280 feet (1,000 m), these corals have a skeletal structure and dimensions that are almost identical to bone (Ehrlich et al., 2003).
- **Collagen.** Bamboo corals also contain gorgonin, which closely resembles collagen, an important component of bone. Collagen can be used for controlled release of medicines, as scaffolding for tissue rebuilding and for a variety of other applications. Scientists hope that by understanding how corals form gorgonin, they can create a synthetic collagen-like material under the low temperature and pressure environments that bamboo corals naturally inhabit (Swatschek et al., 2002).

The deep sea will continue to be a valuable resource for human medical applications. Destructive fishing practices such as bottom trawling, oil and gas exploration, and other threats to this aquatic pharmacy are endangering this resource before its full life-saving potential can be realized.

SARA MAXWELL is Conservation Scientist with Marine Conservation Biology Institute (MCBI). She received a bachelor's degree in Wildlife Ecology and Conservation from University of Florida and will begin a Ph.D. program at University of California at Santa Cruz in 2005 to study migratory patterns of large pelagic animals in relation to seamount ecosystems.

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The deep-water sponge *Discodermia* is now in clinical trials for the treatment of cancer.

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PHOTO CREDIT:

Page 32: Courtesy of NOAA Office of Ocean Exploration

DEEP-WATER REEFS OFF THE SOUTHEASTERN U.S.: RECENT DISCOVERIES AND RESEARCH

BY JOHN K. REED AND STEVE W. ROSS

SOME OF THE MOST SPECTACULAR CORALS found off the southeastern U.S. were discovered as recently as the 1970s in an unexpected place—the deep waters along the edge of the continental shelf. These banks of *Oculina* corals extend for 167 km along the eastern Florida shelf. Unfortunately, even as they were being discovered by scientists, the *Oculina* banks had already been damaged by trawl-fishing activity. Parts of the reef have been protected since 1984, and the protected area was expanded in 2000, but the story of the *Oculina* banks' discovery and their damage by fishing activity is all too typical of the deep-water coral ecosystems that live and die, almost entirely unknown to the average person, in the deep waters off of some of the most populated and well-explored coastlines in the world.

Deep-water coral ecosystems provide important habitat for numerous fishes and invertebrates and are similar in function to shallow reefs. Various types of deep-water reefs occur within the U.S. Exclusive Economic Zone (EEZ) along the southeastern U.S. These include a range of high-relief habitats on the continental shelf from North Carolina to Florida and the Gulf of Mexico. The predominant corals on these reefs are the azooxanthellate, colonial scleractinian hard corals, such as *Lophelia pertusa* and *Oculina varicosa*, plus various species of hydrocorals (family Stylasteridae), black corals (order Antipatharia), bamboo corals (family Isididae), and sea fans (order Gorgonacea). Only a small percentage of deep-water reefs have been mapped or have had their biological resources characterized.

Recent research¹ has provided new discoveries of deep-reef ecosystems off the southeastern U.S. Unfortunately, deep reefs worldwide are being impacted by destructive fishing methods, such as trawling, which destroys the delicate corals. The *Oculina* reefs off Florida were the first deep-water reefs in the world to be designated as a Marine Protected Area (MPA) in order to protect them from destructive fishing gear. Habitat damage from trawling has already occurred on the *Oculina* reefs and also on *Lophelia* reefs in the northeast Atlantic. The resource potential of the deep-water coral ecosystems is unknown in terms of potential fisheries and novel compounds that may be developed as pharmaceutical drugs (see Maxwell, this issue, for more). We are currently developing priority mapping sites within this region, and the resulting data may provide potential targets for new deep-water MPAs.

WHAT IS A DEEP-WATER REEF?

Deep-water coral habitats occur at depths of 70 to greater than 1000 m and are sometimes defined as coral banks, bioherms, lithoherms, or reefs (Rogers, 1999). In general, deep-water coral banks occur below the effects of waves (generally below

100 m), and the corals lack symbiotic algae (zooxanthellae). A bioherm is a deep-water coral reef that over centuries has formed a mound of unconsolidated sediment and coral debris and is capped with thickets of coral, such as *Oculina* and *Lophelia* (Reed, 2002 a,b). Lithoherms are defined as high-relief, lithified carbonate mounds, rather than unconsolidated sediment mounds and also may be covered with thickets of live coral. Deep-water coral reefs are usually found in regions of fairly strong currents or zones of upwelling where the coral structures capture suspended sediment and build up mounds to heights of a few meters to more than 50 m.

DEEP-WATER REEF CORALS



Deep-water coral reef regions off southeastern U.S.A. and Gulf of Mexico. a) North Carolina *Lophelia* Reefs, b) Stetson *Lophelia* Reefs, c) Savannah Lithoherms, d) East Florida *Lophelia* Pinnacles, e) Miami Terrace, f) Poutalès Terrace, g) Southwest Florida *Lophelia* Lithoherms, and h) North-Central Gulf of Mexico *Lophelia* reefs.



Conger eel (*Conger oceanicus*) within a *Lophelia* coral thicket off of North Carolina, 384 m. Note galatheid crabs (*Eumunida picta*), sea urchins, and anemones on the coral.

Two species of deep-water corals dominate the deep reefs off the southeastern U.S.: *Oculina* and *Lophelia*. The deep-water *Oculina* coral reefs form an extensive reef system at depths of 70 to 100 m and exclusively occur off central eastern Florida (Reed, 2002b). These reefs are comprised of numerous pinnacles and ridges, 3 to 35 m in height. Each pinnacle is a bank of unconsolidated sediment and coral debris that is capped on the slopes and crest with living and dead colonies of *Oculina varicosa*, the ivory tree coral.²

Lophelia pertusa is another deep-water coral and is similar in morphology to *Oculina*, forming massive, bushy colonies, 1-2 m in height. It ranges in the western Atlantic from Nova Scotia to Brazil and the Gulf of Mexico, and also occurs in the eastern Atlantic, Mediterranean, Indian, and eastern Pacific Oceans at depths of 60 to 2170 m. It is the major constituent of deep reefs off the eastern U.S., primarily from North Carolina to south Florida and also in the Gulf of Mexico at depths of 370-900 m. In some areas the coral forms bioherms that appear to be unconsolidated rubble and sediment, and other sites appear as lithoherms with coral thickets growing on rocky mounds.³

RECENT RESEARCH

Recent research expeditions have compiled new information on the status, distribution, habitat, and biodiversity of deep-reef ecosystems. Expeditions by the authors and collaborators between 2000 and 2004 explored various deep-water reef sites off the southeastern U.S. and Gulf of Mexico. These were among the first human occupied submersible and remotely operated vehicle (ROV) dives to document the habitat and benthic biodiversity of these relatively unknown deep-water reefs. Ross (2004) and colleagues surveyed three *Lophelia* reefs off North Carolina as well as several from North Carolina to Cape Canaveral, Florida, and initiated studies on the associated fishes and invertebrates. Reed (2004) mapped nearly 300 mounds or pinnacles with heights of 15 to more than 150 m off the east coast of Florida and described their benthic invertebrate and fish communities. Many of these features at

depths of 700 to 800 m were verified as reefs from dives with the *Johnson-Sea-Link* (JSL) submersible. In 2002, multi-beam bathymetric maps were also made of the *Oculina* reefs and were integrated into a Geographic Information System (GIS) with submersible and ROV imagery and observations (visit www.uncw.edu/oculina).

DEEP REEF HABITATS

We have identified at least eight regions of deep-water reef ecosystems from North Carolina to Florida and eastern Gulf of Mexico.

North Carolina *Lophelia* Reefs: These are some of the best developed *Lophelia* bioherms discovered in the western Atlantic and represent the northernmost coral banks in the eastern U.S. (Ross, 2004). Three reef complexes explored to date are 50 to 80 m in height and occur at depths of 370 to 450 m on the western edge of the Blake Plateau. Because these banks appear to be the northern terminus for a significant zoogeographic region, they may be unique in biotic resources and they appear different from much of the coral habitat to the south. These mounds appear to be formed by successive coral growth, collapse, and sediment entrapment. Their tops and sides are mostly covered by dense thickets of living (white) *Lophelia pertusa* and they are surrounded by coral rubble zones. Preliminary analyses suggest that the fish community on these deep reefs is composed of many species that do not (or rarely) occur off of the reefs. Many fish species thought to be rare and/or outside their reported ranges have been found on these reefs.

Stetson Reefs: Hundreds of pinnacles occur along the eastern Blake Plateau off South Carolina, including a 152-m tall pinnacle where recent submersible dives discovered live bushes of *Lophelia* coral, sponges, gorgonians, and black coral (Reed, 2004). This area is about 120 nautical miles southeast of Charleston, South Carolina, at depths of 640-869 m. Over



Living *Lophelia pertusa* bushes off of North Carolina with associated invertebrates, 413 meters.



Oculina varicosa bioherm with large male scamp grouper (*Mycteroperca phenax*), 80 meters.

200 coral mounds may occur in this 6174 km² area that was first described from echo soundings and bottom dredges (Stetson et al., 1962). *Lophelia pertusa* and *Enallopsammia profunda* are the dominant scleractinian coral species and they are concentrated on top of the mounds.

Savannah Lithoherms: Numerous lithoherms occur at depths of 490 to 550 m along the western Blake Plateau, about 90 nautical miles east of Savannah, Georgia (Sedberry, 2001; Reed, 2004). These are 30 to 60 m tall mounds that are covered with fine sediment, dead coral fragments, and thickets of corals, sponges, and gorgonians.

East Florida *Lophelia* Pinnacles: Recent echosounder transects by Reed (2004) along a 222 km stretch off eastern Florida (depth 700 to 800 m) mapped nearly 300 coral bioherms and lithoherms, 15 to 152 m in height. The northern sites off Jacksonville and southern Georgia appear to be primarily lithoherms, which are rocky pinnacles capped with coral debris and live coral thickets (Paull et al., 2000), whereas the features from south of St. Augustine to Jupiter appear to be predominately *Lophelia* mud mounds that are capped with dense, one meter tall thickets of *Lophelia* coral with varying amounts of coral rubble (Reed, 2004).

Miami Terrace and Poutalès Terrace: Miocene-age (about 10 million years old) terraces off southeastern Florida and the Florida reef tract provide high-relief, rocky habitats for rich communities of benthic invertebrates and fish (Reed et al., in press). Along the eastern edge of the Miami Terrace, at a depth of 365 m, a 90 m tall steep rock ridge is capped with *Lophelia* coral, stylasterid hydrocoral, bamboo coral, black coral, and various sponges and octocorals. At the base of the terrace, in the axis of the Straits of Florida, *Lophelia* reefs may occur, but what little is known is primarily from dredge records (Cairns, 1979).

The Poutalès Terrace parallels the Florida Keys for 213 km and provides extensive, high-relief, hard-bottom habitat, covering 3,429 km² at depths of 200 to 450 m. The Tennessee and

Alligator Humps are among dozens of bioherms that lie in a region called "The Humps" by local fishers, about 14 nautical miles south of the Florida Keys. The peaks of some of these mounds are covered with thick layers of stylasterid corals, along with dense and diverse communities of sponges, octocorals, and fish (Reed et al., in press). In addition, numerous sinkholes occur along the outer edge of the Terrace; the bottoms of these sinkholes are 600 m deep and up to 600 m in diameter, making them some of the largest sinkholes in the world.

Gulf of Mexico *Lophelia* Reefs: Three regions are known in the eastern and northern Gulf of Mexico that have fairly extensive areas of *Lophelia* reefs. The southwest Florida Lithoherm Site occurs on the southwestern Florida shelf slope and consists of dozens, or possibly hundreds, of 5 to 15 m tall lithoherms at depths of 500 m. The lithoherms appear to be piles of limestone rock, some of which are capped with thickets of live and dead *Lophelia* coral. In 2003, SEABEAM bathymetric maps and ROV dives were made for the first time to describe this region (Reed, 2004). In addition, in the northern Gulf of Mexico, off Mississippi and Alabama, fairly extensive *Lophelia* thickets grow on upper flanks and peaks of Viosca Knoll, a deep-water salt dome (Schroeder, 2002), and also in an area known as Green Canyon off Louisiana (Sulak and Ross, unpublished data).

DEEP-WATER REEF COMMUNITIES

No detailed compilation of the benthic fauna has been made at any *Lophelia* reef sites in the western Atlantic. The primary sources of knowledge come from historical dredge and trawl surveys. However, recent use of submersibles and ROVs has allowed for direct observations and some collections of the benthic invertebrate and fish communities. A total of 146 species of benthic invertebrates have been identified from six deep-water reef sites off the southeastern U.S. (Reed, 2004; Reed et al., in press). The dominant benthic species include 70 Porifera (sponges) and 58 Cnidaria (corals and anemones). The Poutalès Terrace bioherms are different from the other sites and generally lack *Lophelia* coral but are dominated by stylasterid hydrocorals and have thick deposits of live and dead stylasters on their peaks. A striking difference between the *Oculina* and *Lophelia* reefs is that larger sessile invertebrates such as massive sponges and gorgonians are common on the *Lophelia* reefs (mostly south of North Carolina) but are not common on the deep-water *Oculina* reefs. The coral itself is a dominant component providing habitat on both the *Oculina* and *Lophelia* reefs. The percentage of live coral coverage is generally low on the majority of *Lophelia* and *Oculina* reefs in this region (1 to 10 percent); however, some areas may have nearly 100 percent live cover (such as the North Carolina and Viosca Knoll sites), and, for reasons unknown, some areas may have extensive areas of 100 percent dead coral rubble.

In total, at least 67 fish species have been identified from these deep-water reef sites (Reed, 2004; Ross, 2004; Reed et al., in press). These include 30 species from the Poutalès Terrace sites, 20 from Miami Terrace, 12 from the East



Lophelia pertusa coral and *Echinomuricea atlantica* octocoral on Miami Terrace Escarpment, 284 meters.

Florida *Lophelia* Pinnacles, and 10 each from the Savannah Lithoherms and Stetson *Lophelia* Reefs. Species that are common to most deep-reef sites include the blackbelly rose fish (*Helicolenus dactylopterus*), morid cod (*Laemonema melanurum*), red bream (*Beryx decadactylus*), roughy (*Hoplostethus occidentalis*), conger eel (*Conger oceanicus*), and wreckfish (*Polyprion americanus*). Although the deep-water *Oculina* reefs appear to be more species rich (73 species total), these reefs are shallower (50 to 100 m) than the *Lophelia* reefs, and the *Oculina* fish list also includes cryptic species collected by lockout diving from the *Johnson-Sea-Link* submersibles. Additional sampling of the deeper *Lophelia* reefs may significantly add to this faunal list.

WHY PROTECT DEEP-WATER REEFS?

Deep-water coral reefs are irreplaceable resources that are ecologically diverse and vulnerable to physical destruction. Bottom-trawl fishing, oil and gas production, cable laying, mining, or coral harvest could negatively impact these reefs. Protection is needed since damage from bottom trawling is a global threat. The National Oceanic and Atmospheric Administration's (NOAA's) 2001 Islands in the Stream Expedition demonstrated extensive damage from apparent shrimp trawling on the *Oculina* reefs. After trawlers were banned from the *Oculina* MPA, there was concern that trawlers might move to deeper habitats in search of valuable fisheries, such as royal red shrimp or benthic finfish. Removal by fisheries of apex predators such as groupers, snappers, sharks, and other ecologically important species may have severe long-term repercussions. Many deep-water fishes are very long lived and can not sustain long-term fishing pressure.

FUTURE OF DEEP-WATER REEFS

Compared to their shallow-water counterparts, deep reefs are relatively unknown. NOAA Fisheries and the Fishery

Management Councils are developing reports on the state of knowledge for deep-reef ecosystems. The deep-water *Oculina* reefs were the first deep-water reefs in the world to be designated as a MPA. Meanwhile the need to protect other deep-water reefs has gained worldwide attention. Norway enacted its first MPA to protect deep-water *Lophelia* coral reefs. In Canadian waters, the Northern Coral Forest Marine Protected Area has been proposed for deep-water, soft-coral habitats off Nova Scotia. As a result of our recent research, the South Atlantic Fishery Management Council is proposing six deep-water coral areas from North Carolina to South Florida as Habitat Areas of Particular Concern (HAPC). Also, a Deep Sea Coral Protection Act has been drafted and is being considered for federal legislation (see Frame and Gillelan, this issue, for more).

Education is needed for the public, the fishing community, resource managers, and legislators so they have a better understanding of the value and vulnerability of these reefs. Deep-water reefs are barely accessible to scientists; however, only by bringing knowledge of them to the public through videos, photos, and education will we gain understanding for the need to protect these unseen resources.

JOHN K. REED, Senior Scientist at Harbor Branch Oceanographic Institution (HBOI), has studied deep-water *Oculina* and *Lophelia* reefs since 1976 and has 50 publications on deep reefs. His research helped establish the *Oculina* Marine Protected Area (MPA). He has been Chief Scientist on 60 worldwide expeditions for biomedical research with HBOI's *Johnson-Sea-Link* submersibles.

STEVE W. ROSS, Research Faculty at the University of North Carolina at Wilmington (currently on assignment to the U.S. Geological Survey), has studied fishes and ecosystem ecology in the southeastern U.S., mostly North Carolina, for over 25 years. His research has spanned riverine, estuarine, continental shelf, and slope habitats. He has conducted numerous research cruises, many using submersibles and has been studying deep coral areas since the early 1990s.

FOOTNOTES

1. Funded in part by the National Oceanic and Atmospheric Administration's (NOAA's) Office of Ocean Exploration (OE), NOAA Fisheries, NOAA Undersea Research Program, NOAA Coral Reef Conservation Program, U.S. Geological Survey, and the State of Florida's Center of Excellence in Biomedical and Marine Biotechnology.
2. *Oculina* reefs were visited during NOAA's 2001 Islands in the Stream Expedition: <http://oceanexplorer.noaa.gov/explorations/islands01/log/sep5/sep5.html>.
3. *Lophelia* reefs were part of various NOAA Ocean Exploration Expeditions from 2001 through 2004: (<http://oceanexplorer.noaa.gov>).

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FOR MORE RESOURCES:

NOAA's Office of Ocean Exploration:
<http://oceanexplorer.noaa.gov>

NOAA's Ocean Exploration expeditions - 2001 to 2005:
<http://oceanexplorer.noaa.gov/explorations/explorations.html>

University of North Carolina, Wilmington - Highlighting the Deep-Water *Oculina* Coral Reefs:
<http://www.uncw.edu/oculina/>

Oceanica Oculina website - 2001 NOAA OE/ HBOI *Oculina* Deep-Water Reef Expedition:
<http://oceanica.cofc.edu/oculina/home.htm>

HBOI's At Sea website - Nature's Pharmacy and Eyes In the Sea Missions:
<http://www.at-sea.org/missions/fathoming/preview.html>

PHOTO CREDITS:

Page 34: Courtesy of S.W. Ross

Pages 35-36: Courtesy of J. Reed, Harbor Branch Oceanographic Institution

Did You Know?

The deep-sea coral family *Isididae*, found to depths of 1,000 meters, may someday be used as a basis for new bone grafting material.

Coral has been used as jewelry since antiquity; it may have been a source of currency for trade by Paleolithic humans. Today, coral used for jewelry is known as precious coral, and this includes black, red, pink, and gold corals.



| ACTIVITY: HOW AM I SUPPOSED TO EAT THAT? |

FOCUS

Feeding adaptations among benthic organisms

GRADE LEVEL

7-8 (Life Science)

FOCUS QUESTION

What physical feeding adaptations are found among benthic organisms typical of deep-water coral communities?

LEARNING OBJECTIVES

Students will be able to describe at least three nutritional strategies used by benthic organisms typical of deep-water coral communities.

Students will be able to describe physical adaptations associated with at least three nutritional strategies used by benthic organisms.

MATERIALS

- Popped popcorn
- Circulating electric fan
- Protective eyewear
- Baseball gloves (optional)
- Materials for student-generated adaptations (optional)

AUDIO/VISUAL MATERIALS

- Chalkboard, marker board, or overhead projector with transparencies for brainstorming sessions.

TEACHING TIME

One or two 45-minute class periods, plus time for group research

SEATING ARRANGEMENT

Groups of 4-6 students

MAXIMUM NUMBER OF STUDENTS

30

KEY WORDS

Charleston Bump
Sponge
Filter feeding

Deep-water coral
Feeding strategies
Feeding adaptations

BACKGROUND INFORMATION

The Blake Ridge is a large sediment deposit located approximately 400 km east of Charleston, South Carolina on the continental slope and rise of the United States. The crest of the ridge extends in a direction that is roughly perpendicular to the continental rise for more than 500 km to the southwest from water depths of 2,000 to 4,800 m. About 130 km east of the Georgia-South Carolina coast, a series of rocky scarps, mounds, overhangs, and flat pavements rise from the surface of the Blake Plateau to within 400 m of the sea surface. This hard-bottom feature is known as the Charleston Bump. While the Blake Ridge has been extensively studied over the past 30 years because of the large deposits of methane hydrate found in the area, benthic communities on the continental shelf of the United States are virtually unexplored (visit http://198.99.247.24/scng/hydrate/about-hydrates/about_hydrates.htm for more information about methane hydrates and why they are important). Although this area has been important to commercial fishing for many years, until recently it was generally assumed benthic communities of the continental shelf were scattered and relatively unproductive, and useful fisheries were the result of migrations from other areas and/or nutrients carried in from deeper or coastal waters. But once scientists actually began exploring the area more thoroughly, they found many diverse and thriving benthic communities.

As the Gulf Stream flows around and over the Charleston Bump it is deflected, producing eddies, gyres, and upwellings downstream (to the north). These kinds of water circulation patterns are associated with increased concentrations of nutrients and marine organisms in many other areas of the Earth's oceans, and may be an important factor to the productivity of the southern U.S. continental shelf.

The 2001 "Islands in the Stream" Expedition to the Charleston Bump found a series of very complex habitats, and numerous fishes and invertebrate species involved in communities that we are just beginning to understand. (Visit http://oceanexplorer.noaa.gov/explorations/islands01/log/sab_summary/sab_summary.html, and click on logs from September 27, 28, and 29 for more information). These organisms have a variety of physical adaptations that enable them to use various nutritional strategies. In this activity, students will investigate these strategies and adaptations, and will use this information to infer adaptations that might improve the feeding efficiency of an experimental organism (themselves).

LEARNING PROCEDURE

[NOTE: Portions of this activity were adapted from "Why we aren't filter feeders..." by Naturalists at Falls of the Ohio State Park, Clarksville, Indiana, on the Geologic and Paleontologic

Cook Book website. Visit <http://www.uky.edu/KGS/education/cookbook.html> for more edible education ideas!]

1. Lead an introductory discussion of the Charleston Bump and the 2001 and 2003 Ocean Exploration expeditions to the area. The website for the 2001 Islands in the Stream expedition is: http://oceanexplorer.noaa.gov/explorations/islands01/log/sab_summary/sab_summary.html; click on logs from September 27, 28, and 29. The website for the 2003 Charleston Bump expedition is: <http://oceanexplorer.noaa.gov/explorations/explorations.html>; click on "Charleston Bump." You may want to show students some images from the Ocean Explorer website and/or <http://pubs.usgs.gov/of/of01-154/index.htm>.

Tell students that detailed surveys of the Charleston Bump are just beginning, but we can have a general idea of what to expect based on explorations in other deep-water, hard-bottom habitats. Preliminary observations on the Charleston Bump in 2001 revealed a variety of complex communities involving a variety of different organisms and habitats. Animals in these communities typically use a variety of feeding strategies that often involve specialized physical adaptations that allow the animals to efficiently use a particular type of food. Tell students that their assignment is to investigate these strategies and adaptations, and to use this information to design adaptations that could make them (the students) more efficient filter-feeders.

2. Tell students that we will begin this activity with a demonstration of human abilities as filter feeders.

Students should be spread out so they are just beyond hand-to-hand with their arms outstretched (baseball gloves optional). Some students should sit on the floor, others should stand behind them. Use a circulating fan set on its highest setting and gently pour popcorn directly in front of the fan so it sails through the air. (You may want to practice without students first, so you can place them at the proper distance.) Students can move their arms (but cannot move their body) up and down/back and forth, but cannot grab popcorn that is beyond their grasp. They can either eat any popcorn they catch or hold and count it (i.e., on a paper plate) in order to see who caught the most food. To prevent choking, discourage students from catching popcorn with their mouths.

– from *"Why we aren't filter feeders..."* by Naturalists at Falls of the Ohio State Park, Clarksville, Indiana.

Be sure students use protective eyewear during the above activity!

You may also want to have the students do the companion activity on scavenger feeding described on the same web page (see Resources).

3. Tell student groups that their assignment is to:

- find out what sorts of organisms are typical of deep-water coral communities;
- identify at least three different feeding strategies found among these organisms; and
- identify what physical adaptations allow organisms to use these strategies.

Trip logs from the 2001 Islands in the Stream Expedition are a good starting point, and general descriptions of these communities can be found at <http://southeast.fws.gov/vbpdfs/commun/reef.pdf>, and http://www.fnai.org/dev/PDF/Natural_Communities_Guide.pdf. You may also want to have students find pictures or illustrations of these organisms from printed reference books, the Ocean Explorer Gallery (<http://oceanexplorer.noaa.gov/>, click on "Gallery"), and/or <http://biodicac.bio.uottawa.ca>.

Lists of typical organisms should include soft corals (such as gorgonians, sea fans, sea feathers, sea fingers, sea pansies, sea plumes, sea rods, sea whips), sea anemones, sponges, mollusks, tube worms, burrowing shrimp, crabs, isopods, amphipods, sand dollars, and fishes. Feeding strategies may include filter feeding (suspension feeding), deposit feeding, scavenging, grazing (i.e., scraping organic material from living or non-living surfaces), and carnivory.

4. Have each group present their research findings. Discuss and list the feeding strategies and their associated physical adaptations. Lead a discussion of which strategies seem most prevalent, and why this is the case. Students should recognize that photosynthesis is virtually absent in deep-sea communities because these communities receive very little light. However, photosynthesis is still an important source of nutrition in these communities due to the influx of organic material produced by photosynthesis in shallower water. Similarly, the remains of dead organisms that inhabit shallower waters settling to the bottom provide another source of nutrition that originates outside the deep-sea communities.
5. Have students brainstorm about adaptations they might use to make themselves more efficient filter feeders based on adaptations used by other filter-feeding organisms. Strainers, nets, and/or sticky substances (e.g., masking tape wound around hands with the sticky side out), for example, may be suggested as analogous to gills and mucous nets. You may want to offer an opportunity to test these ideas by repeating Step 2 with the addition of one or more suggested adaptations. Retaining the pieces of popcorn (rather than eating them immediately) provides an objective means for evaluating potential improvements to feeding efficiency.

THE BRIDGE CONNECTION

Click on "Ocean Science" in the navigation menu to the left, then "Biology," then "Invertebrates," then "Other Inverts," for resources on corals and sponges. Click on "Ecology" then "Deep Sea" for resources on deep sea communities: www.vims.edu/BRIDGE/

THE "ME" CONNECTION

Have students write a short essay describing their own nutritional strategy and the physical adaptations that enable them to use this strategy.

CONNECTIONS TO OTHER SUBJECTS

English/Language Arts

EVALUATION

You may want to have students prepare written reports (either individually or in groups) prior to the group discussion in Step 4. You may also want to have them include ideas for adaptations discussed in Step 5.

EXTENSIONS

Log on to <http://oceanexplorer.noaa.gov> to keep up to date with the latest Charleston Bump Expedition discoveries, and to find out what researchers are learning about deep-water hard-bottom communities.

Log onto <http://www.uky.edu/KGS/education/cookbook.html> for more edible education ideas.

RESOURCES

Project Oceanica website, with a variety of resources on ocean exploration topics:

<http://oceanica.cofc.edu/activities.htm>

U.S. Geological Survey Open-File Report 01-154 "Sea-Floor Photography from the Continental Margin Program":

<http://pubs.usgs.gov/of/of01-154/index.htm>

Summary report of the 2001 Islands in the Stream Expedition:

http://oceanexplorer.noaa.gov/explorations/islands01/log/sab_summary/sab_summary.html

Activities on scavenger feeding and filter feeding upon which Step 2 is based:

<http://www.falloftheohio.org/education/filter-feeders.html>

U.S. Fish and Wildlife Service report on coral communities on the continental shelf:

<http://southeast.fws.gov/vbpdfs/commun/reef.pdf>

Guide to the natural communities of Florida, including a general description of octocoral communities:

http://www.fnai.org/dev/PDF/Natural_Communities_Guide.pdf

The Geologic and Paleontologic Cookbook:

<http://www.uky.edu/KGS/education/cookbook.html>

NATIONAL SCIENCE EDUCATION STANDARDS

Content Standard A: Science As Inquiry

- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

Content Standard C: Life Science

- Structure and function in living systems
- Populations and ecosystems
- Diversity and adaptations of organisms

Content Standard F: Science in Personal and Social Perspectives

- Populations, resources, and environments

FOR MORE INFORMATION

Paula Keener-Chavis, National Education

Coordinator/Marine Biologist

NOAA Office of Exploration

2234 South Hobson Avenue

Charleston, SC 29405-2413

843.740.1338

843.740.1329 (fax)

paula.keener-chavis@noaa.gov

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Did You Know?

Deep-sea, cold-water *Lophelia* reefs in Norway are estimated to have persisted for over 8,000 years. These reefs can grow to be 35 meters high and several kilometers long!

INTEGRATED EUROPEAN RESEARCH INTO COLD-WATER CORAL REEFS

By J. MURRAY ROBERTS AND ANDRÉ FREIWALD

ALL THOSE INVOLVED IN MARINE EDUCATION, CONSERVATION, OR RESEARCH will at some stage struggle to convince the public or those in power of the value of understanding ecosystems that remain hidden from view at the bottom of the sea. However, in recent decades greater access to survey and visualization tools has given us opportunities to study benthic ecosystems and pass on a shared sense of wonder and excitement to the general public. Here we describe how efforts across the European Union have been focused to study and understand cold-water coral reefs, until recently a curiosity known only to a handful of marine scientists.

Imagine you are standing on the deck of a ship in the northeast Atlantic. To the south is Scotland and to the east the convoluted coastline of Norway extends up through the Arctic Circle to reach Murmansk in Russia. In the summer, you are bathed in 20 hours of daylight, but during the winter, the sun will appear above the horizon only briefly. Now imagine that you are able to peer through 300 m of seawater beneath the ship to the seafloor. What might you see? Perhaps a few fish like cod or tusk making stately progress through the chilly 8°C Atlantic waters. Pull further back and you begin to see occasional boulders dropped by icebergs in the last ice age. Further back still, and the huge scars gouged by these icebergs as the ice sheet retreated from northern Europe 12,000 years ago become visible. On some of these scars, you begin to make out clusters of white rocky outcrops. Move in to take a closer look and you quickly realize these weren't rocks at all but intricately branching reefs growing to form what look like giant white cauliflowers on the seabed.

These are coral reefs formed predominantly by a species called *Lophelia pertusa*. Of course, we can't peel back 300 m of seawater like this, but by using sophisticated sonar we can now survey the seafloor using sound waves and gradually build a map of the shape and structure of the seafloor (Figure 1). These acoustic techniques, coupled with research submersibles able to navigate the complex reef structures on the seabed, are allowing researchers unparalleled access to these hidden ecosystems. Cold-water coral reefs aren't only found off the Norwegian coast, they extend along the ocean margins and on underwater mountains or seamounts around the world (Freiwald et al., 2004).

EUROPE'S OCEAN MARGIN RESEARCH CONSORTIUM

From 2000 to 2003 the European Union supported a family of deep-water marine research projects designed to find out more about the geology and biology of cold-water coral reefs. Through the fifth Framework Programme, European universities and marine research institutes teamed up to focus research efforts onto a series of sites along Europe's Atlantic margin. The GEOMOUND and ECOMOUND projects

examined the geological processes underlying the formation of giant carbonate mounds. These massive seabed mounds were first discovered just over 10 years ago in the Porcupine Seabight, southwest of Ireland. Using geophysical tools to make profiles through the seafloor, geologists discovered clusters or provinces of giant mounds up to a mile in diameter and 100 m high. When the first cameras were lowered onto these mounds, some were found to support diverse cold-water coral reefs. The biology and ecology of cold-water coral reefs was the focus of a third European project, the Atlantic Coral Ecosystem Study (ACES).

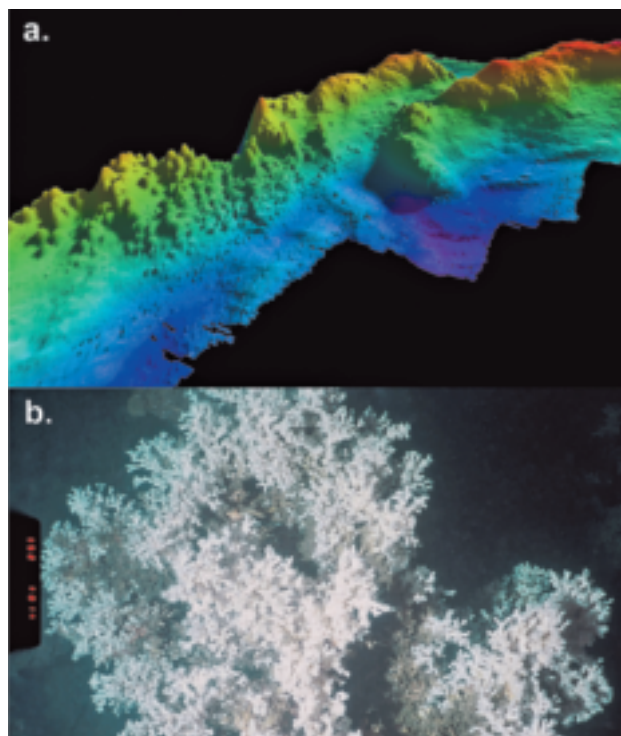


Figure 1. (top) a) Multibeam echosounder survey showing the characteristic seabed mounds formed by a *Lophelia* reef. (bottom) b) Live colonies of *Lophelia pertusa* form these mounds.



Figure 2. Study sites for the European Atlantic Coral Ecosystem Study.

The ACES project studied a series of cold-water coral sites from the Galicia Bank off Spain to the Sula Ridge on the mid-Norwegian continental shelf (Figure 2). Biologists, chemists, and geologists from six nations provided a diverse range of expertise, equipment, and research vessels to tackle the major interdisciplinary themes of the project. These themes included: mapping and describing the physical and biological characteristics of cold-water coral ecosystems, assessing sediment and current dynamics, coral biology and behavior, and coral sensitivity to natural and anthropogenic stressors.

These research themes were intimately linked with the goals of identifying conservation concerns and management issues affecting cold-water corals, increasing public and political awareness of these issues, and making recommendations for the sustainable use of cold-water coral ecosystems. Thus, at its outset, ACES was designed with both scientific and environmental management issues in mind. This approach has proved very effective in raising the profile of an ecosystem otherwise out of sight and out of mind.

NEW FINDINGS

By integrating cold-water coral research across Europe, the ACES project gave individual marine scientists access to the large-scale infrastructure they needed to work on an ecosystem found beneath many hundreds or even thousands of feet of water in the challenging environment of the northeast Atlantic. Ask the most basic question about any deep-water ecosystem—what lives there, for example—and the logistical problems and expense of collecting the data needed to test your hypotheses quickly spiral. Simply gathering a sample of cold-water coral and its associated fauna from the surface of a carbonate mound will require an offshore research vessel with a crew of between 20 and 100, the technology to find your target over 600 m beneath the hull, and the equipment to

collect, transport, and deliver the sample to scientists anxiously waiting on deck. Manned submersibles, unmanned remotely operated vehicles (ROVs), and benthic landers have provided researchers with the technology to survey the reefs, put instruments in place, and recover samples—safely and without damaging the reef ecosystem (Figure 3). Over its three years, the ACES project used 11 research vessels, completed 19 offshore cruises and 73 inshore cruises, and gave participating scientists 361 days at sea to study cold-water coral reefs. This intense research effort has revealed some exciting new aspects of cold-water coral reefs.

The skeletons of cold-water corals like *Lophelia pertusa* form a complex framework that can trap and retain seafloor sediments. As the coral framework grows, it can develop over time to produce a reef. *Lophelia* reefs are characterized by broad zones of live coral colonies, areas of dead coral framework, and deposits of coral rubble mixed with sediment. This diversity of seabed structures, combined with the complexity of the coral framework, produces a huge range of physical niches for different organisms to occupy. This is reflected in the high biodiversity associated with cold-water coral reefs. The ACES project compiled a list of over 1,300 species recorded from cold-water coral reefs in the northeast Atlantic. However, our understanding of how these species interact with one another in the reef ecosystem remains poorly developed. The highest recorded species diversity is associated with the coral rubble habitats, where suspension-feeding epifaunal taxa colonize coral rubble and infaunal taxa are found in the sediment caught within coral rubble. Here, sponges, bryozoans, tunicates, and crinoids are often abundant, but our ability to produce quantitative studies of biodiversity are often hampered by the difficulties of collecting intact reef samples.

Relatively few species occur in the live coral habitat, where the coral surface is well-protected from settling organisms by a layer of mucus. Despite this, a few animals are able to survive among live *Lophelia* polyps by adopting different strategies. For example, the foraminiferan *Hyrrokin sarcophaga* seems to parasitize live polyps. It is able to overcome the polyp's defenses and embeds itself into the coral's skeleton where it appears to grow and develop fuelled by its host polyp (Cedhagen, 1994). On the other end of the spectrum, *Lophelia* corals form a mutualistic symbiosis with the polychaete worm *Eunice norvegica*. This large polychaete, growing to over 10 cm in length, forms a delicate parchment tube that entwines with the coral's branching skeleton and is eventually calcified by the coral. By studying the coral-polychaete association in aquaria, researchers have observed some intriguing features of this relationship. The polychaete appears to clean the coral polyps, sometimes to steal food caught in their tentacles (Mortensen, 2001), and, surprisingly, is able to move adjacent coral fragments and join them. This effectively allows sessile corals some limited mobility and seems likely to enhance the rate of reef aggregation and patch formation (Roberts, 2005). These are some of the first glimpses of the natural history of cold-water coral reefs.

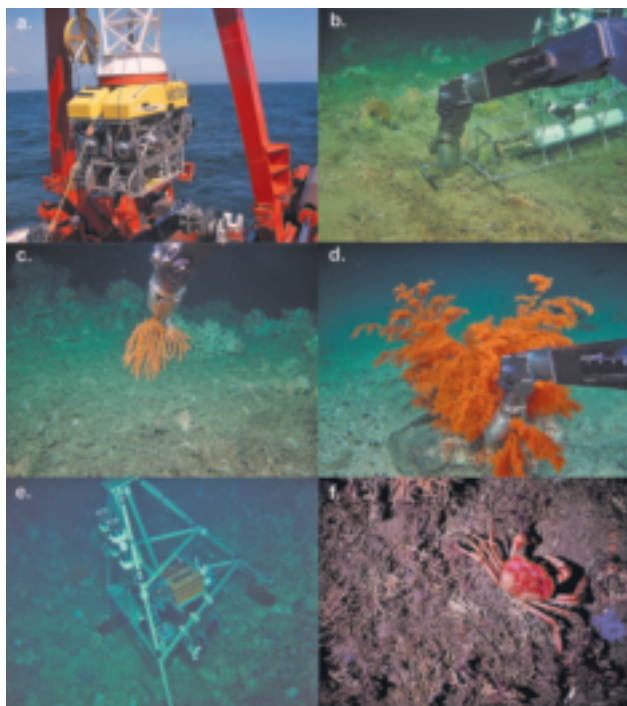


Figure 3. Submersibles and benthic landers provide the technology to study cold-water coral ecosystems at great water depths. A giant carbonate mound at 2400 feet water depth is shown. (a) The Victor 6000 ROV. (b) An ROV manipulator arm used to move a current meter and put it into position. (c,d) An ROV manipulator arm used to gather precise samples of gorgonian and antipatharian corals. (e) The SAMS photolander deployed on the Galway carbonate mound to record environmental variability and take time-lapse photographs. (f) A lander photograph showing a benthic crab (probably *Geryon (Chaceon) affinis*) on the coral-covered surface of the carbonate mound.

The ACES project has shed light on many other important aspects of cold-water coral biology in the northeast Atlantic. For example, it is now known that *Lophelia* colonies are separate sexes and they seem to be preparing to spawn in the first or second month of the year (Waller, 2005). Using molecular genetic techniques to compare coral populations along the European margin, researchers found that certain coral populations, such as those associated with the Darwin Mounds in the northern Rockall Trough, are composed predominantly of genetic clones, suggesting that they will be slow to recover if damaged (Le Goff-Vitry and Rogers, 2005). Fundamental information of this sort not only improves our basic scientific understanding of these species, but provides valuable, practical insights to help conservation managers when they consider strategies to form linked networks of marine protected areas (MPAs).

Deep-water ecosystems in the northeast Atlantic are profoundly influenced by the seasonal input of food to the benthos following spring phytoplankton blooms. As well as providing evidence that the dominant reef framework-forming corals reproduce on a clear seasonal cycle, research from the ACES consortium investigated the seasonality of food flux to the coral community. Using a benthic lander equipped with a

sediment trap and fluorometer, Duineveld and colleagues (2004) recorded the seasonal flux of food particles to the coral community of the Galicia Bank. By analyzing stable isotopic composition, they were able to show that this community feeds on a mixed diet of phytoplankton and zooplankton. Looking at trophic relationships in more detail, Kiriakoulakis and colleagues (2005) analyzed the lipid and isotopic composition of corals and particles trapped by pump sampling near the seabed. Their results suggest that some species, such as *Lophelia pertusa*, could be more carnivorous in their diet than others, such as *Madrepora oculata*, which may be more likely to feed on a higher proportion of algal debris. Using a lander equipped with time-lapse cameras, current meters, and optical instruments, Roberts and colleagues (2005) recorded the density of large, mobile animals near a *Lophelia* reef complex in addition to measuring water currents and estimating sediment movement. Such *in-situ* observations and measurements are fundamental to developing our understanding of the natural dynamics and variability of cold-water coral reef environments. By understanding this variability, we begin to predict how sensitive these species may be to environmental impacts and changes.

PUBLIC AWARENESS AND CONSERVATION EDUCATION

Until the late 1990s, cold-water coral reefs were known only to a few specialists. Increased research interest has improved their visibility in the scientific community, but it is the reports of damage inflicted by bottom trawling that have attracted the most media and political attention. It is now clear that many, if not most, cold-water coral habitats show scars inflicted by trawling for deep-water fish stocks. In 2002, Norwegian researchers estimated that between 30 and 50 percent of Norway's cold-water coral reefs had been damaged by bottom trawling (Fosså et al., 2002). From the other side of the globe, heavily-fished seamounts near Tasmania were shown to be stripped of their suspension-feeding coral fauna (Koslow et al., 2001). During the ACES project, several research teams found evidence of direct physical damage to cold-water coral reefs caused by bottom trawling as well as lost fishing nets and ropes (Figure 4).

As similar evidence has accumulated around the world, legislation to limit bottom trawling in areas where cold-water coral reefs are found has been put into effect. (Examples of such MPAs and the processes followed in their designation can be found in Freiwald et al., 2004). Many vulnerable cold-water coral reef habitats are found on the high seas, beyond the jurisdiction of any single nation, making their protection and conservation uncertain. However, the conservation of the Darwin Mounds in waters fished by several member states of the European Union provides an interesting case study of offshore conservation involving several nations. Discovered in 1998 at water depths of almost 1,000 m, the Darwin Mounds support scattered colonies of cold-water corals and were known to have been damaged by bottom trawling (Masson et al., 2003).

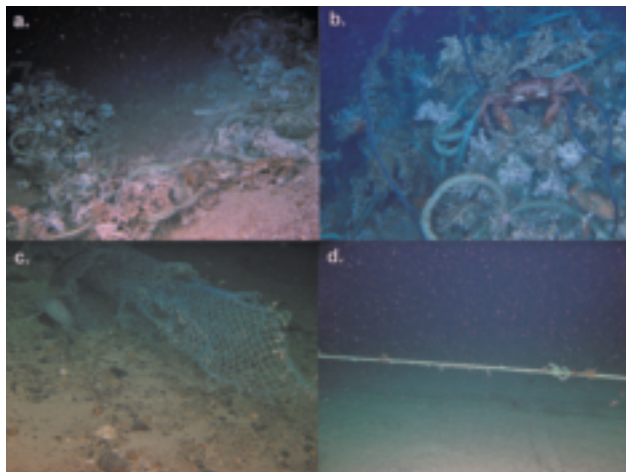


Figure 4. Fishing impact recorded on carbonate mounds in the Porcupine Seabight. (top: a,b) Coral debris caught in a lost trawl net. (bottom: c,d) Lost fishing net and lines.

In 2003, following a formal request from the UK government, the European Commission imposed an emergency measure to close this area to bottom fishing for six months under the European Common Fisheries Policy. This emergency closure was repeated for a further six months, and from August 2004, bottom-trawl fishing was permanently banned from the area of the Darwin Mounds. The UK government now intends to designate this area as a Special Area of Conservation following the European Union Habitats Directive.

The issues of marine conservation are many and varied. Offshore in high seas areas, these issues are only compounded by the legal and diplomatic complexities of agreeing to establish MPAs in international waters. The work to protect the Darwin Mounds from bottom-trawl fishing shows that agreement on the conservation of cold-water coral areas can be reached in an area fished by several European nations. How successfully this approach translates to truly international waters farther offshore remains to be seen.

NEW DIRECTIONS

From 2005-2009 the European Union sixth Framework program includes a large-scale integrated project, Hotspot Ecosystem Research on Europe's Deep-Ocean Margins (HERMES), focusing on four broad ecosystems:

- cold-water coral ecosystems and carbonate mounds;
- cold seep and microbially driven ecosystems;
- canyon ecosystems; and
- open-slope ecosystems.

These will be studied by a consortium of 45 partners from 15 European nations (see Weaver et al., 2004 for summary).

Work on cold-water coral ecosystems and carbonate mounds will develop themes started by the ACES, ECOMOUND, and GEOMOUND projects, and use the latitudinal spread

of coral ecosystems from the Norwegian margin to the Mediterranean Sea to study topics from biodiversity trends to trophic relationships. Researchers will benefit from access to research vessels and equipment available in other nations. Life-history studies will be completed at specific study sites and the physical characteristics important in cold-water coral reef sites will be assessed using long-term benthic landers and moorings. Sites where cold-water corals are known to exist close to active hydrocarbon seepage, such as near pockmarks on the Norwegian Shelf or mud volcanoes in the Gulf of Cadiz, will be used to examine any direct coupling between coral communities and the geosphere. The potential environmental archive stored in the skeletal remains of cold-water coral reef fauna will be used to examine mixing processes between productive surface waters and the deeper ocean environment. The colonization of cold-water coral ecosystems after the retreat of ice sheets will be followed using radiocarbon and uranium-thorium dating techniques (see Tsao, this issue, for more).

The overarching objectives of the HERMES project are to closely link scientific assessment and measurement with the efforts of ecosystem modelers to produce integrated models to quantify geochemical or food-web flows. Such objectives are intended to provide fundamental new insights into the functioning of Europe's oceanic margin ecosystems that will inform environmental policy. However, to really understand the ecological significance of cold-water coral reefs, one needs to consider their occurrence and potential linkage on an ocean basin scale. As research in the U.S. and Canada to map and characterize cold-water coral reefs develops, it is time to consider an integrated trans-Atlantic approach to understanding these largely hidden ecosystems.

ACKNOWLEDGMENTS

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J. MURRAY ROBERTS is a marine biologist based in the UK who has been studying the biology and ecology of cold-water coral reefs since 1997. He is co-editor of the forthcoming *Cold-Water Corals & Ecosystems* (Springer, Berlin Heidelberg).

ANDRÉ FREIWALD is a geobiologist from Germany. He has worked on cold-water coral reefs since the early 1990s, led the European ACES project, and is coordinating the cold-water coral ecosystems component of the HERMES project.

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FOR MORE RESOURCES:

Scottish Association of Marine Sciences:
www.sams.ac.uk

The Atlantic Coral Ecosystem Study (ACES):
www.cool-corals.de/

HERMES Project:
<http://www.eu-hermes.net/>

For more information on Cold-Water Corals:
www.lophelia.org

PHOTO CREDITS:

Page 42: Map Courtesy of J. Guinotte, MCBI

Did You Know?

You can help...

Bottom trawling is the gravest human-induced threat to the survival of deep-sea corals. This destructive fishing method crushes and uproots fragile corals, and leaves innumerable fishes that live in and around corals homeless. You as a consumer can help stop this habitat demolition by opting not to purchase seafood caught by destructive fishing gears!

Want to be savvy in your seafood choices? Learn how at:
Seafood Watch program of Monterey Bay Aquarium (<http://www.mbayaq.org/cr/seafoodwatch.asp>);
Blue Ocean Institute (http://www2.blueocean.org/Seafood_Detail/36); and
Seafood Choices Alliance (<http://www.seafoodchoices.com>).

THREATS TO DEEP-SEA CORALS AND THEIR CONSERVATION IN U.S. WATERS

BY CAITLIN FRAME AND HANNAH GILLELAN

U.S. FISHERIES MANAGEMENT

The borders of the United States do not end at the coast. U.S. jurisdiction extends to 200 nautical miles beyond its coastlines. These vast marine holdings—about 4.4 million square miles—are divided into state waters, which extend from each state's coastline out to three nautical miles, and federal waters, which include the area from 3 to 200 nautical miles, also known as the U.S. Exclusive Economic Zone (EEZ). The Magnuson-Stevens Fishery Conservation and Management Act is the primary law dealing with U.S. fisheries management. The Act charges the National Oceanic and Atmospheric Administration (NOAA) Fisheries, an agency in the Department of Commerce, with managing the living resources within the EEZ. It also creates eight regional fishery management councils, which help manage federal fisheries by developing and implementing regional fishery management plans. The Magnuson-Stevens Act provides basic standards and guidelines for the management of fisheries, including the prevention of overfishing and the protection of essential fish habitat. Fishery-specific decisions on how to meet these standards are left to the discretion of each council.

DEEP-SEA CORALS: THREATS AND MANAGEMENT STRATEGIES

Conservation of deep-sea coral species depends on carefully planned management strategies. Many deep-sea corals are slow growing and therefore take decades or even centuries to regenerate if they are damaged or destroyed. Thus, the most effective conservation tools prevent or strictly limit the initial amount of anthropogenic damage done to corals. Currently, the main threat to deep-sea corals is mechanical destruction by bottom-impacting fishing gear, particularly bottom trawls, which crush corals as gear is dragged along the ocean floor (see figures below). Oil and gas drilling operations also pose a threat, because corals can be crushed or smothered in toxic

debris at drill sites. Pipelines that service drill sites may also destroy deep-sea corals.

Managers have used a variety of methods to contain or prevent damage done to deep-sea corals by fishing gear. Deep-sea corals are often associated with rough, structurally complex benthic habitats. Rockhopper and roller gears are rubber or steel discs and balls attached to the leading edge of a bottom-trawl net that allow trawlers to drag their nets over rough terrain without snagging. Larger rockhopper gear allows trawl nets to enter more complex terrain. Therefore, size restrictions on gear can prevent the expansion of bottom-trawl fisheries into some deep-sea coral habitats. The Pacific, New England, and Mid-Atlantic Fishery Management Councils have used rockhopper-size restrictions to keep bottom trawls out of habitats that include deep-sea corals. In addition, a few states have implemented roller restrictions in state waters. For example, Connecticut restricts rollers to a six-inch diameter. New Jersey and New York also have roller restrictions although they are less stringent (rollers up to 18 inches are allowed).

New trawl gear that can be used at increasingly greater depths has rapidly increased the area of seafloor accessible to trawl fleets throughout the world. As a result, deep-sea habitats that were once protected by intrinsic gear limitations have come under increased trawling pressure. Like gear-size restrictions, freezing the "footprint" of bottom-trawl fisheries is meant to prevent the continued expansion of bottom trawling into previously unfished waters. This management tool restricts damage to habitats on the seafloor that have already been repeatedly trawled. The North Pacific Fishery Management Council recently decided to use this containment strategy when it limited trawling off the Aleutian Islands to 25,000 mi² of ocean floor currently trawled.

Areas of known or suspected importance to deep-sea corals can also be closed to gears that are known to damage bottom



Figure 1a (left) and b (right): Groupers were abundant on deep-sea *Oculina* coral reefs off Florida's Atlantic Coast before trawling began; legal and illegal trawling has nearly eliminated the corals and large fishes in this ecosystem.

habitat. Marine protected areas (MPAs) are ocean zones designed to preserve specific habitats and marine populations. For example, Washington has protected benthic habitats in its state waters using a combination of area closures in the bottomfish trawl fishery and complete bans on other bottom-trawl fisheries. The seafloor is also protected in the Flower Garden Banks National Marine Sanctuary, located 100 miles offshore of Texas in the Gulf of Mexico. Anchoring within the sanctuary is prohibited except at designated mooring sites, and the use of trawls is also illegal.

Deep-sea coral habitats can also be protected from destructive fishing practices under Magnuson-Stevens Act protections for essential fish habitat (EFH) and habitat areas of particular concern (HAPC). A 1996 amendment to the Act defined essential fish habitat as “those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity.” Under the amendment, councils must add EFH considerations to their fishery management plans by identifying and describing essential habitat for managed fish species, minimizing the fishing impact on EFH, and identifying additional steps to conserve EFH. A region within an essential fish habitat may be designated a HAPC based on its ecological importance, sensitivity to human impact, rarity, and the degree of stress that development activities put on the habitat. Several management councils have made an effort to put meaningful protections on deep-sea coral habitats designated as EFH. For example, under their monkfish fishery management plan, the New England and Mid-Atlantic Fishery Management Councils have banned monkfish bottom trawling in two deep-sea canyons known to contain corals. The South Atlantic Fishery Management Council created the 300 nm² *Oculina* Bank coral HAPC as part of its coral management plan and closed the area to all bottom-impacting fishing gears.

THE FUTURE

While some fishery management councils have taken steps to protect deep-sea corals from bottom-impacting gears, protections in U.S. waters remain inconsistent and are not yet comprehensive. In December 2004, the President highlighted deep-sea coral protection as an action item in his Ocean Action Plan. The issue also has reached both houses of Congress: a 2003 congressional hearing was held on coral protection measures, and the Deep Sea Coral Protection Act (DSCPA) was introduced in both the House and Senate in 2003-2004. The DSCPA aligns with the efforts of some of the regional fishery management councils' efforts to protect deep-sea corals. It declares coral ecosystem protection to be a national policy, and in many ways, would mirror action of the North Pacific Fishery Management Council. The Act freezes the footprint of bottom trawls in all fishery management regions. Trawling effort would be prevented from expanding into previously untrawled regions until deep-sea corals in those regions are surveyed and mapped, and then would be allowed, only, if potential habitat damage from proposed new bottom trawling is judged “minimal and temporary.” Additionally, the Act would require implementation of a comprehensive research plan to collect information on deep-sea coral locations and life

history. The DSCPA is one of a number of strategies to protect deep-sea corals and maintain their functional role in deep-sea ecosystems. A number of effective strategies are available to managers, but meaningful protections must be adopted swiftly while there are still deep-sea corals to protect.

CAITLIN FRAME is Research Assistant at Marine Conservation Biology Institute (MCBI). She graduated with a bachelor's degree in Biology from Harvard University where she studied marine microbiology. She will be pursuing a Ph.D. in Geobiology at the University of Connecticut this fall.

HANNAH GILLELAN, J.D., is Ocean Policy Analyst for Marine Conservation Biology Institute (MCBI). She is co-author of the first comprehensive legislative history of the National Marine Sanctuaries Act, *The History and Evolution of the National Marine Sanctuaries Act*, and has worked over the past four years to elevate and define a protective strategy for deep-sea corals in the United States.

FOR MORE RESOURCES:

Marine Conservation Biology Institute (MCBI):
<http://www.mcbi.org/destructive/Destructive.htm#deepseacorals>

Magnuson Stevens Fishery Conservation and Management Act:
<http://www.nmfs.noaa.gov/sfa/magact/>

Flower Garden National Marine Sanctuary:
<http://flowergarden.noaa.gov/>

New England Fishery Management Council Monkfish Bottom-Trawl Closures:
http://www.nefmc.org/monk/planamen/amend_2/mf_amend2_proposed_rule.pdf

North Pacific Fishery Management Council Trawl Restrictions:
http://www.fakr.noaa.gov/npfmc/current_issues/HAPC/HAPCmotion205.pdf

Oculina Bank HAPC:
http://oceanexplorer.noaa.gov/explorations/islands01/background/islands/sup6_oculina.html

Washington State fishing Regulations:
<http://wdfw.wa.gov/fish/regs/2004/04regs-5.pdf>

Deep Sea Coral Protection Act:
<http://www.mcbi.org/destructive/Justification%20of%20DSCPA.pdf>

PHOTO CREDITS:

Page 46 (left): Courtesy of Dr. R. Grant Gilmore, Dynamac Corporation

Page 46 (right): Lance Horn, National Undersea Research Center/University of North Carolina at Wilmington

CLIMATE CHANGE AND DEEP-SEA CORALS

BY JOHN GUINOTTE

WILL CLIMATE CHANGE HAVE NEGATIVE EFFECTS ON DEEP-SEA CORALS? *The answer is uncertain as very few manipulative experiments have been conducted to test how deep-sea corals react to changes in temperature, salinity, seawater chemistry (pH), water motion (currents), and food availability. It is likely that the effects of climate change will not be positive for deep-sea corals, because they are highly specialized and have evolved under very stable (cold, dark, nutrient-rich) conditions. Temperature, salinity, seawater chemistry, and light availability control calcification rates in shallow, tropical reef systems and with the exception of light (because deep-sea corals lack algal symbionts), these factors are probably important controls on deep-sea coral calcification as well.*

TEMPERATURE

Global sea temperatures are rising both in surface waters and in the deep sea due to an influx of anthropogenic carbon dioxide to the atmosphere. Since the Industrial Revolution, there has been a documented increase in shallow water coral bleaching events, and in many cases, massive coral mortality has followed. Deep-sea corals cannot bleach, since they lack symbiotic algae, but rising temperatures will probably influence their calcification rates, physiology, and biochemistry. Deep-sea corals grow very slowly (4 to 25 mm/yr or less, see Tsao, this issue; Freiwald et al., 2004), an order of magnitude slower than tropical corals. This difference is probably due to the cold temperatures in which deep-sea corals live (about 4° to 13°C). Preliminary findings suggest *Lophelia pertusa* respiration rates increase when the coral is exposed to higher ambient temperatures, but the synergistic effects of increased respiration and temperature on calcification are not known.

SALINITY

Climate change is altering the salinity of the world's oceans. Increased evaporation in tropical waters has led to more saline conditions in lower latitudes, whereas glacial ice melt in polar waters has led to less saline conditions in higher latitudes. Deep-sea corals tolerate salinity in the range of about 32 to 39 ppt (Freiwald et al., 2004) so any climate-induced change in salinity that puts deep-sea corals outside this optimal range will probably be detrimental. Physiological responses to salinities outside this optimal range are not known and warrant further study.

SEAWATER CHEMISTRY (pH)

Seawater chemistry and the calcium carbonate saturation state of the world's oceans are changing with the addition of fossil fuel CO₂ to the atmosphere (Feely et al., 2004). This influx of CO₂ is causing the world's oceans to become more acidic, which is bad news for corals and other marine organisms

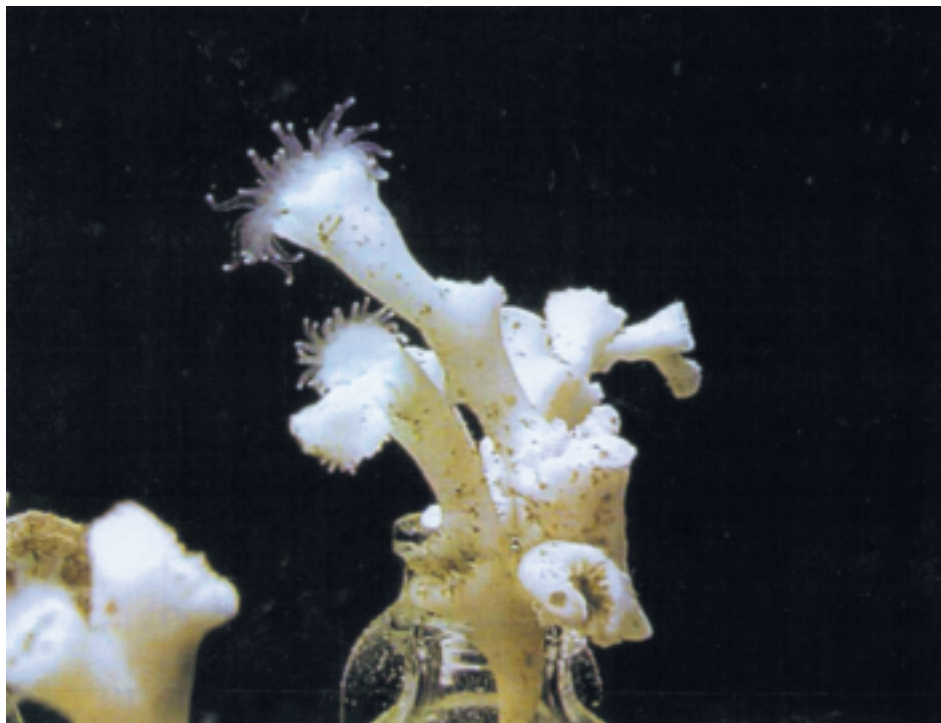
that use calcium carbonate to build their skeletons and protective shells. Although little is known about the effects of decreasing carbonate saturation state on deep-sea corals, lab experiments have conclusively shown that lowering carbonate ion concentration reduces calcification rates in tropical reef builders by 7 to 40 percent (Marubini et al., 2003; Langdon et al., 2000; Gattuso et al., 1999). In fact, all marine calcifying organisms tested to date have shown a similar negative response. As the world's oceans become less saturated over time, corals are expected to build weaker skeletons (a process similar to osteoporosis in humans) and/or to experience slower growth rates. If saturation state is as important to deep-sea coral calcification as it is to shallow reef builders, then this is an important issue.

FOOD AVAILABILITY

Very little information exists on the food sources of deep-sea corals. It is probable that they depend on suspended organic matter and zooplankton for nourishment (Freiwald et al., 2004). Since corals are sessile filter-feeding organisms, they can obtain nourishment either from organic matter falling from the surface or via currents that bring organic matter and zooplankton to the coral. Deep-sea corals occur in waters that have higher than average surface primary productivity, indicating that food falling from the surface is important to their survival. Many species of plankton (e.g., coccolithophores and foraminiferans) build calcium carbonate shells and are sensitive to the seawater chemistry changes previously noted. If ecosystem changes due to climate change reduce surface productivity, food sources for deep-sea corals will probably also be reduced.

WATER MOTION (CURRENTS)

The majority of deep-sea coral ecosystems are found in relatively high-energy areas and are exposed to steady currents.



Close-up of *Lophelia pertusa*.

Freshwater inputs to high-latitude waters are expected to increase as global temperatures continue to rise. The influx of freshwater causes seawater density changes, which slows down water circulation and may reduce upwelling and/or alter the trajectory of present-day current patterns. Since deep-sea corals are sessile organisms that depend on currents to bring them nourishment, any change in the direction and/or velocity of currents could have a significant impact on their distribution. Projections for changes in water circulation are uncertain at best, but if the Atlantic conveyor slows down as predicted, it will probably have negative consequences for deep-sea corals.

SUMMARY

Deep-sea coral ecosystems have probably not experienced a combination of stresses of the types described above for a very long time. The synergistic effects of these stresses occurring in concert are uncertain, but changes in the environmental factors identified above will probably have serious implications for deep-sea coral ecosystems. In situ monitoring and lab experiments are needed to help us understand and quantify how these changes might affect deep-sea coral ecosystems.

JOHN GUINOTTE is Marine Biogeographer/GIS Analyst at Marine Conservation Biology Institute (MCBI). He is a Ph.D. candidate in James Cook University's School of Tropical Environment Studies and Geography, and has authored several peer-reviewed papers on climate-related threats to coral ecosystems.

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