Large-scale Mapping and Characterization of Deep Reef Habitats in the US Caribbean

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ABSTRACT

While the distribution and status of shallow-water reefs in many parts of the world has been well documented in the last 40 years, benthic characterization studies and large-scale mapping of deep reef habitats, are very rare. Recent studies on mesophotic coral ecosystems (30 - 100 m) in the eastern Puerto Rico Shelf describe abundant and structurally complex coral reefs on low-gradient platforms at depths of 35 - 45 m. Information on deep coral communities (> 200 m depth) in the US Caribbean is even more scarce and largely limited to taxonomic listings from incidental collections by coral entanglement devices. In recent years, the Seabed autonomous underwater vehicle (AUV), which was designed for high-resolution underwater optical and acoustic imaging, has provided unprecedented information on the distribution, community structure, and status of mesophotic reefs throughout the U.S. Caribbean. Preliminary surveys of two deep coral communities off western Puerto Rico show diverse azooxanthellate coral and invertebrate fauna at depths of over 200 m. For both mesophotic and deep coral communities, the AUV benthic assessments can provide the required information for selecting unique areas of high biodiversity and structural complexity for habitat protection and ecosystem based management.

KEY WORDS: Mapping, deep reefs, mesophotic, US Caribbean, Seabed AUV

Cartografía a Gran Escala y Monitoreo de Arrecifes Mesofóticos en la Plataforma de Puerto Rico

Mientras que la distribución y estado de los arrecifes de aguas someras en muchas partes del mundo ha sido bien documentado durante los últimos 40 años, la cartografia a gran escala y los estudios de caracterización béntica de arrecifes profundos son muy raros. Estudios recientes de ecosistemas de arrecifes mesofóticos (30-100 m) en la plataforma insular oriental de Puerto Rico describen arrecifes de coral estructuralmente complejos en plataformas de baja pendiente a profundidades de 35-45 m. Información de comunidades profundas de coral (>200 m) dentro de la jurisdicción de los Estados Unidos en el Caribe es aun mas escasa y mayormente limitada a listados taxonómicos de colecciones obtenidas por aparatos que traen a la superficie corales enredados. En años recientes, el vehiculo autónomo submarino (VAS) Seabed, diseñado para obtener imágenes subacuaticas ópticas y acústicas de alta resolución, ha brindado información sin precedentes de la distribución, estructura de la comunidad, y el estado de los arrecifes mesofóticos a lo largo de la jurisdicción de los Estados Unidos en el Caribe. Muestreos preliminares de dos arrecifes profundos al oeste de Puerto Rico muestran una fauna diversa de invertebrados y corales azooxantelados a profundidades mayores de 200 m. Tanto para los arrecifes mesofóticos y los profundos, las evaluaciones bénticas del VAS pueden proveer la información necesaria para la selección de áreas únicas de alta diversidad y complejidad estructural para la protección de habitáculos y manejo basado en ecosistemas.

PALBRAS CLAVE: Cartografía, arrecifes mesofóticos, Puerto Rico, vehiculo autónomo submarino (VAS)

Cartographie à Grande Échelle et Caractérisation des Récifs Profonds dans les Etats-Unis Caraïbes

Bien que la distribution et l'état des récifs en eaux peu profondes dans plusieurs régions du monde aient été bien documentés dans les dernières quarantaines d'années, des études de caractérisation benthiques et de cartographie à grande échelle des habitats de récifs profonds sont très rares. Des études récentes sur les écosystèmes coralliens mésophotiques (30 - 100 m) dans l'Est du plateau de Porto Rico décrivent des récifs coralliens en abondance et structurellement complexes, sur des plates-formes de faible gradient à des profondeurs de 35- 45 m. L'information sur des communautés coralliennes profondes (> 200 m de profondeur) dans les Caraïbes des Etats-Unis est encore plus rare et largement limitée à des inventaires taxonomiques à cause de collections accidentelles par des appareils d'enchevêtrement coralliens. Ces dernières années, le Seabed véhicule sous-marin autonome (AUV), qui a été conçu pour recueillir des données à haute résolution d'imagerie optique et acoustique sous-marine, a fourni des informations sans précédent sur la distribution, la structure de la communauté, et de l'état des récifs mésophotiques dans les Caraïbes des Etats-Unis. Des enquêtes préliminaires de deux habitats des récifs profonds au large de l'Ouest de Porto Rico montrent une diversité des coraux azooxanthellés et de la faune invertébrée à des profondeurs de 210 m. Pour les deux communautés coralliennes mésophotiques et profondes, les évaluations benthiques du AUV peuvent fournir les informations nécessaires pour sélectionner des zones uniques de haute biodiversité et de complexité structurelle pour la protection de l'habitat et de la gestion fondée sur les écosystèmes.

MOTS CLÉS: Cartographie, récifs profonds, Porto Rico, véhicule sous-marin autonome (AUV)

Introduction

Deep reefs, typically dominated by zooxanthallate or azooxanthellate corals are important habitats for marine sessile-benthic and motile megabenthic 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, low-gradient platforms, and high-gradient insular slopes. Two distinct deep reef systems are described here: 1) Mesophotic coral ecosystems (MCEs), which are light-dependent coral, algal, and sponge communities that extend from 30 m to over 100 m in tropical and subtropical regions, and 2) Deep coral communities (DCC), which extend to deeper, colder waters to form banks, bioherms and other aggregations of azooxanthellate corals and other organisms.

In the Puerto Rico Shelf, MCEs are found in high-gradient slopes and low-gradient insular platforms (Locker et al. 2010). They achieve their greatest development on low-gradient platforms, where relic reefs and terraces provide favourable hard substrates for colonization. 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 and dominated by benthic algae, sponges and corals of the genus *Agaricia*.

Since 2002 we have used the imaging capabilities of the Seabed autonomous underwater vehicle (AUV) to map and characterize MCEs throughout the Puerto Rico Shelf (Armstrong et al. 2002, Singh et al. 2004, Armstrong et al. 2006, Armstrong and Singh 2006, Armstrong 2007, Armstrong et al. 2009, Rivero-Calle et al. 2009, Rivero-Calle 2010, Armstrong and Singh In press).

Although the U.S. Caribbean and the wider Caribbean region contain a huge diversity of deep water corals (Lutz and Ginsburg 2007), the available information on benthic communities associated with DCC 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 (Garcia 2004). To this day, quantitative characterizations of sessile-benthic populations as well as relative abundance of motile-megabenthic invertebrates and fishes in these deep reef habitats are still lacking.

METHODS

The Seabed AUV, designed for high-resolution underwater optical and acoustic imaging, is a stable platform that provides high resolution color imagery of benthic environments. It is composed of two torpedo-like body sections joined by vertical structural members. This design makes the vehicle hover capable and passively stable in pitch and roll. The AUV can be programmed to maintain a fixed distance from the bottom to avoid collisions in case sudden changes in bottom relief are encountered. Measurements of velocity over the bottom, heading, altitude, pitch, roll and integrated position are provided by a 1,200 kHz acoustic Doppler current profiler (ADCP), which projects four sonar beams into the water. The forward pointing beam is utilized 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 sensors of this vehicle are two Prosilica GC-1380C CCD cameras with 1360 x 1024 resolution and large, 12 bit dynamic range in a downward looking and forward facing configuration. The downward looking camera is used for benthic quantitative analysis since it provides more uniform illumination and minimal distortion. The size of the images is 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 are 3.12 m wide by 2.3 m long. A 150 Ws strobe provides the only source of illumination. 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). More information on Seabed capabilities and sensors can be found in Singh et al. (2004).

RESULTS

Mesophotic Reefs

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 nadir-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 (Figure 1). 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.

Large, structurally complex MCEs are abundant off the eastern Puerto Rico Shelf between the US Virgin Islands and the islands of Vieques and Culebra (Smith et al. 2010). 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 (Armstrong et al. 2006). 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 (Figure 1). 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 (Figure 2).

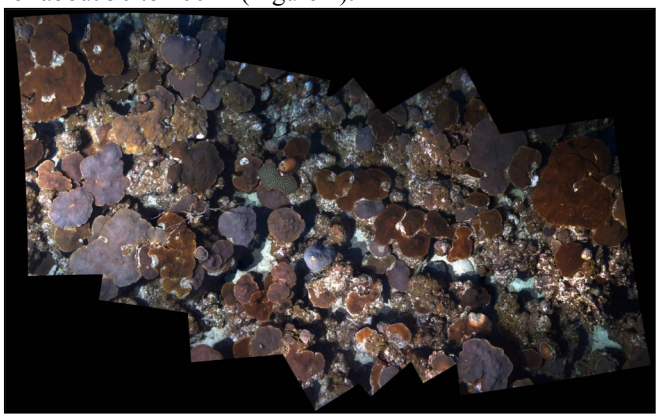

Figure 1. One-dimensional photomosaic consisting of seven overlapping images from the Hind Bank Marine Conservation District (MCD) at a depth of 35 m. The mosaic measures approximately 6.3 m long and covers an area of about 20 m^2.

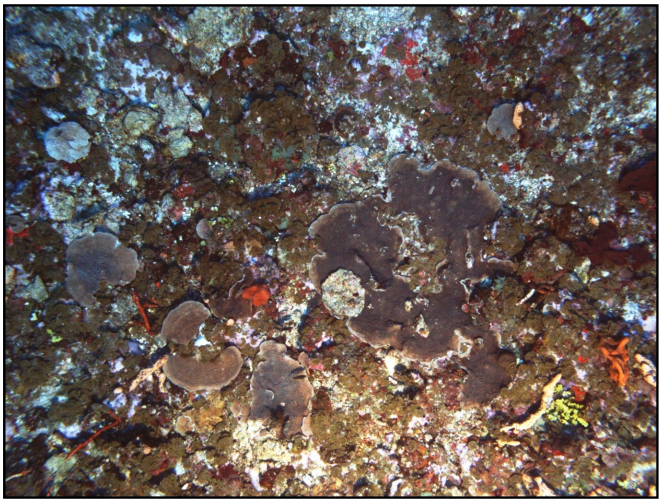

Figure 2. Low-relief mesophotic reef at a depth of 65 m in Bajo de Cico showing high live cover, mostly by the macroalgae *Lobophora variegata*, sponges, and several flattened colonies of the genus *Agaricia*.

Landscape-level mapping of MCEs 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. At the end of one of the Hind Bank MCD missions, a series of images were obtained from the same reef area during the ascent of the vehicle. These images show decreasing levels of detail and image quality as the altitude of the vehicle increased (Figure 3). The level of detail provided by the high dynamic range camera with artificial illumination was unexpected considering the exponential attenuation of light in the water column. While the closest camera to bottom distances (2.6 and 3.6 m) provided the highest level of detail and color rendition, higher altitudes of 5.0 and 6.3 m were sufficient for assessing living coral cover (Figure 3). At altitudes higher than 10 m, the basic reef geomorphology was still evident but the image resolution was not adequate for quantitative analysis. Landscape-level analysis of coral bleaching and mortality can be obtained from altitudes of 5 or 10 m, depending on the level of detail required, while covering an area of 5.2 and 10.4 km^2, respectively, for each km of transect length. At 14.4 m altitude the area covered by each image is 163 m^2. A one km transect at this altitude will cover an area of approximately 14.9 km^2, providing rapid assessments of the distribution of mesophotic reefs over large 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. An example image from the forward-looking camera is shown in Figure 4. A red hind grouper (*Epinephelus guttatus*), seen near the center of the image, could not be seen in the corresponding nadir-looking camera images.

Deep Coral Communities

Preliminary surveys of deep coral communities 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*). 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 (Figure 5). Abundant coral and sponge communities were also present including large, unidentified sponges and numerous colonies of ahermatypic corals, probably *Madracis myriaster*, at a depth of 206 m (Figure 6).

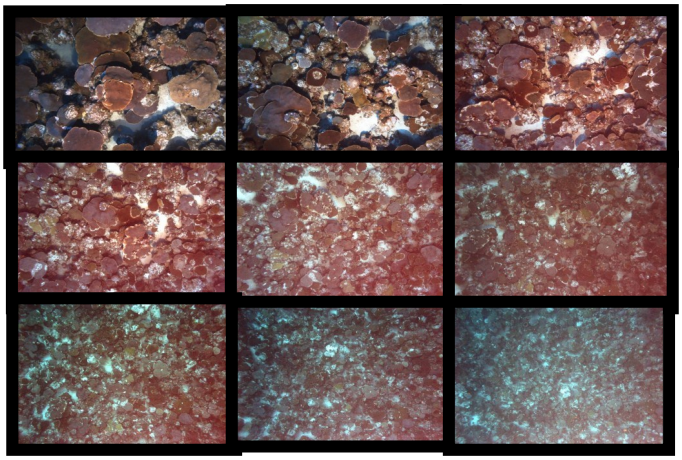

Figure 3. Nadir-looking camera sequence from the Hind Bank MCD obtained at 2.6 m, 3.6 m, 5.0 m, 6.3 m, 7.5 m, 8.7 m, 10 m, 11.9 m, and 14.4 m altitudes from the bottom.

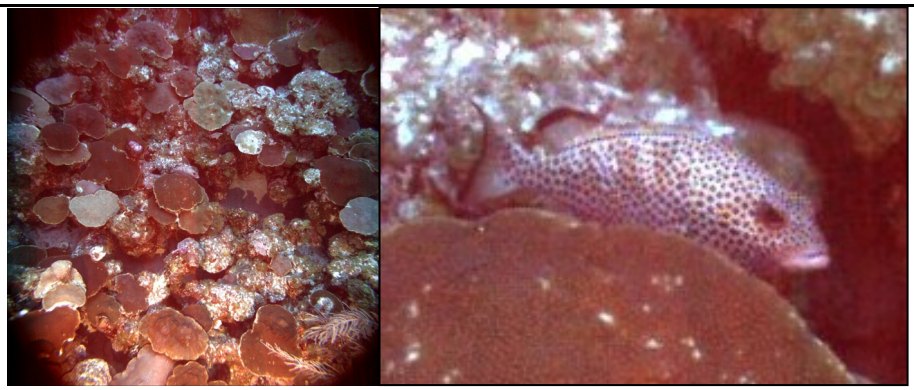

Figure 4. Forward-looking camera image showing a red hind grouper (*E. guttatus*) (A) and enlargement of the fish (B).

Figure 5. Silk snappers (*Lutjanus vivanus*) at 21 m from the bottom (total depth 198 m) (A) and near the bottom at a depth of 219 m (B).

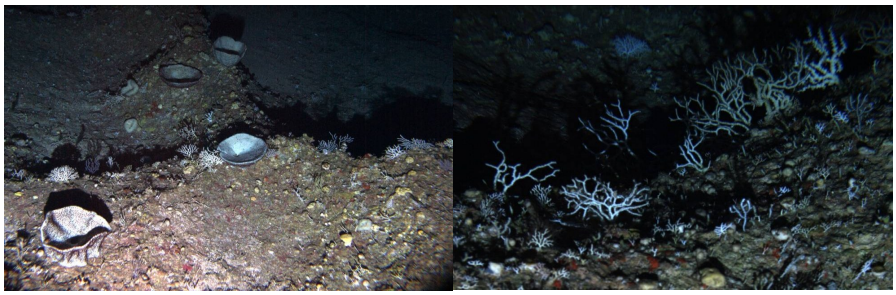

Figure 6. Deep water sponges and corals off western Puerto Rico (A) and close up of small ahermatypic coral colonies (B).

DISCUSSION

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.

Geomorphology, depth, light availability (and its surrogate, water turbidity) are factors affecting the community structure of MCEs in Puerto Rico (Rivero-Calle 2010). This author compared five known MCE areas around the island and found that coral cover, macroalgae cover and total live cover tend to increase with distance from land and decrease with water turbidity. These relationships were considerably stronger in the lower mesophotic ranges (50 - 100 m) than the upper mesophotic ranges (30 - 50 m).The effect of depth is indirect and related to the amount of incident light since light is attenuated exponentially with depth and is a limiting factor for the maximum depth distribution of zooxanthellate corals (Kahng et al. 2010).

Preliminary surveys of two deep coral communities 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.

Multi-sensor data fusion, image-based navigation, 3-D image reconstruction, and chemical sensors are promising technologies that will augment the Seabed capabilities for remote sensing surveys and ecological assessments of deep reef communities. Mapping the locations of deep coral habitat would be a valuable component of any meaningful ecosystem based management program for the U.S. Caribbean (Lutz and Ginsburg 2007). For both mesophotic and deep coral communities, the AUV benthic assessments can provide the required information for selecting unique areas of high biodiversity and structural complexity for habitat protection and management.

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LITERATURE CITED

Armstrong, R.A., H. Singh, and F. Gilbes. 2002. Benthic Survey of Insular Slope Coral Reefs Using the Seabed AUV. *Backscatter* **13** (3):22-25.

Armstrong, R.A. and H. Singh. 2006. Remote Sensing of Deep Coral Reefs in Puerto Rico and the U.S. Virgin Islands Using the Seabed Autonomous Underwater Vehicle. In: C.R. Bostater, Jr., X. Neyt, S.P. Mertikas, and M. Vélez-Reyes (eds.) *Remote Sensing of the Ocean, Sea Ice, and Large Water Regions*. Proceedings of SPIE Vol. 6360, 63600A.

Armstrong, R.A., H. Singh, J. Torres, R. Nemeth, A. Can, C. Roman, R. Eustice, L. Riggs, and G. Garcia-Moliner. 2006. Characterizing the deep insular shelf coral reef habitat of the Hind Bank Marine Conservation District (US Virgin Islands) using the Seabed Autonomous Underwater Vehicle. *Continental Shelf Research* **26**:194-205.

Armstrong, R.A. 2007. Deep zooxanthellate coral reefs of the Puerto Rico - U.S. Virgin Islands insular platform. *Coral Reefs* **26**(4):945.

Armstrong, R.A., H. Singh, S. Rivero, and F. Gilbes. 2009. Monitoring coral reefs in optically-deep waters. Pages 593-597 in: *Proceedings 11th International Coral Reef Symposium*. Ft. Lauderdale, Florida USA.

Armstrong, R.A. and H. Singh. [In press]. Mesophotic coral reefs of the Puerto Rico Shelf. In: P. Harris and E. Baker, (eds.) *Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of Seafloor Geomorphic Features and Benthic Habitats*. *Chapter 24*. Elsevier Science, New York, New York USA.

Kahng, S.E., J.R. Garcia-Sais, H.L. Spalding, E. Brokovich, D. Wagner, E. Weil, L. Hinderstein, and R.J. Toonen. 2010. Community ecology of mesophotic coral reef ecosystems. *Coral Reefs* **29**:255-275.

Locker, S.D., R.A. Armstrong, T.A. Battista, J.J. Rooney, C. Sherman, and D.G. Zawada. 2010. Geomorphology of Mesophotic Coral Ecosystems. *Coral Reefs* **29**:329-345.

Lutz S.J. and R.N. Ginsburg. 2007. State of the U.S. Deep Coral Ecosystems in the United States Caribbean Region: Puerto Rico and U.S. Virgin Islands. Pages 307-365 in: S.E. Lumsden, T.F. Hourigan, A.W. Bruckner, and G. Dorr (eds.) *The State of Deep Coral Ecosystems of the United States*. NOAA Technical Memorandum CRCP-3. Silver Spring, Maryland USA. 365 pp.

Rivero-Calle, S. 2010. Ecological Aspects of Sponges in Mesophotic Coral Ecosystems. M.S. Thesis, University of Puerto Rico, Mayaguez, Puerto Rico. 85 pp.

Rivero-Calle S, R.A. Armstrong, and F.J. Soto-Santiago. 2009. Biological and physical characteristics of a mesophotic coral reef: Black Jack reef, Vieques, Puerto Rico. Pages 567-571 in: *Proceedings of the 11th International Coral Reef Symposium*. Ft. Lauderdale, Florida USA.

Singh, H., R.A. Armstrong, R. Eustice, C. Roman, O. Pizarro, and J. Torres. 2004. Imaging Coral I: Imaging Coral Habitats with the SeaBED AUV. *Subsurface Sensing Technologies and Applications* **5**(1):25-42.

Smith, T.B., J. Blondeau, R.S. Nemeth, S.J. Pittman, J.M. Calnan, E. Kadison, and J. Gass. 2010. Benthic structure and cryptic mortality in a Caribbean mesophotic coral reef bank system, the Hind Bank Marine Conservation District, U.S. Virgin Islands. *Coral Reefs* **29**:289-308.