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Smithsonian underwater research

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Scientific diving, biology, research, review article, general interest

Abstract

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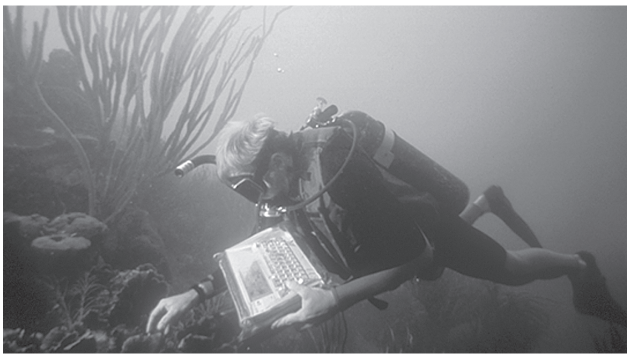
More than a century and a half ago, the Smithsonian Institution was established to promote the "*increase and diffusion of knowledge*". It is one of the oldest and most distinguished scientific institutions in the United States and scientific diving has been a research tool integral to its marine research efforts for over 30 years. The Smithsonian operates a unique Marine Science Network of coastal laboratories and long-term research sites along the latitudinal gradient of the western Atlantic Ocean, and bridging the Panamanian isthmus from the Caribbean Sea to the Pacific Ocean. Many of the most pressing environmental issues in marine ecosystems are studied using scientific diving techniques. To illustrate this, specific examples of the Institution's underwater research are used.

Introduction

The Smithsonian Institution was established more than a century and a half ago to promote the "*increase and diffusion of knowledge*" by a gift to the United States from an English chemist and mineralogist, James Smithson, and an act of Congress. The Smithsonian is one of the oldest and most distinguished scientific institutions in the United States and, indeed, science was the only mission of the Smithsonian for nearly a century. Outside the Smithsonian Castle in Washington DC is a statue of the first Secretary, Joseph Henry – the most eminent physicist in the United States.

The Institution was almost exclusively dedicated to basic science until the latter half of the twentieth century, when it became increasingly the home of America's public art treasures and memorabilia, housed today in 16 museums and research institutes. The science enterprise of the Smithsonian was often invisible in the glare of the brilliance of the expanding set of museums of art, history, and culture on the Mall. Many people register surprise on learning that the Smithsonian has any science mission at all, above or under water.

Figure 1
Smithsonian scientist with 'dive computer' on a reef census dive



Scientific diving is a research tool integral to the Smithsonian's marine research efforts for over 30 years (Figure 1). The Smithsonian operates a unique Marine Science Network of coastal laboratories and long-term research sites along the latitudinal gradient of the western Atlantic Ocean, and that bridges the Panamanian isthmus from the Caribbean Sea to the Pacific Ocean (Figure 2). Many of the most pressing environmental issues in marine ecosystems are studied using scientific diving techniques, including investigation of the following questions:

Figure 2
Map of Smithsonian Marine Science Network
1 – SERC; 2 – SMSFP; 3 – CCRE; 4 – Bocas del Toro; 5 – Galeta; 6 – Coibita; 7 – Naos
(see text for explanation)

- What is this species? (taxonomy)
- How are species related? (phylogenetics)
- Where are they found? (biogeography)
- How do species interact? (ecology)
- How did they come to be? (evolution)
- How are they used? (ethnobiology)
- How do they respond to change? (paleobiology and conservation biology)

In the face of the global biodiversity crisis, the need could not be more urgent to discover, describe, and classify the species of our planet in order to allow us to conserve, manage, understand, and enjoy the natural world. Our generation is the first to fully comprehend the threat of this crisis and the last with the opportunity to explore and document the species diversity of our planet.[1]

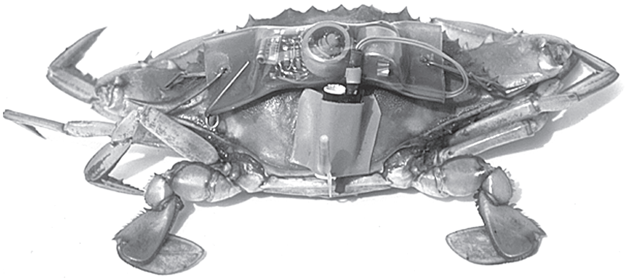
Smithsonian Marine Science Network

ENVIRONMENTAL RESEARCH CENTER (CHESAPEAKE BAY)

The Smithsonian Environmental Research Center (SERC) advances stewardship of the biosphere through interdisciplinary research and education. SERC laboratories, education facilities and field sites are located 25 miles east of Washington DC, on the western shore of Chesapeake Bay. SERC's long-term studies have focused on the interactions among ecosystems in complex landscapes, tidal marshes and estuaries. With the Rhode River, 3,200 acres of land and 16 miles of undeveloped shoreline as its hub, SERC's comparative marine research radiates to sites around the world.

SERC has explored connections in Chesapeake Bay's food web leading from plankton production up to commercially important species of fish and crustaceans, like the blue crab (Figure 3). Fisheries in Chesapeake Bay have collapsed as a result of over-fishing and environmental degradation, and the blue crab is now the only species with a sustained commercial catch.[2,3] Marine biological invasions by non-native species, introduced through human activities, have disrupted ecosystems around the world, causing major ecological change and enormous economic impact. SERC is the national centre for the study of alien invasive species in coastal ecosystems. Ballast water in commercial ships is the major vector for the introduction of alien marine species.

Figure 3
Blue crab (*Callinectes sapidus*) wired for ultrasonic biotelemetry study



MARINE STATION AT FORT PIERCE (INDIAN RIVER LAGOON, FLORIDA)

The Smithsonian Marine Station at Fort Pierce (SMSFP) is a marine science research centre located on the Indian River Lagoon alongside 156 miles of Florida's central-Atlantic coast. The Indian River Lagoon is a long, narrow and shallow estuary adjacent to the Atlantic Ocean, separated from it by a strip of barrier islands just 20 miles from the Florida current. This stream of warm water from the Caribbean moves northward past Florida's coastline as part of the larger, complex system of currents known as the Gulf Stream.

SMSFP's location in this biogeographic transition zone allows researchers to work at the interface of the hemisphere's tropical and temperate regions. The facility provides access to an extraordinary diversity of marine and estuarine species and to a variety of habitats. These include: mangroves, salt marshes and sandy beaches, rocky intertidal substrates, seagrass beds, mud and sand flats, coral reefs, deep coral rubble zones, shallow- to deep-water sandy plains, and the blue waters of the Gulf Stream. SMSFP has developed the Indian River Lagoon Species Inventory as a relational database that documents more than 3,000 species of plants and animals found in the estuary, which is likely to have the highest biodiversity in the nation.

CARIBBEAN CORAL REEF ECOSYSTEMS PROGRAM (BELIZE)

Coral reefs are unique biogeological structures that thrive in clear, nutrient-poor (oligotrophic) tropical oceans and support a rich and diverse biological community. Reef ecosystems are driven by the symbiosis between scleractinian corals and microscopic dinoflagellate algae (zooxanthellae) as their chief energy source. The largest, best-developed, least-polluted and commercially exploited coral reef in the Atlantic region is the Mesoamerican Barrier Reef.[4,5] It is a complex of reefs, atolls, islands, oceanic mangroves, and seagrass meadows that extends over 160 km. For its unique characteristics and relatively unperturbed condition, the Belize barrier reef has been declared a World Heritage Site.

Carrie Bow Cay (Figure 4), only three hours by plane and boat from Miami, was chosen as the Smithsonian site in former British Honduras for an interdisciplinary, long-term study of systematics, ecology, behaviour, evolution of reef organisms and the dynamics and historical development of reef communities: the Caribbean Coral Reef Ecosystems Program (CCRE). Carrie Bow Cay is located on top of the barrier reef, only metres away from a variety of habitat types: reef flats, deep spur and groove, patch reefs, seagrass meadows and mangroves.

Figure 4
Carrie Bow Cay, Belize: a one-hectare island atop the Mesoamerican Barrier Reef

TROPICAL RESEARCH INSTITUTE (REPUBLIC OF PANAMA)

The Smithsonian Tropical Research Institute (STRI) operates marine stations at Bocas del Toro (Figure 5) and Galeta Point in the Caribbean, the Naos marine laboratory complex and Coibita Island in the Pacific, and a 96-foot, near-shore, coastal oceanographic vessel, *R/V Urraca*.

At the Panama Canal, the Isthmus of Panama narrows to less than 100 km, separating oceans that are very different tropical marine ecosystems. The Caribbean is a relatively stable ocean, with small fluctuations in temperature and relatively low tidal variation. Its transparent, nutrient-poor waters are ideal for the growth of reefs, and it ranks just behind the Indian Ocean and the west Indo-Pacific in terms of numbers of marine species. The tropical eastern Pacific, in contrast, exhibits much greater fluctuations in tides and temperature, with local seasonal upwelling and longer-term variation due to the El Niño southern oscillation cycle. Its more nutrient-rich waters support commercial fisheries of major importance. The creation of these two distinct marine realms by the rise of the Isthmus of Panama during the last 10 million years also contributed to the formation of the modern biological and geological world. During this interval, the Gulf Stream was established, the mammals of North America conquered a newly connected South America, the Ice Ages began, and modern man arose. The rise of the Isthmus set in motion a fascinating natural experiment, as the animals and plants of the two oceans went their separate evolutionary ways.

In celebration of STRI's role in coral reef research, the Smithsonian's 150th anniversary and the International Year of the Reef in 1996, the Smithsonian hosted the Eighth International Coral Reef Symposium in Panama.[6]

Smithsonian research projects – a sampler

ALGAL SEXUAL REPRODUCTION ON CORAL REEFS

A remarkable spectacle while studying damselfish reproduction at the Smithsonian's San Blas field station in Panama was observed by Ken Clifton. Documenting over 850 natural spawning events involving 24 different species, Clifton's observations provided the first intimate details of a seaweed's love life (Figure 6).[7]

Figure 5
The Bocas del Toro Marine Research Laboratory at the border of Panama and Costa Rica; dedicated in October 2003

Common tropical seaweeds such as *Caulerpa* are a familiar sight to divers on coral reefs. With their relatively large size and abundant distributions, these calcified green algae have long been recognised as an important source of food, shelter, competition, and sediment within reef and seagrass communities (Figure 7). Green seaweeds, like some invertebrates (including corals), regularly undergo bouts of 'mass spawning'. Resulting clouds of sperm and eggs often shroud the reef in a pall of green, though few scientists have observed this phenomenon. Synchronous gamete release among neighbours boosts the concentration of eggs and sperm, increasing the likelihood that gametes from different individuals will meet. Each species has a highly specific time of gamete release and more closely related species spawn at different times (reducing the likelihood that similar, but potentially incompatible, gametes will encounter one another).

As primary producers, these algae contribute significantly to nutrient flux on reefs and help sustain many reef-

Figure 6
Green algal spawn on a Caribbean reef

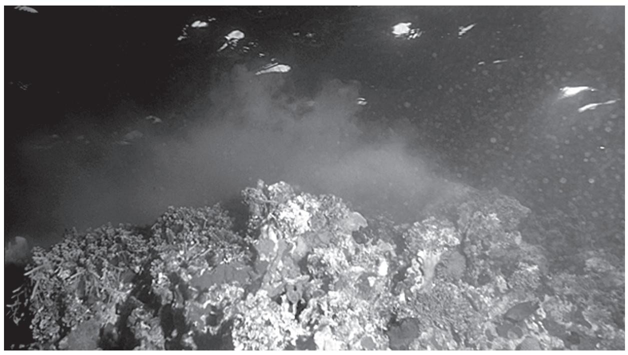
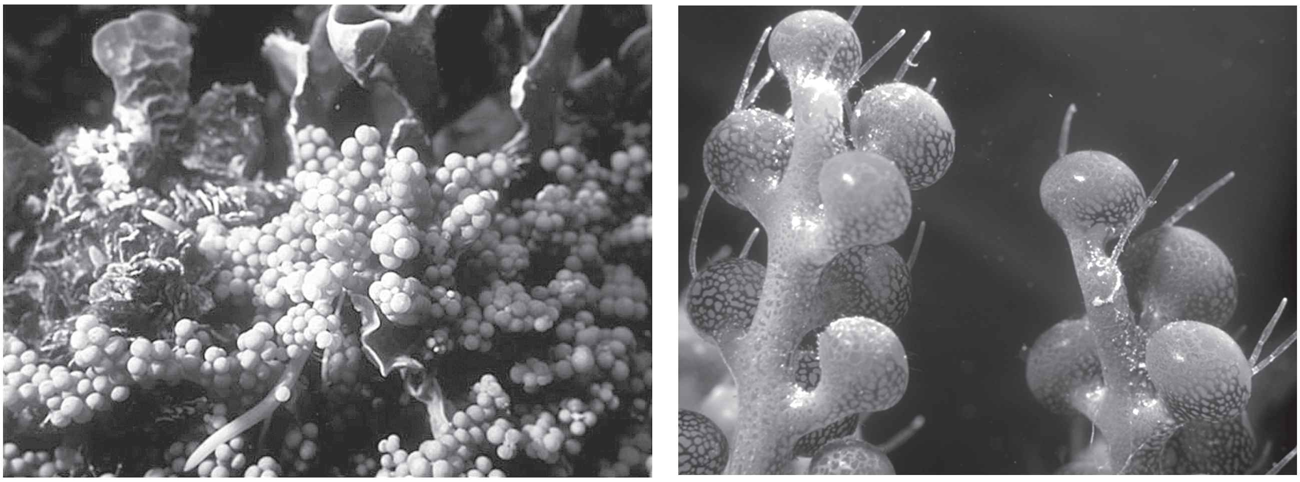


Figure 7

(a) The green algae *Caulerpa racemosa* **(b) *Caulerpa racemosa* magnified**



associated herbivores. As relatively large, structurally complex members of the benthic community, green algae compete directly with corals and other sessile marine organisms for space on reefs while simultaneously providing shelter for myriad others. Correlation between increasing green algal abundance and declining coral cover and reef biodiversity emphasise their importance as a trophic node within the reef community. These algae also produce complex defensive compounds that alter the foraging of herbivorous fishes and invertebrates and have potentially useful biomedical properties. Even in death, the heavily calcified thalli of the *Udoteacae* contribute to sand production, reef building, and other important geological processes.

CORAL SPAWNING

Corals are the building blocks of coral reefs and are renowned for the diversity of organisms they shelter. Nancy Knowlton's studies have revealed that marine tropical environments contain four to five times more species on average than has been generally realised. The most abundant and best-studied coral 'species' (*Montastraea spp*.) of the Caribbean is in fact a complex of at least three species: *M. annularis*, *M. franksi* and *M. faveolata*. All three spawn in approximate synchrony, typically seven to eight days after the full moon in August (Figure 8).[8] Even more surprisingly, these species each host a diverse array of symbiotic algal partners, so that the combined diversity of Caribbean reefs is an order of magnitude greater than previously assumed.

The ecological importance of this diversity was sharply highlighted during an episode of coral bleaching caused by a Caribbean-wide temperature increase in the summer of 1995. Which corals and parts of corals would be bleached, and the pattern of bleaching, could only be predicted by knowing which algae occurred where.[9] Thus, basic research on patterns of biodiversity has led to important insights into the likely consequences of global warming.

In the recent past, *Montastraea* and several other corals have declined in abundance. This poses a threat to reefs both now and for future generations of corals, because in order for this or any species to persist it must reproduce. *Montastraea* does not fragment prolifically, and thus sexual reproduction is critical for its long-term survival. What critical densities are needed to ensure fertilisation success during mass spawning is not known. This phenomenon of reduced population growth at low population size can place endangered species in a downward spiral from which recovery may be impossible. Corals are long-lived organisms, making it difficult to assess how present reproduction will affect future abundance.

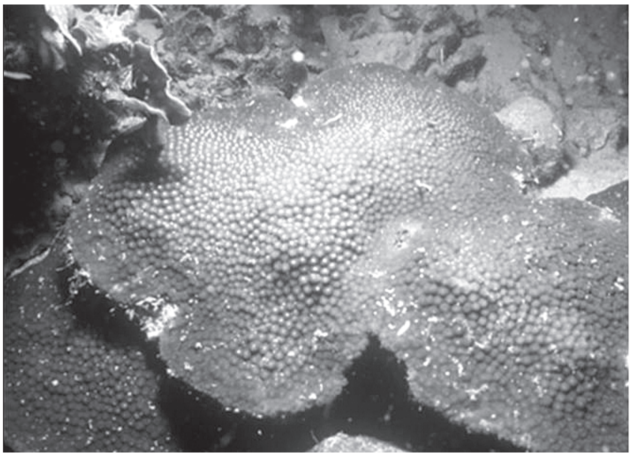
BLACK SEA URCHINS IN THE CARIBBEAN

Tropical marine environments are highly dynamic on many temporal scales. Perhaps the most dramatic revelation of long-term major change was the demise of the long-spined sea urchin (*Diadema antillarum*, Figure 9) throughout the western Atlantic.[10] Apparently due to a disease originating near the mouth of the Panama Canal in 1983, 95% of this once abundant organism disappeared over the course of two years. Notwithstanding the high reproductive output of this urchin, recovery has largely failed to occur and many over-fished reefs throughout the Caribbean have been smothered under algae freed from the urchin's grazing.

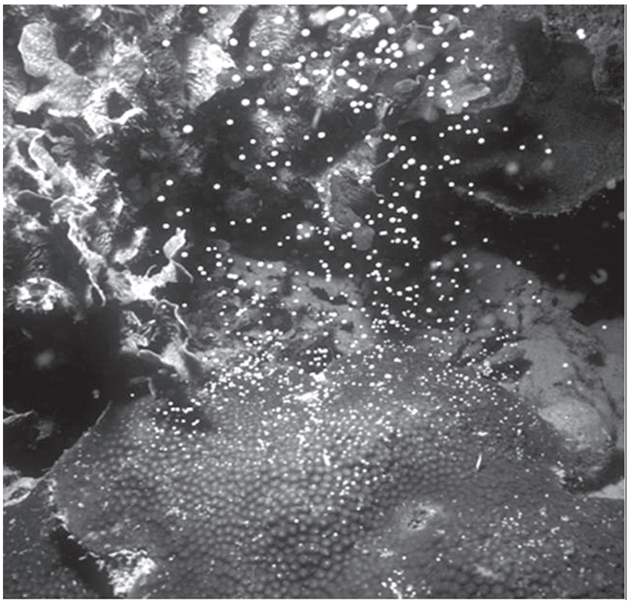
Haris Lessios' diving research showed how over-fished reefs persisted for years with high coral cover prior to the urchin die-off, but then rapidly succumbed to the decimation of this single keystone species, showing that synergy between multiple stresses on marine environments can have unpredictably severe consequences. The sea urchin saga (the most severe, widespread epidemic ever documented for a species of marine animal) also demonstrates how even extraordinarily abundant organisms (> 70 animals.m^{-2}) are potentially vulnerable to rapid elimination by diseases that combine the lethality of *Ebola* with the contagion of the common cold.

Figure 8

(a) 'Setting' colony of *Montastraea annularis* showing gamete bundles protruding through coral pharynx

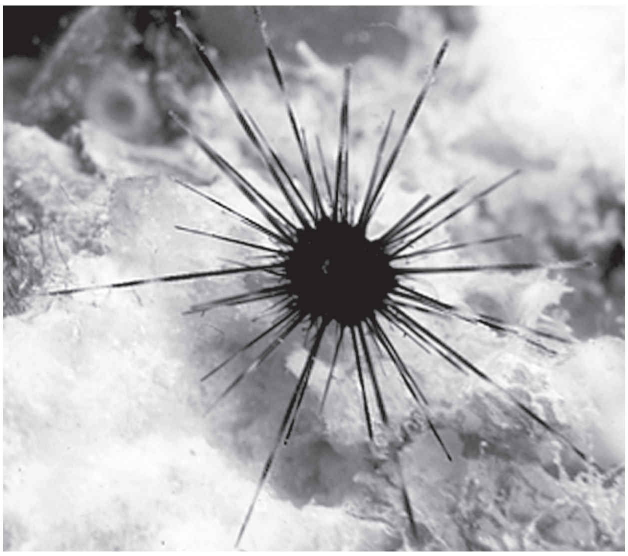


(b) Simultaneous release of gamete bundles of the same colony as in (a)



Diadema is the first marine species affected by mass mortality to have been monitored continuously for over 10 years.[11] The data, from both Panama and Jamaica, indicate that a one-time historical event can not only reduce the density of a previously abundant species throughout a whole region but also maintain it at constant low levels for a long time. This occurs even though the affected species is known for high fecundity and planktonic larvae. These characteristics are thought to reduce the chance of catastrophic mortality and extinction. It is possible that the high pre-mortality *Diadema* densities on some reefs were a recent phenomenon, perhaps a side-effect from man's over-fishing of its predators and competitors. However, historical information on the composition of most communities is lacking. Therefore, we cannot be sure that currently rare species may not always have been rare. Rarity of a species may not be due to any continuing process (such as competition or predation), but rather because of some catastrophe similar to that of *Diadema* in their past. The only way to evaluate the potential importance of historical events is through long-term studies of their consequences, so that their persistence can be assessed.

Figure 9
Juvenile Carribean black sea urchin, *Diadema antillarum*



BIOGEOGRAPHY OF REEF FISHES

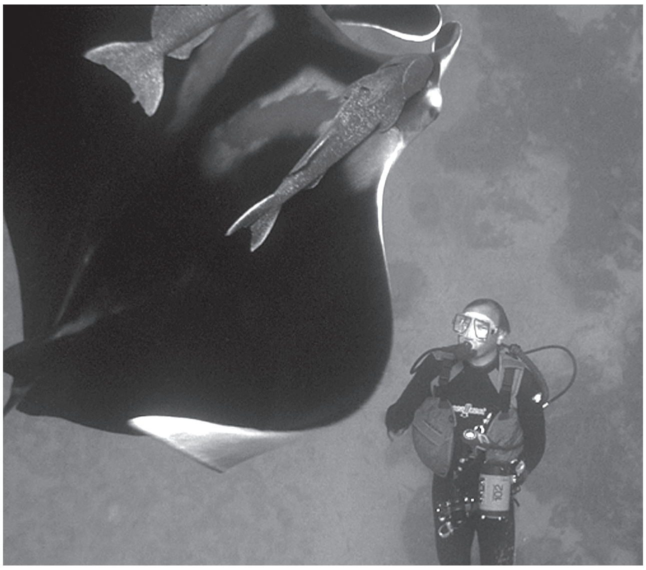
Populations of individual species of most reef fishes are generally thought to 'operate' on large spatial and temporal scales, due to a fundamental characteristic of their life cycles – the production of pelagic larvae. The larval life lasts weeks to months and begins as a relatively passive particle (an egg or a 1–2 mm swimming larva that has every chance of being carried well away from its natal reef). Consequently, larvae from one reef seem likely to seed populations on other reefs, and populations of reef fishes tens to thousands of kilometres apart may have strong demographic and genetic connections.

While most species of coral reef fishes have broad distributions (hundreds of thousands of square km), a very few occur only on single, small, isolated tropical islands.[12] Such small-island endemics may provide important information about the long-term maintenance of reef fish biodiversity precisely because they exist on mere specks of habitat for very long time periods (100,000–1,000,000s of years). If such species (or their island environments) do not have special life-history attributes that facilitate long-term persistence then reef fishes whose populations operate on large spatial scales also may be quite capable of surviving severe, widespread population decline and habitat stress.

Ross Robertson's underwater research projects to investigate the biological characteristics of small-island endemics in the tropical eastern Pacific have dived the Revillagigedos Islands, Clipperton Island, Cocos Island, the Galapagos Islands and Malpelo Island.[13] Clipperton Island, the only atoll and the largest coral reef in the eastern Pacific, is the most isolated reef in the tropical Indo-Pacific (950 km from the nearest shoals, Figure 10). It has a depauperate fish fauna (98 shorefish species), including a relatively large number of endemics: eight species from seven families (squirrelfishes, groupers, angelfishes, damselfishes, wrasses, blennies and gobies) that have a range of adult and larval ecologies. Population sizes of adult Clipperton endemics were estimated to range between 100,000 and 3,000,000. These are remarkably small populations for short-lived marine organisms that produce pelagic larvae. Mainland congeners of the endemics probably have populations about a thousand times as large. Recruitment of pelagic larvae of reef fishes often fluctuates considerably over time. Populations of short-lived species are more susceptible to local extinction from short-term recruitment failures. Interestingly, most Clipperton endemics are relatively small and thus appear to be short lived. Otoliths (ear bones) have growth rings that form on different time scales (daily, lunar cyclic, seasonal) and can be used to determine the age and growth rate of individuals, and population age structure and longevity.

The loss of endemics' larvae from Clipperton represents an extinction risk. Successful endemics have adaptations that aid the retention of their larvae near the island. Unique oceanographic characteristics may also aid larval retention. For species with planktonic eggs this factor is most acute in that released eggs are completely passive for the first 24 hours of their pelagic life. Species that have benthic eggs, on the other hand, release swimming larvae that should have some ability to resist offshore loss.

Figure 10
Smithsonian scientific diving officer (the author) 'sampling' manta rays at Clipperton Atoll



GEOLOGICAL HISTORY OF CORAL REEFS

Ian Macintyre of the National Museum of Natural History studies the recent history of coral reefs, particularly in the Caribbean region, by collecting cores from these reefs with a diver-operated drill. This sample of recent history (the past 18,000 years) represents the interval since the earth's last major glaciation. In this recent period, sea level has risen about 100 m, because of the runoff from melting ice sheets.

In the 1960s, modern coral reefs were considered immature, thin growths having inherited topographic relief. Since then, many coral reef core-drilling projects have brought new information to light about reef history.[14] Many reefs of the western Atlantic have an impressive record of Holocene accumulation, in terms of both the amount and duration of deposition.

A series of holes can be drilled along transects across modern coral reefs by a three-man dive team operating a submersible hydraulic drill (Figure 11). The resulting coral reef cores produce valuable data on reef community succession, rate of framework construction, and post-depositional processes for interpretation by coral reef geologists.

Core drills have a 0.6-metre core barrel attached to the wrench. The drilling unit weighs about 68 kg and can be handled easily by two science divers for shallow penetration such as the coring of an individual coral head. A tripod-winch assembly must be used, however, when working with the larger 1.5-metre core barrel and additional drill pipes. After every 1.5 m of penetration, the core barrel is retrieved and the core removed from the inner barrel. Under ideal conditions a 12 m core can be taken in about two days. A typical Caribbean fringing reef is dominated by *Acropora palmata*, with a mixed coral-head community on its outer slope. As the reef kept pace with the rising sea level, it formed a thick structure that masked the relief of the erosional surface on which it was established and began to construct its own topographic relief. When the rise in sea level started to subside, about 3,000 to 4,000 years ago,

Figure 11
Hydraulic core drilling of large coral head in Panama

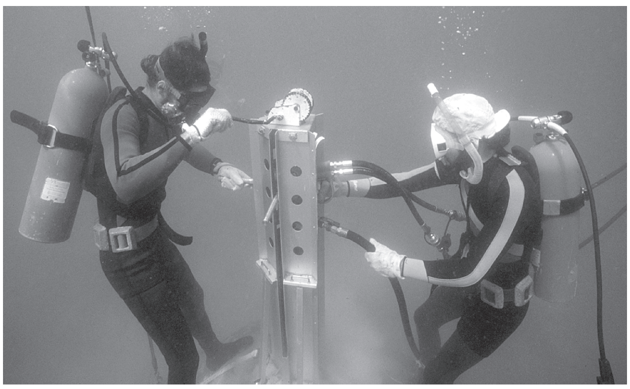
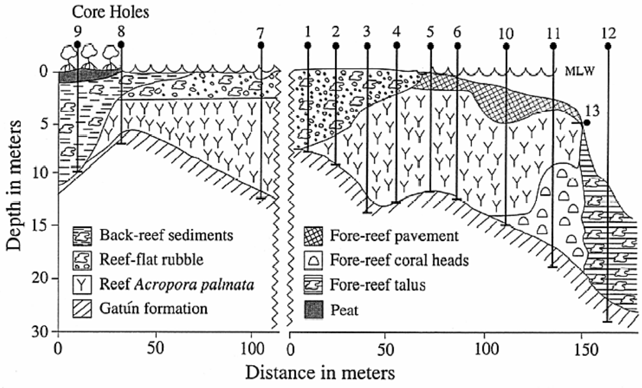


Figure 12
Profile of typical Caribbean reef face from coring data



vertical development of the reef became restricted. At the same time, a loose sediment apron formed in the fore reef, and restricted lateral reef growth. The encroachment of mangroves over the back-reef sediments, absence of present-day active framework construction, and thick talus deposits on the fore-reef slope all indicate that a fringing reef has passed the climax of its development (Figure 12).

SPONGE-INHABITING SHRIMP (Figure 13)

Emmett Duffy's underwater study of a sponge-inhabiting shrimp (*Synalpheus regalis*) confirmed eusociality, an advanced social structure, for the first time in a marine animal.[15] This marine model provides competition for land-bound ants and airborne bees as a suitable subject for the study of cooperative animal societies in which queens rule.

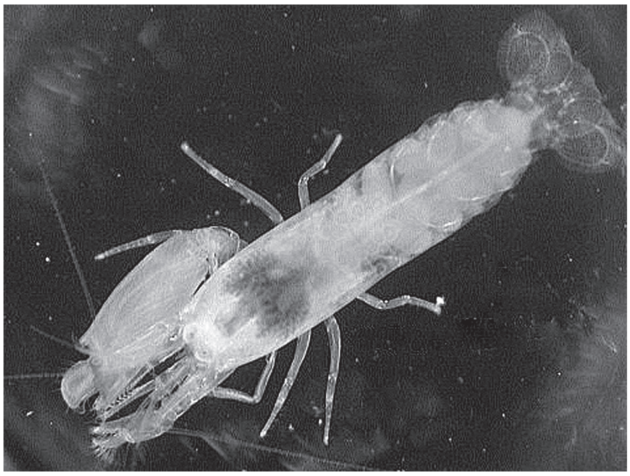
CORAL DECLINE

A monitoring programme was established to quantify the long-term effects of temperature change on the distribution and progress of black-band disease in reef corals. A bleaching event in 1998 killed almost all the corals in the Pelican Cays, and those in the surrounding lagoon area.[16] A two-year scientific diving project at Cayos Cochinos, Honduras, documented the vigorous recovery process of coral reefs after Hurricane Fifi and the enforcement of a ban on all types of indigenous fishing pressures.[17]

The effects of oil spills on reefs

Marine environments are subject to man-made disasters. The escape of 100,000 barrels of oil into the mangroves and reefs of Bahia Las Minas (Caribbean) has had unexpectedly prolonged effects.[18] Oil seeps into the sediments around mangroves and returns to coat the coral reefs year after year as heavy rainfalls (exacerbated by the effects of deforestation) slowly wash it out (Figure 14). The skeletons of corals record the history of acute disasters as well as chronic stresses. X-ray analyses of corals undertaken in response to the oil spill document a worrying decline in coral growth over the past century.

Figure 13
Belizean sponge-inhabiting snapping shrimp,
Synalpheus regalis



Diving education and outreach

For former divers or non-divers, the closest one might come to reminiscing about the underwater world or contemplating dive training certification is to visit the Smithsonian's 3-D IMAX film *Galapagos*, a virtual ticket to the underwater world. June and July of 1998 was spent aboard the Harbor Branch Oceanographic Institution's *R/V Seward Johnson*, complete with underwater film crew, scientific staff and the *Johnson Sea-Link* submersible (Figures 15 and 16). Several of the Galapagos Islands were visited, but most spectacular were Wolf and Darwin, the northernmost islands. The El Niño conditions of 1998, a tragic ultralight flying accident, and the technological difficulties of filming with a 1,700-pound underwater 3-D IMAX camera and housing made it necessary to reshoot certain sequences in February and March, 1999.

Other Smithsonian educational products available to the general public and marine scientists alike are in the form of field guides, electronic interactive identification keys, and natural history lessons disguised as cookbooks.[19–21]

Conclusions

The Smithsonian Marine Science Network and the Scientific Diving Program provide the facilities and support for the efficient conduct of underwater research. The primary objective of the scientific diving effort is the advancement of science. The deliverables are peer-reviewed publications and public outreach/education programmes. The Smithsonian supports an extensive array of underwater research projects involving scientific diving that address many of the most pressing environmental and biodiversity issues in marine ecosystems. More complete information can be found on the Smithsonian web site: Smithsonian Scientific Diving Program (<www.si.edu/dive>) and the Smithsonian Marine Science Network (<www.si.edu/marinescience>).

Figure 14
Galeta reef oil spill

Figure 15
Scientist and cinematographer with underwater 3-D IMAX camera in the making of *Galapagos*

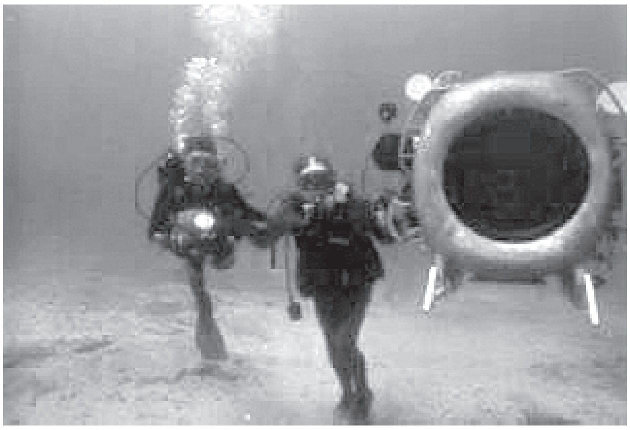
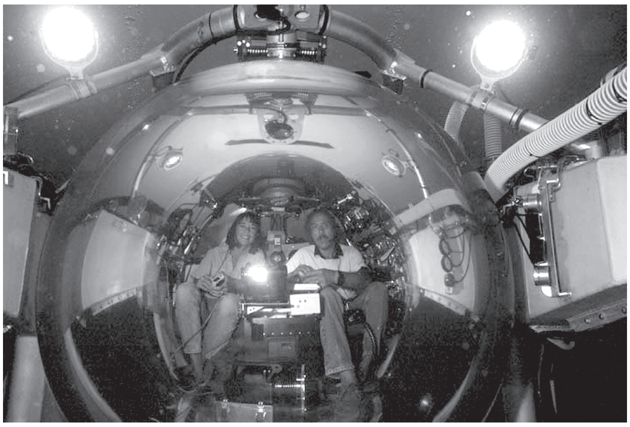


Figure 16
***Johnson Sea-Link* submersible used in the Galapagos Islands to maximum depths of 1,000 msw, resulting during 15 dives in the discovery of 15 marine species new to science**



Acknowledgements

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