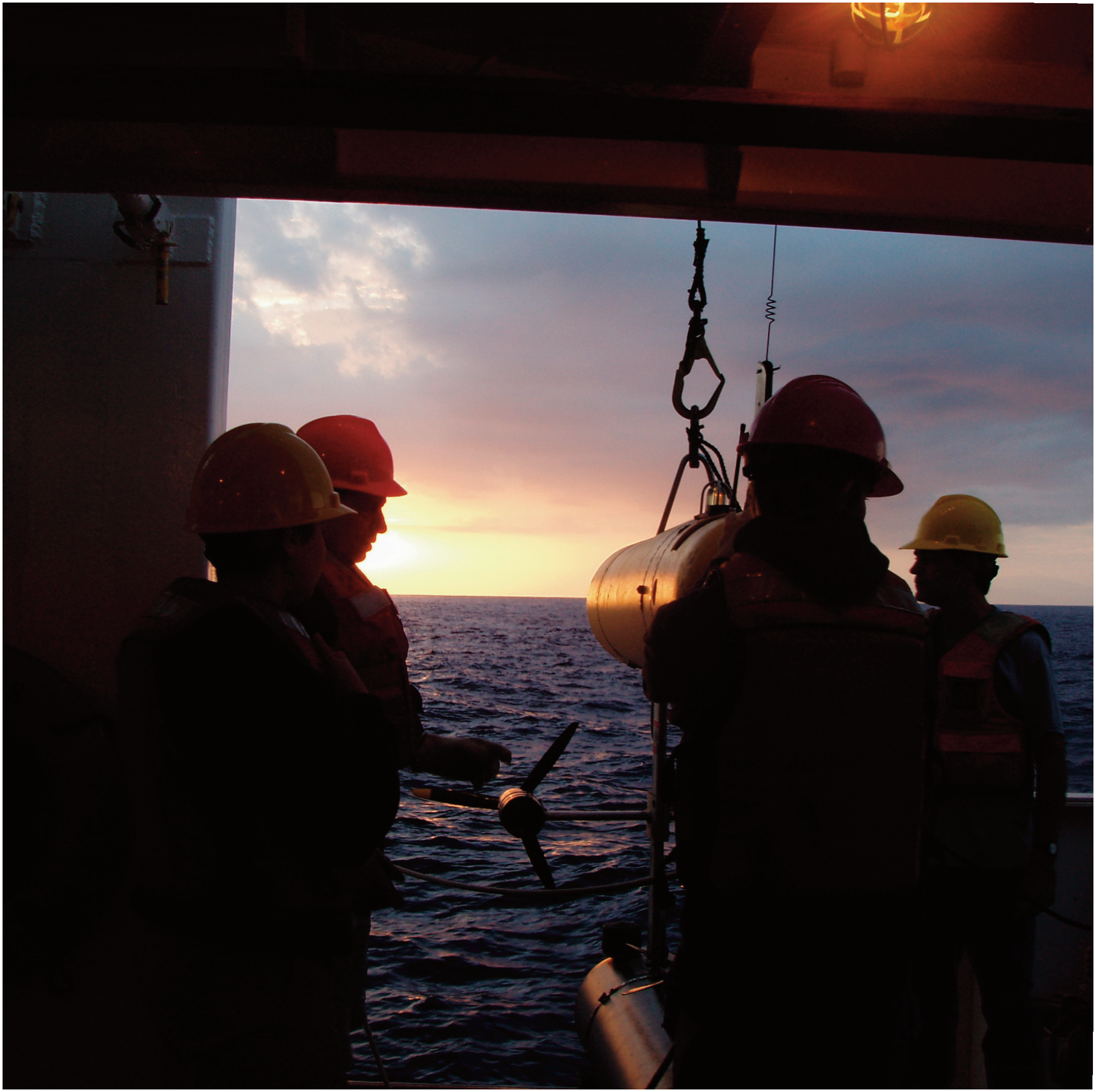


We know more about the surface of the Moon than the surface of our own planet, considering that nearly seventy percent of the Earth is covered by water.

The first comprehensive study of the shallow water stony corals of Puerto Rico reported that this fauna appeared to be depauperate. The work that we did in the seventies and eighties proved otherwise. Likewise, the first surveys of the deep-water environments around the island by the Johnson Sea-Link manned submersible also showed low abundance and diversity of fishes and benthic communities. Our work with the Seabed AUV at mesophotic depths and the E/V Nautilus ROV surveys to depths of 3,000 meters has proven that deep-water communities can be as productive and diverse as their shallow-water counterparts.

I am always amazed at how little we know about the sea around us and about science in general. Just when we think we have it figured out, a technological breakthrough provides a quantum leap of information, bringing us back to a new starting point.

Roy A. Armstrong

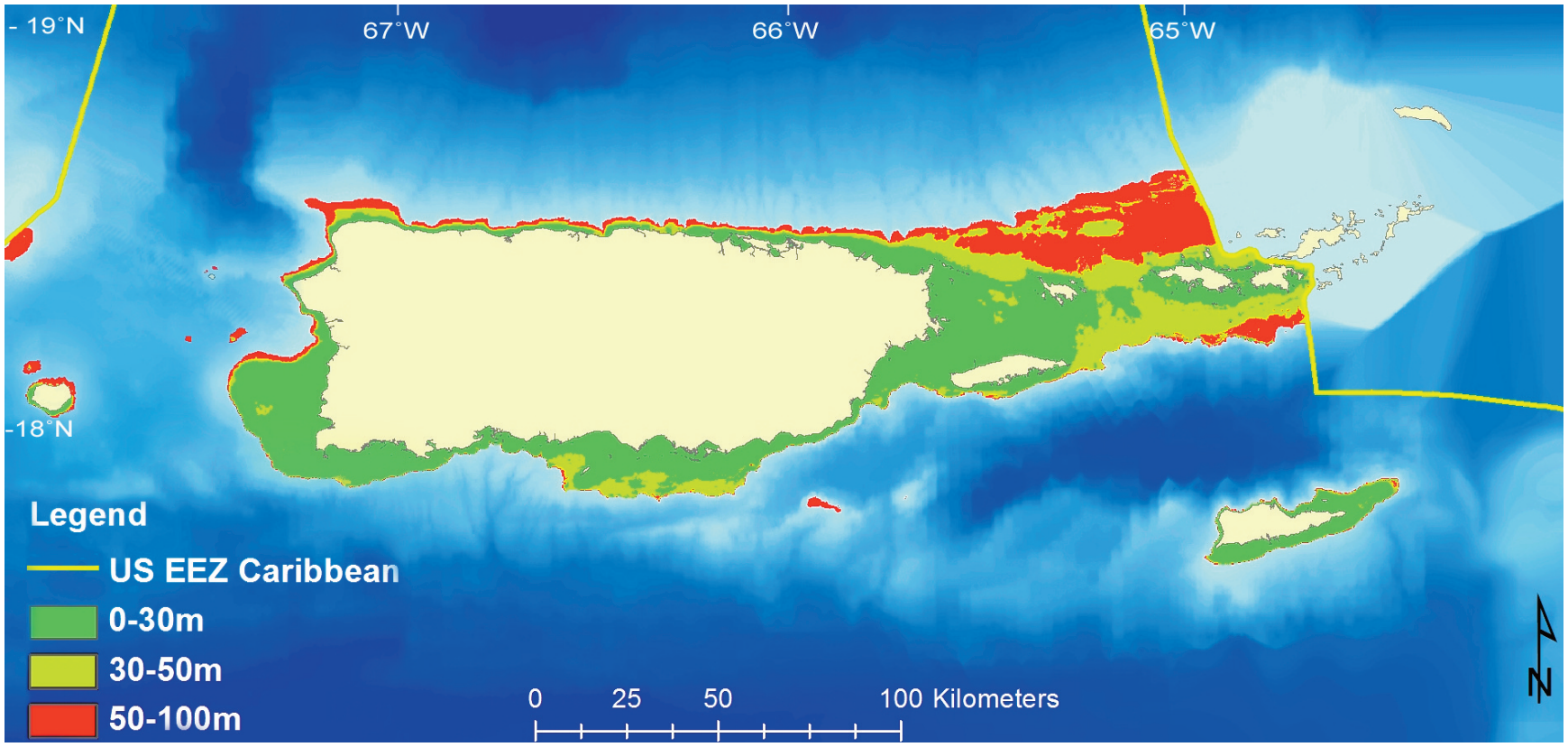
The Autonomous Underwater Vehicle (AUV)

Recent studies on mesophotic coral ecosystems, those within 30 and 100-150 m in depth throughout the US Caribbean, describe, for the first time, abundant and structurally complex coral reefs on low-gradient platforms. Information on deep coral ecosystems, those beyond 150 m in depth, in this region is even more scarce and largely limited to taxonomic listings from incidental collections by coral entanglement devices. The Seabed AUV, which was designed for high-resolution underwater optical and acoustic imaging, has provided unprecedented information on the distribution, community structure, and status of twilight-inhabiting or mesophotic or twilight zone reefs throughout the U.S. Caribbean. Preliminary surveys of deep coral ecosystems off western Puerto Rico show diverse corals which lack zooxanthellae —the microscopic algae often embedded within coral tissues— and other invertebrate fauna, at depths of over 200 m. For both mesophotic and deep coral ecosystems, the AUV benthic assessments can provide the required qualitative and quantitative data for selecting unique areas of high biodiversity and structural complexity for habitat protection and

ecosystem-based management.

Deep reefs, typically dominated by corals with and without zooxanthallae, and sponges, are important habitats for marine sessile and motile large bottom-dwelling invertebrates and fish communities. Deep reef habitats in Puerto Rico and the U.S. Virgin Islands are mostly associated with submerged volcanic ridges, rocky outcrops, gently sloping platforms, and steep insular slopes. Two distinct deep reef systems are described here: (1) Mesophotic —twilight— coral ecosystems (MCE), which are light-dependent coral, algal, and sponge communities that extend from 30 m to 100-150 m in tropical and subtropical regions, and (2) Deep coral ecosystems (DCE), which extend to deeper, colder waters to form banks, structures and other aggregations of zooxanthellae-lacking corals, sponges and other organisms.

In the Puerto Rico Shelf, MCE are found in high-gradient slopes and low-gradient insular platforms with a potential mesophotic reef area of 3,892 km^2. They achieve their greatest development on low-gradient platforms, where relic reefs and terraces provide favorable hard substrates for colonization. The upper mesophotic zone (30-50 m) comprises about 23% of the total Puerto Rico Shelf area while the lower mesophotic (50-100 m) accounts for approximately 21% of the total area. In the U.S. Caribbean, the area of potential MCE habitat in high-gradient slopes is minimal when compared to low-gradient platforms, where two distinct types are found. One type is characterized by a structurally complex, high rugosity coral reef dominated by a flattened morphotype of *Montastraea annularis* complex. The other type of MCE formation is associated with extensive algal rhodolith deposits —rhodolith: stones or rubble consisting of red algae. literally: pink stone— and dominated by benthic algae, sponges and corals of the genus *Agaricia*. Since 2002 we have used the imaging capabilities of the Seabed AUV to map and characterize MCE throughout the Puerto Rico Shelf.



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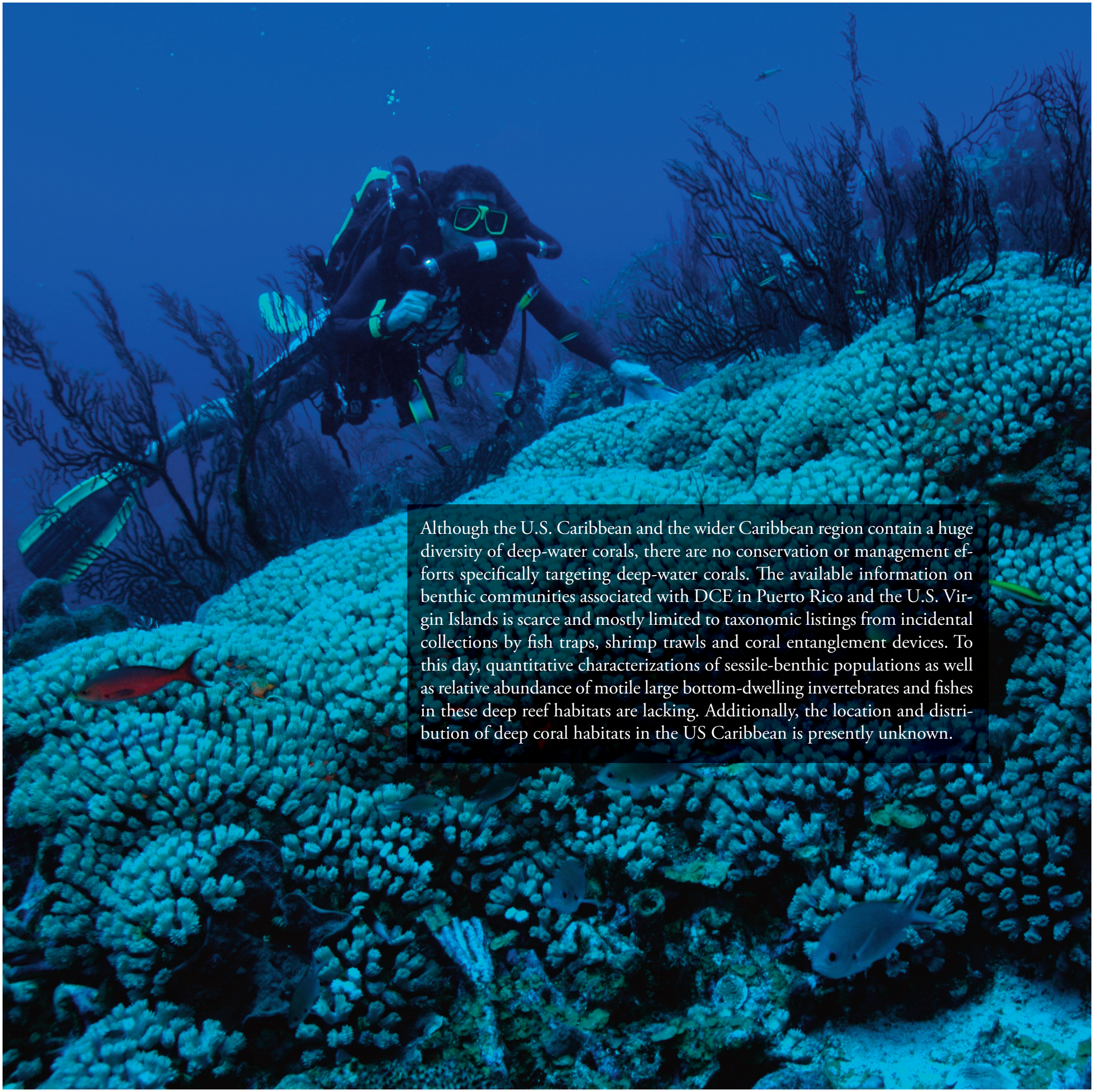
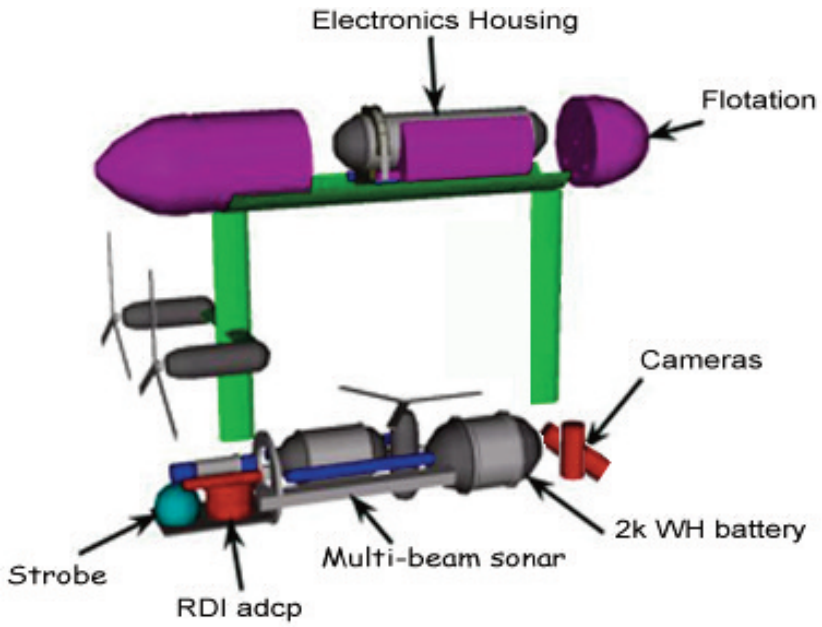


Although the U.S. Caribbean and the wider Caribbean region contain a huge diversity of deep-water corals, there are no conservation or management efforts specifically targeting deep-water corals. The available information on benthic communities associated with DCE in Puerto Rico and the U.S. Virgin Islands is scarce and mostly limited to taxonomic listings from incidental collections by fish traps, shrimp trawls and coral entanglement devices. To this day, quantitative characterizations of sessile-benthic populations as well as relative abundance of motile large bottom-dwelling invertebrates and fishes in these deep reef habitats are lacking. Additionally, the location and distribution of deep coral habitats in the US Caribbean is presently unknown.

The Seabed AUV

The Seabed AUV was designed for benthic imaging applications using multi-beam sonar and optical camera systems. It is composed of two torpedo-like body sections joined by vertical structural members (Figure 2b). This design makes the vehicle capable of hovering and remaining passively stable in pitch and roll. The AUV was programmed to maintain a fixed distance from the bottom to avoid collisions in case sudden changes in bottom relief were encountered. Measurements of velocity over the bottom, heading, altitude, pitch, roll and integrated position, are provided by a 300 kHz acoustic Doppler current profiler (ADCP), which projects four sonar beams into the water. We utilize the forward pointing beam for obstacle avoidance. A Paroscientific™ Model 8DP depth sensor provides depth information that, when combined with a dedicated vertical thruster, delivers depth accuracies in the order of 3.5 cm during the missions.

The main imaging sensor of this vehicle is a Prosilica™ GC-1380C CCD camera with 1360 x 1024 resolution and large, 12 bit dynamic range. The camera was outfitted with a Schneider Optics Cinegon™ 8 mm focal length, f/1.4, C-mount lens. The angular fields of view in the horizontal and vertical directions are 55° and 42°, respectively. The size of the images was determined based on the altitude of the vehicle to the bottom and the field of view of the camera. From an altitude of 3 m, the images were 3.12 m wide by 2.3 m long. Dividing these numbers by the corresponding CCD dimensions resulted in both horizontal and vertical spatial resolutions of 2.2 mm per pixel. A 150 Ws strobe provided the only source of illumination since the AUV missions were conducted at night. The strobe is mounted 1.4 m aft of the camera to reduce the effects of lighting backscatter in the images. The frequency of photos is a function of strobe recharge time (2.5 s). Two cameras were used, a downward looking camera and a forward facing camera. We used the downward-looking camera for the benthic quantitative analysis since it provides more uniform illumination and minimal distortion.



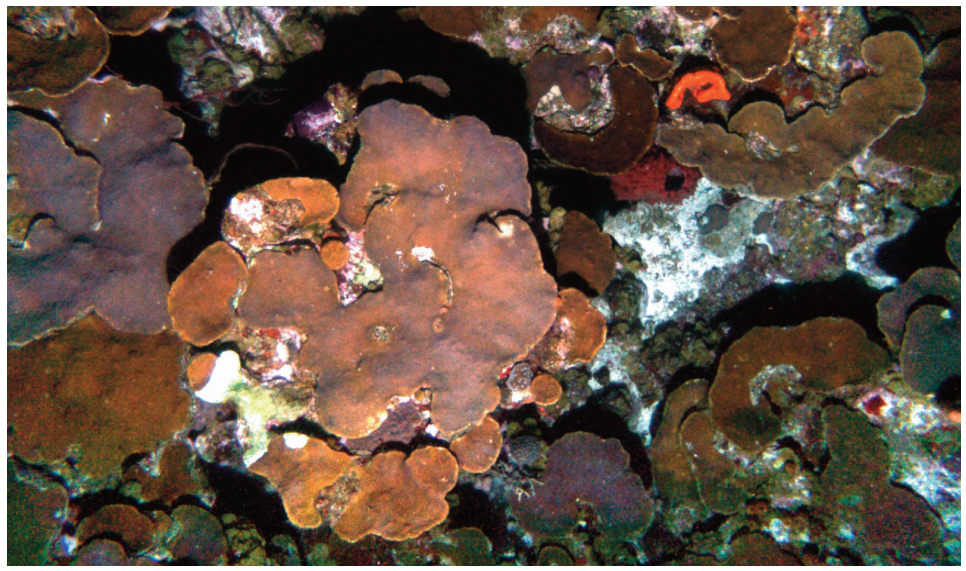
The Seabed sensor suite includes two high dynamic range CCD cameras, multi-beam sonar and a 300 kHz acoustic Doppler current profiler.

The Seabed AUV is a two hull hovering design with a 2000m depth capability designed by Dr. Hanumant Singh (background facing camera) from the Woods Hole Oceographic Institution. It has an endurance of 8 hours at speed ranging from 0-1.5m/s.

Coral Reef Imaging and Mosaics of Mesophotic Reefs

Large, structurally complex MCE are abundant off the eastern Puerto Rico Shelf between the US Virgin Islands and the islands of Vieques and Culebra. At the Hind Bank Marine Conservation District (MCD), south of St. Thomas, USVI, well-developed coral reefs with 43% mean living coral cover were found at depths of 40-47 m. In these low-gradient platforms, high-rugosity coral reefs, dominated by a flattened morphotype of *Montastraea annularis* complex are common at depths of 30 to 45 m. A different type of low-gradient MCE formation is associated with extensive algal rhodolith deposits and dominated by benthic algae, sponges and corals of the genus *Agaricia*. These reefs are typical of oceanic islands and isolated banks in the Mona Passage, west of Puerto Rico at depths of about 50 to 100 m.

Over 100,000 high-resolution images of deep reef environments have been obtained by the Seabed AUV since 2002. Conventional AUV transects are approximately one km long and take about two hours to complete. From an altitude of 3 m the area covered is about 3,120 m^2 for each km of transect length. Individual images from the bottom-looking camera are used for quantitative analysis of benthic communities. The high overlap (30-50%) of these images can be used for creating one-dimensional photomosaics of large reef tracts along individual transects.



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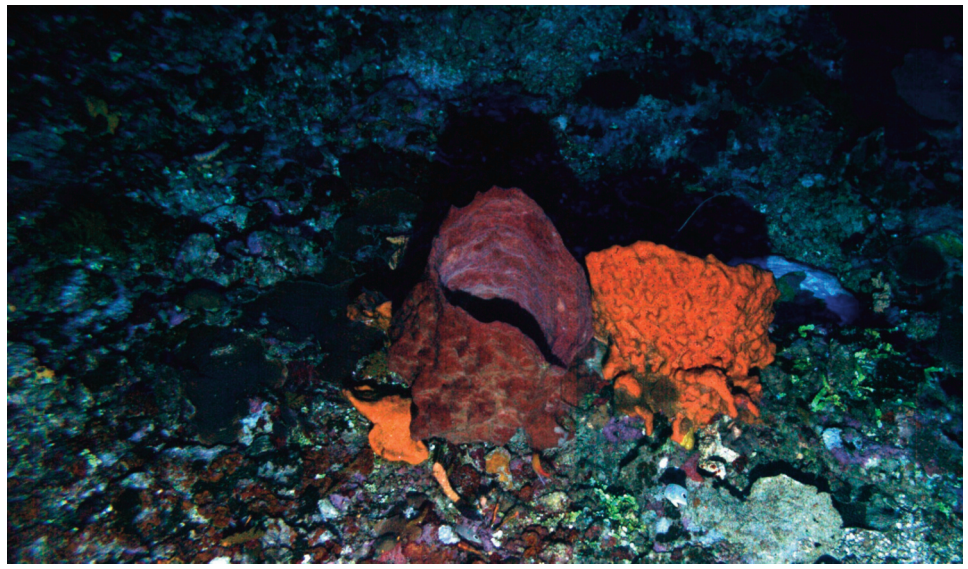

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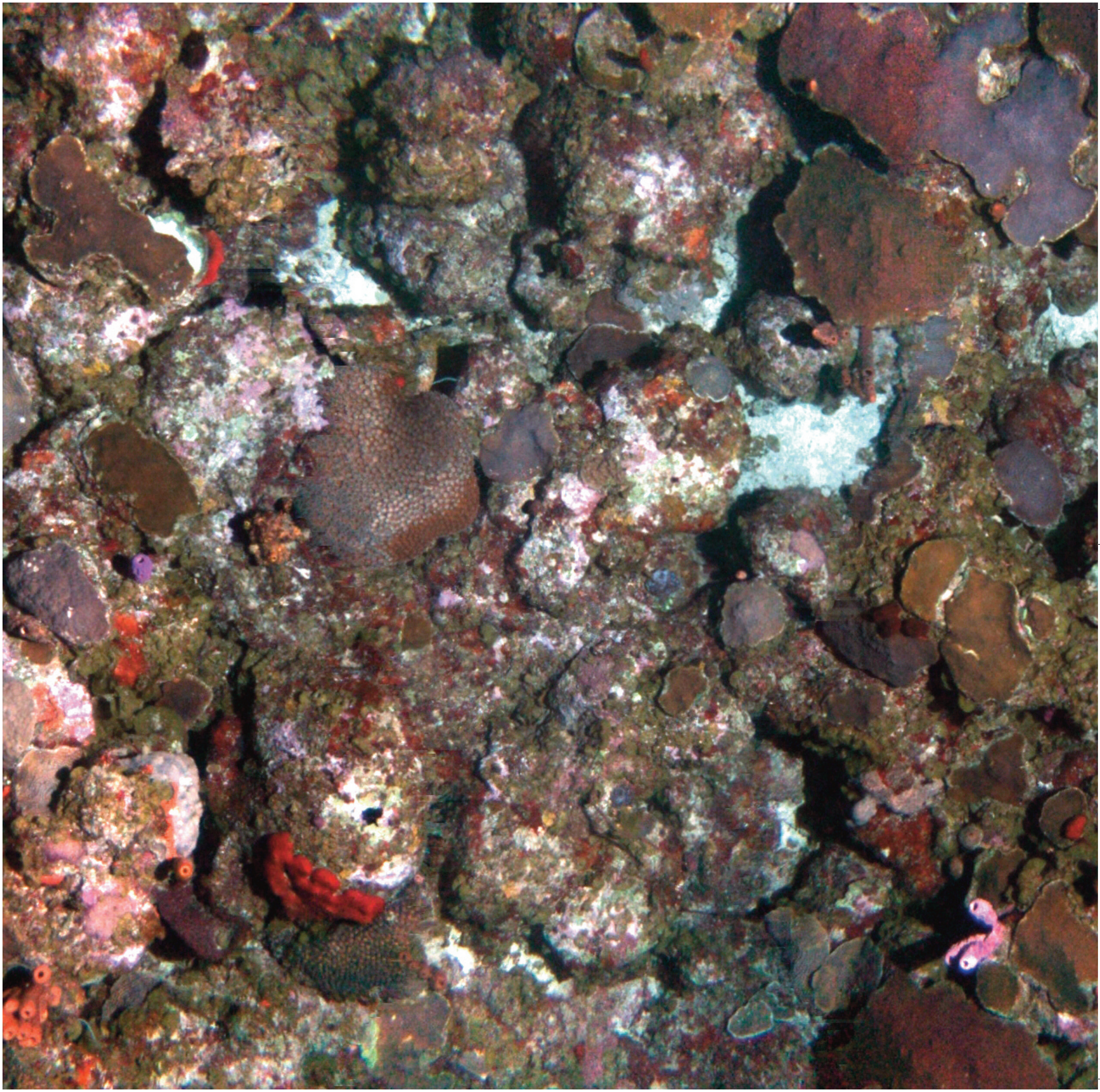
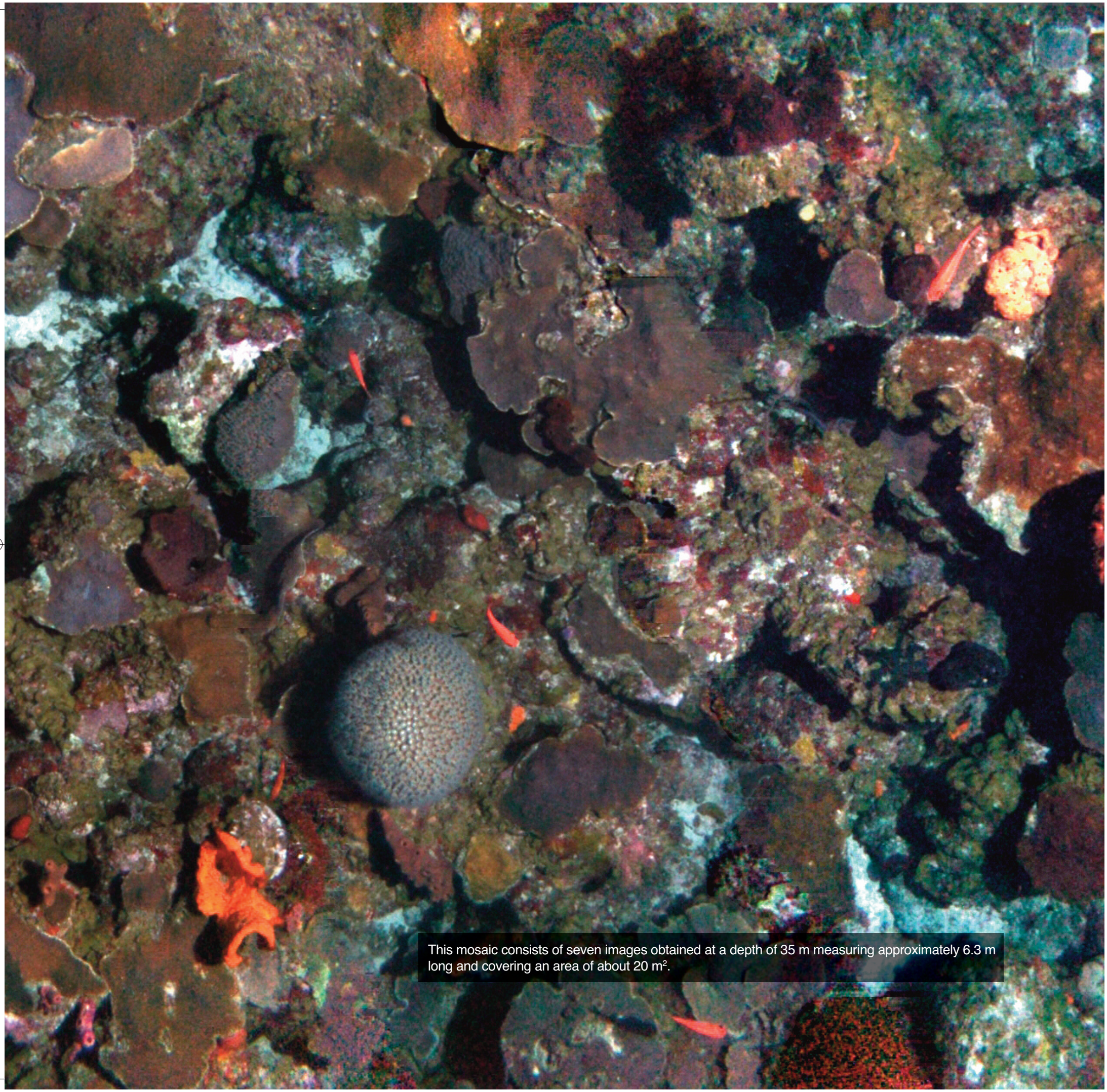




This mosaic consists of seven images obtained at a depth of 35 m measuring approximately 6.3 m long and covering an area of about 20 m^2.

The creation of large two-dimensional mosaics, using adjacent and overlapping AUV transects, is also possible with the use of a true-north seeking, 3 axis fiber optic gyro. The enhanced precision and accuracy of the heading and other attitude measurements available dramatically reduces the error growth of the integrated Doppler velocity log (going from ~5% with the current navigation system to ~0.1% with an Octans™ in place). This mosaic measures approximately 2,500 m^2 resolution were used to create this mosaic measuring 4.5 m wide by 14 m long. Two-dimensional mosaics allow visualizing large reef features and the ability to measure distances and the size of coral reef components directly from the images once a scale has been established.

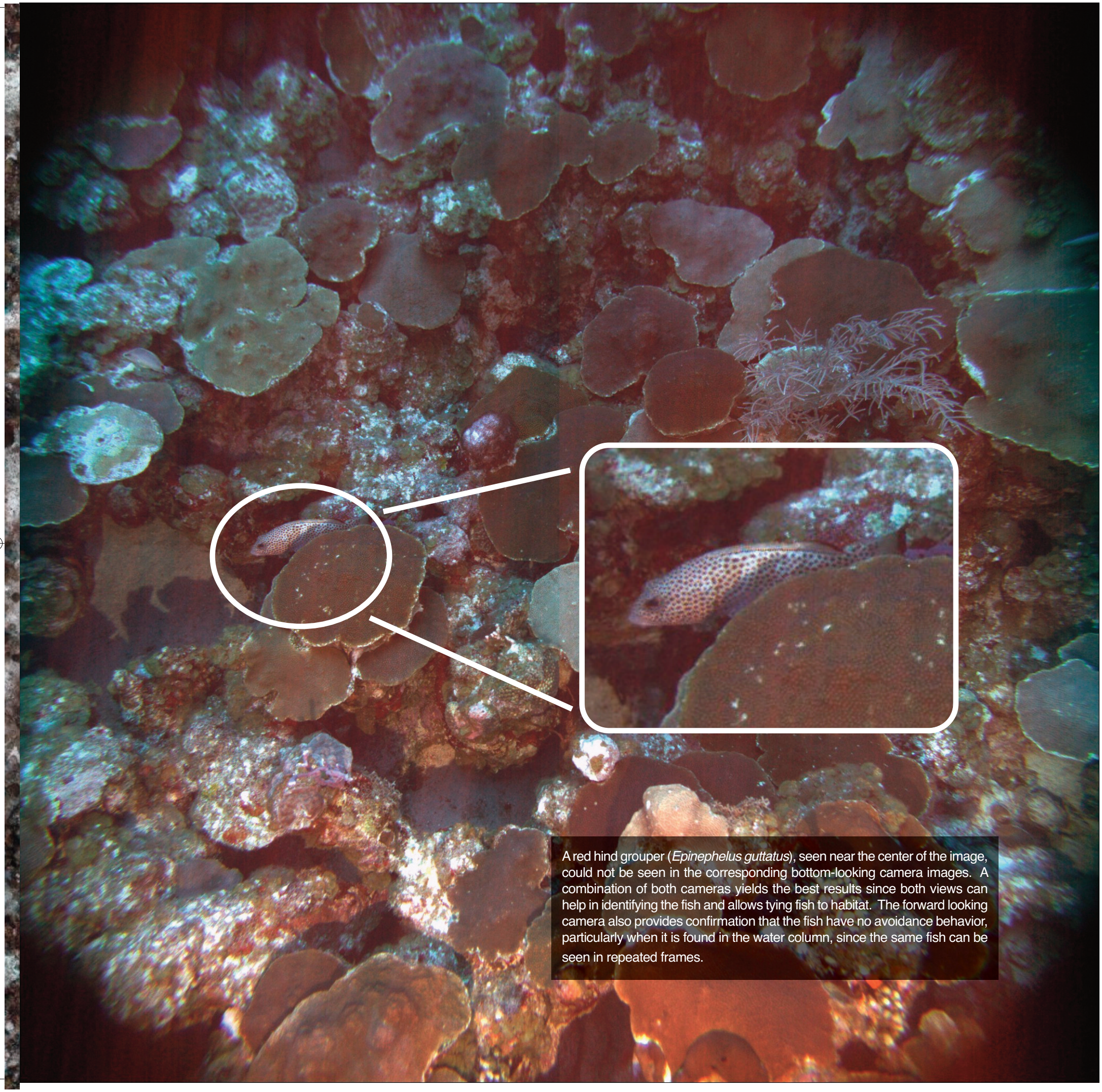
The clear oligotrophic waters of the MCD have a mean light attenuation coefficient of 0.035 m-1 resulting in the euphotic (naturally illuminated) zone (1% of surface values) reaching depths of approximately 131 m.

Landscape-level mapping of Mesophotic Coral Ecosystems in the Puerto Rico Shelf, using the AUV, is possible due to the low particle backscattering in these waters, which allows for extended camera-to-bottom substrate distance and therefore, a larger area of coverage.

The autonomous underwater vehicle is capable of surveying transects up to 6-7 km long per mission, facilitating mapping the distribution of coral reef and other benthic habitats over extensive areas.

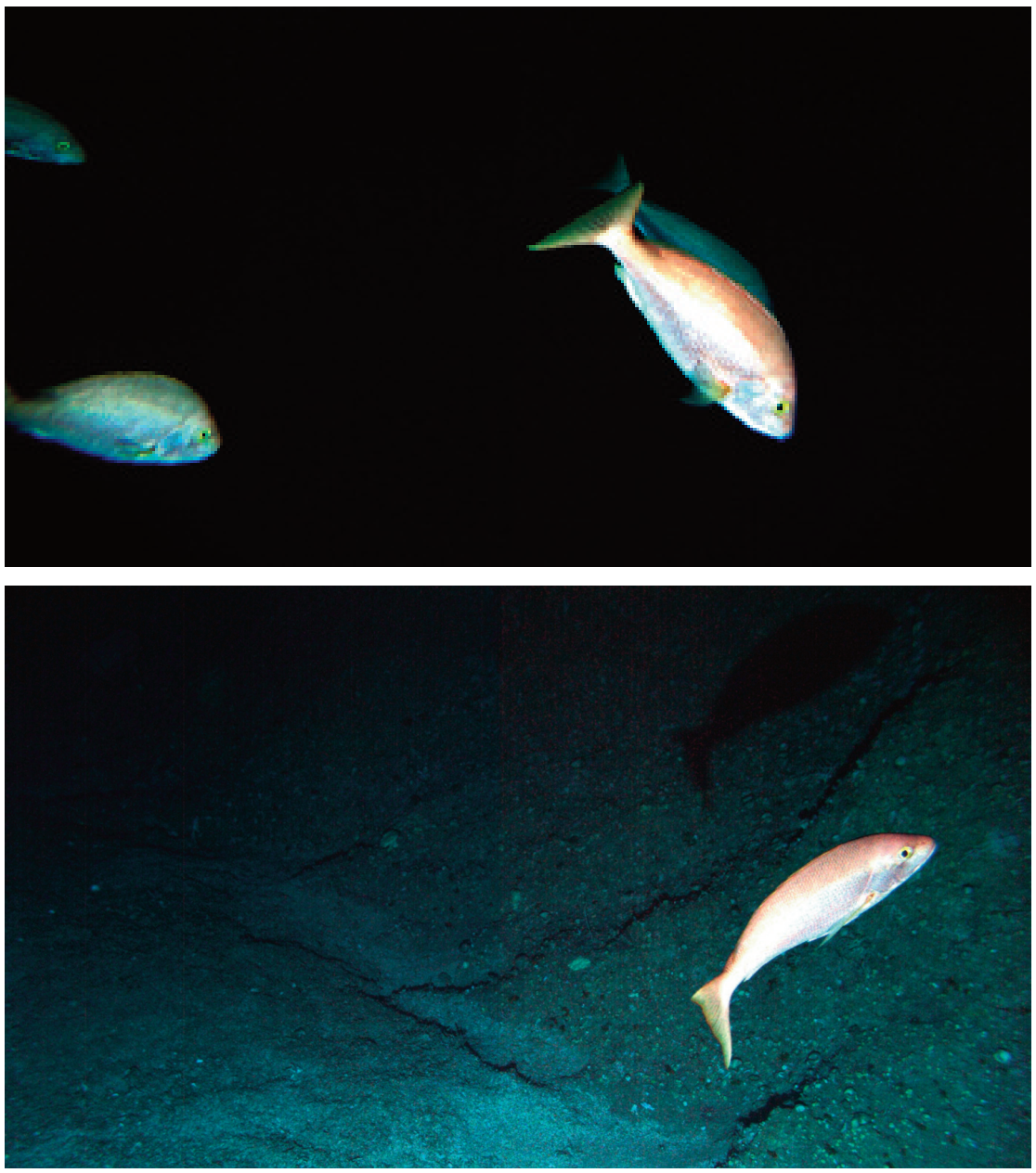
The forward-looking camera is better suited for fish surveys since it provides a lateral view of the fish, facilitating species identification. This oblique view is also preferable for qualitative descriptions of reef structural complexity and rugosity. It also helps with the identification of sponges and other organisms with high relief.

Photo mosaic capability, for a shelf-edge reef off southwestern Puerto Rico



A red hind grouper (*Epinephelus guttatus*), seen near the center of the image, could not be seen in the corresponding bottom-looking camera images. A combination of both cameras yields the best results since both views can help in identifying the fish and allows tying fish to habitat. The forward looking camera also provides confirmation that the fish have no avoidance behavior, particularly when it is found in the water column, since the same fish can be seen in repeated frames.

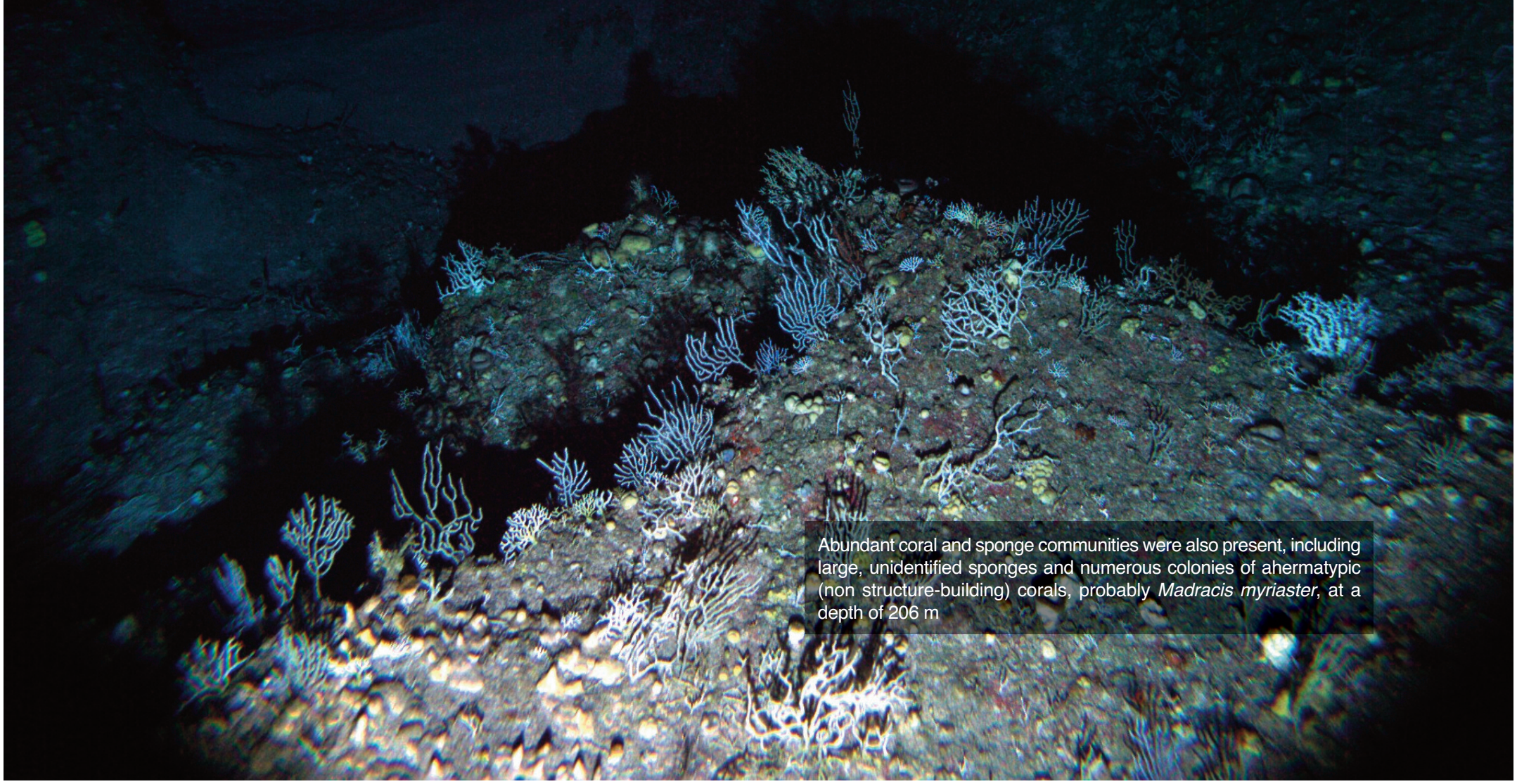
Deep Coral Ecosystems



Preliminary surveys of deep coral ecosystems were conducted by the Seabed AUV in 2008. Two 0.5 km long photo transects were obtained at depths ranging from 198 to 280 m in the Mona Passage west of Puerto Rico. These sites are known habitats of the commercially important silk snapper (*Lutjanus vivanus*). The only previous information available on the description of the essential fish habitat for silk snapper in Puerto Rico dates to 1985, when areas where these fish are normally fished were described as "depaupered". This original description was probably a consequence of the avoidance behavior of fish, fleeing from the Johnson Sea-Link submersible floodlights.

Silk snappers were observed during the descent of the AUV at 21 m from the bottom (total depth 198 m) and near the bottom at a depth of 219 m.

The Magnuson-Stevens Fishery Management and Conservation Act requires the identification, description and mapping of essential fish habitat (EFH) in terms of feeding, growing to maturity, and breeding, and introduces the need to identify habitat areas of particular concern (HAPC) such as spawning aggregation sites. The AUV allows for the identification and description of these EFH and HAPCs. Once the high-resolution benthic images are analyzed quantitatively, estimates of fish abundance and the use of the habitat can be described.



Abundant coral and sponge communities were also present, including large, unidentified sponges and numerous colonies of ahermatypic (non structure-building) corals, probably *Madracis myriaster*, at a depth of 206 m

The Seabed AUV was conceived as an inexpensive alternative to provide high resolution imaging capabilities typically associated with large remote operated vehicles (ROVs) and other tethered vehicles. This technology has made possible, for the first time, the large-scale mapping and quantitative characterization of deep coral communities in the US Caribbean. Fish, coral and other macro invertebrates can be identified in most cases to the species level. However, only major groups of algae, within the mesophotic zone, could be identified from the digital photo transects.

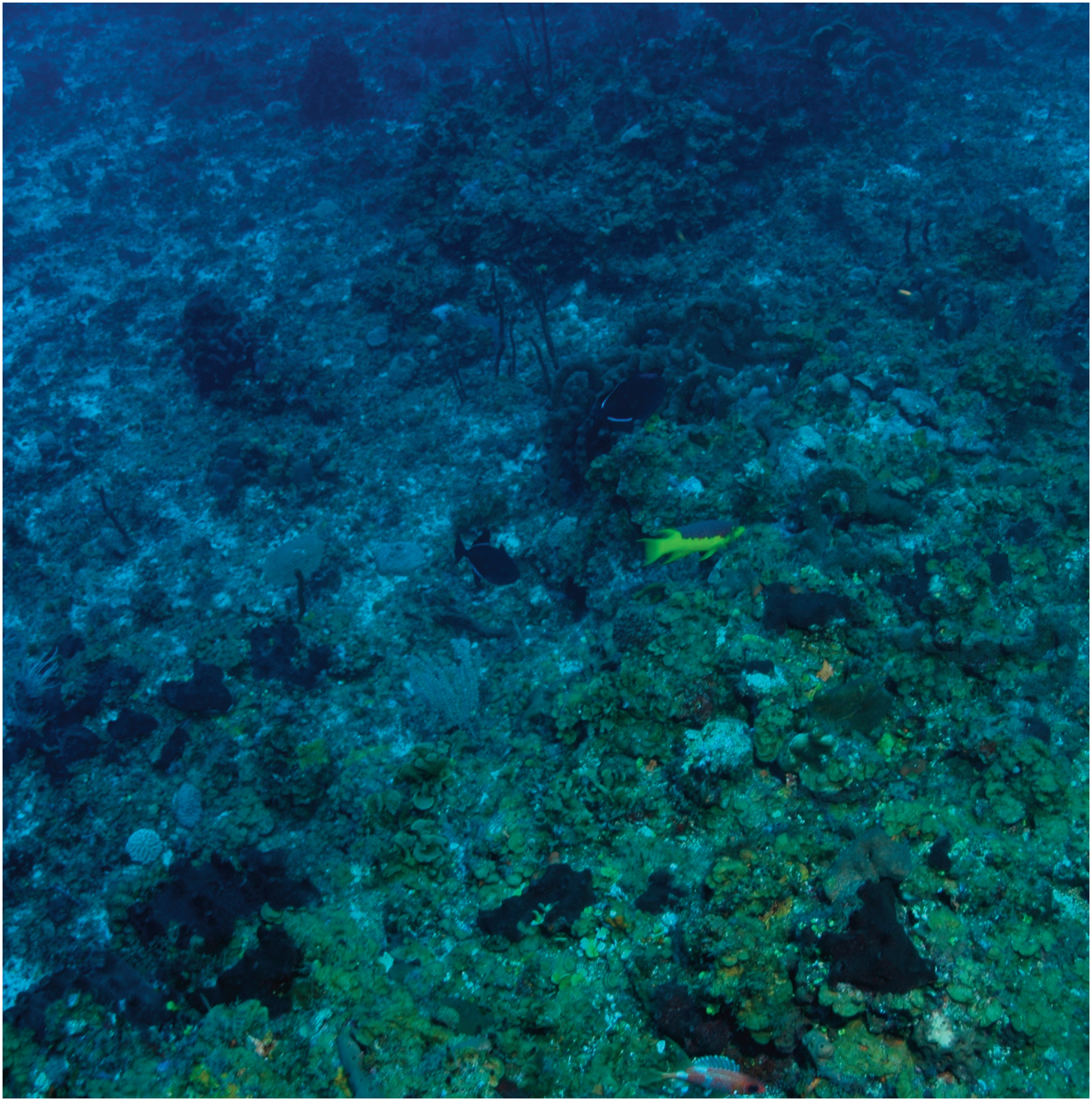
Conventional Seabed AUV transects are one km long and take about two hours to complete. From an altitude of 3 m the area covered is approximately 3,120 m^2. In contrast, diving surveys at the MCD have involved the capture of 25 to 100 non-overlapping frames from 10 m (minimum) to 30 m (maximum) video transect. Each frame covers an area of approximately 0.31 m^2 (0.64 m x 0.48 m) per image for a total area sampled from 7.7 to 31 m^2. This is less than 1% of the total area covered by the AUV in a one km transect. On the other hand, the identification of most algae to species level and detection of cryptic organisms is facilitated by diver surveys. Divers can also collect specimens for later identification. Underestimates in percent cover of Octocorals occurs with diver transects since the video coverage of benthic organisms is often below the canopy of tall gorgonians. While coral cover estimates using both methods are very similar, sponge cover estimates are more variable with SCUBA surveys. These and other comparisons between AUV phototransects and traditional diver video surveys have been addressed.

Large-scale mapping of the large MCE (~300 km^2), situated between St. John, USVI and the islands of Vieques and Culebra in the east Puerto Rico Shelf, is feasible using the Seabed AUV at altitudes of 5 to 10 m above the bottom. From initial landscape level surveys obtained at coarse resolution, areas that appear to be impacted by recent mortality or bleaching can be re-surveyed at lower altitudes for more detailed characterization and for monitoring purposes. This vehicle's capability of acquiring km-level transects and the creation of one- and two-dimensional mosaics of very large areas makes it the ideal platform for large-scale mapping and monitoring of the little-known insular shelf mesophotic reefs.

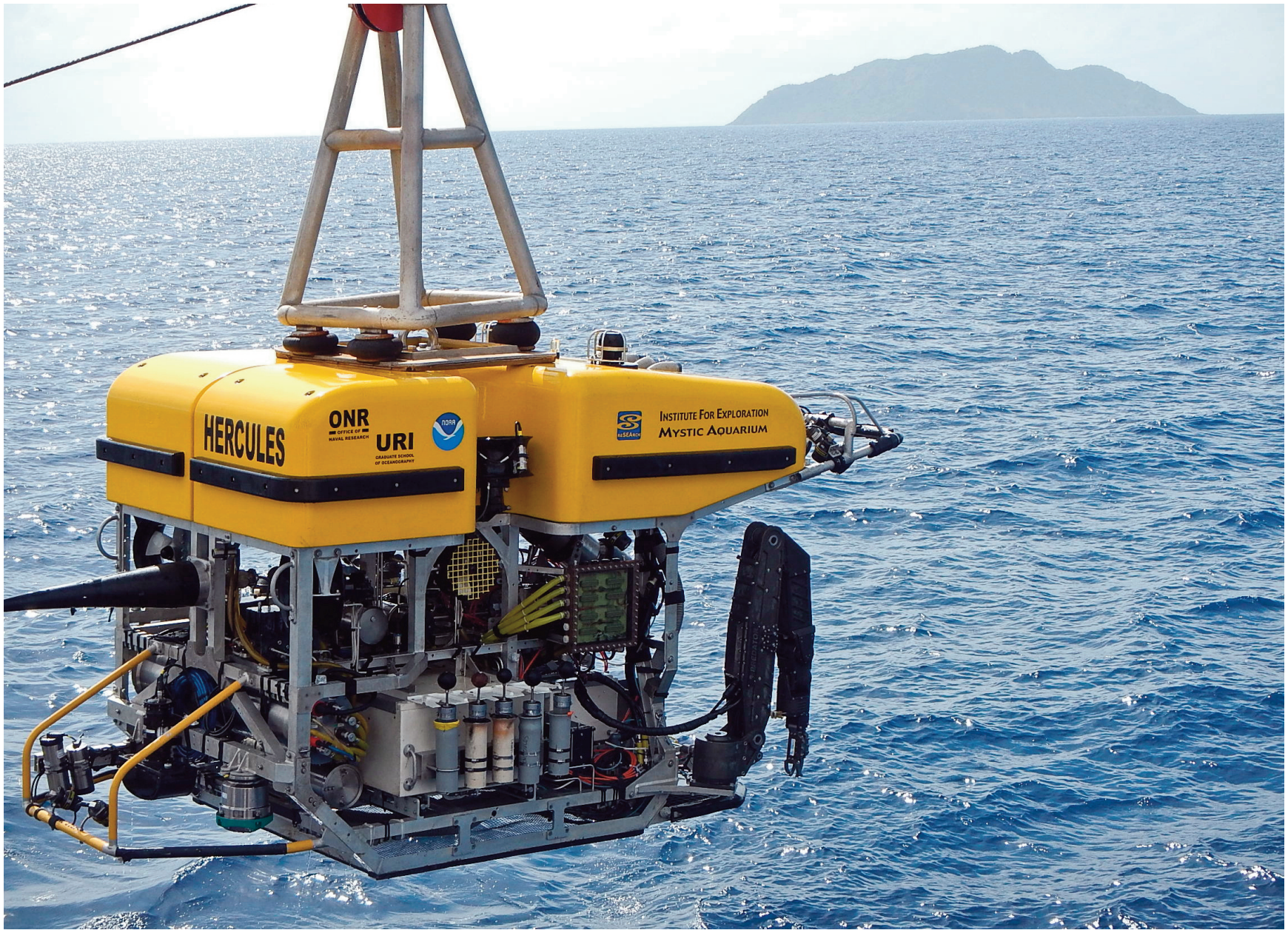
In the US Caribbean, deep reef habitat and fish observations to depths of 100-450 m have been limited to video records of the Seward Johnson-Sea Link II submersible survey until the arrival of the Nautilus E/V in 2013. However, quantitative assessments of sessile-benthic populations as well as information on densities and relative abundance of fishes and motile bottom-dwelling invertebrates from these important habitats is still lacking. Preliminary surveys of deep coral ecosystems by the Seabed AUV in 2008 off western Puerto Rico show diverse coral and invertebrate fauna at depths of 200 to 240 m. Identification of commercially-important fish species, such as the silk snapper, was facilitated by the forward-looking camera of the AUV. However, accurate identification of deep-sea corals and other macro invertebrates, particularly to the species level, will require the creation of an image-based catalog validated by reference collections.

Acoustic and optical data fusion, image-based navigation, and 3-D image reconstruction are promising technologies that will augment the Seabed AUV capabilities for remote sensing surveys and ecological assessments of deep reef habitats. Mapping the locations of deep coral habitat would be a valuable component of any meaningful ecosystem based management program for the U.S. Caribbean. For both mesophotic and deep coral ecosystems, the AUV benthic assessments can provide the required information for selecting unique areas of high biodiversity and structural complexity for habitat protection and management.

Hanumant Singh, Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, has contributed to this section.

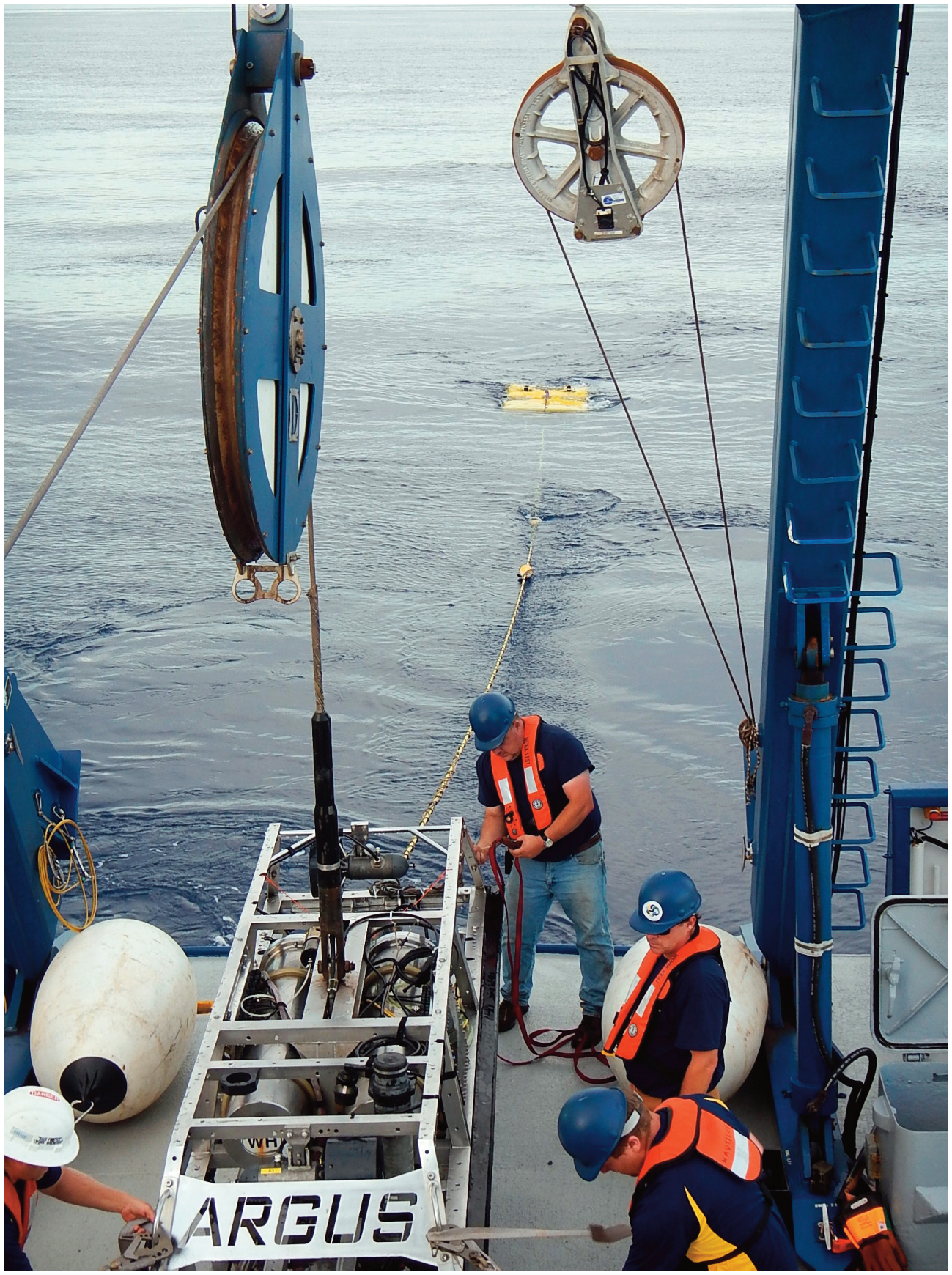


Hercules and Argus Remotely Operated Vehicles



Lowering the Hercules ROV in the Mona Passage. Desecheo Island can be seen in the background.

Hercules is a large remotely operated vehicle (ROV) with a depth rating of 4000 m. It measures 11' long x 6' wide x 7.5' tall (3.4 m x 1.8 m x 2.3 m) and weights 5400 pounds (2450 kg) in air. In the water it is neutrally buoyant and is always attached to its mating vehicle, the Argus. Hercules is equipped with six thrusters that allow it to move slowly in any direction. Hercules is used for close-up visual inspection using its high definition video camera, sampling using its two manipulators, and precision acoustic and visual mapping of a site using its high-resolution sonars and/or digital stereo still cameras. Its sensor array consists of a pressure/depth sensor, altimeter, and Doppler.



Argus is an ROV that is tethered via a steel-armored fiber-optic cable directly to the E/V Nautilus. It can be used in two different modes of operation: alone, or with another ROV. Alone, Argus is towed behind the ship as a towsled for broad-area visual and/or sonar surveys. In tandem mode, Argus is typically used with ROV Hercules. In this tandem mode, Hercules is connected to Argus via a 30 m fiber-optic tether. By working in tandem, Argus removes the heave of the ship from Hercules so that it can work on the seafloor as a stable platform. Argus measures 11' long x 4' wide x 4' tall (3.4 m x 1.2 m x 1.2 m) and weights 4000 pounds (1800 kg) in air and 3000 pounds (1350 kg) in water. Its depth rating is 6000 m.

Hercules (in the water) is attached to ARGUS by a 30 m tether.