Status of coral reefs southwest Puerto Rico

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Abstract

Assessments of coral reefs off the west and south coasts of Puerto Rico, between Mayagüez and Ponce, were conducted over the last 20 years to determine the status and trends of important reef-building species. Species composition, abundance and cover of stony corals were determined from photoquadrats (0.7 m^2 area) placed along 30 m transects that followed depth contours. Coral cover varied from more than 50% to less than 1% and has exhibited an accelerating decline over the 20 year study. The most notable changes have been seen on nearshore reefs affected by coastal runoff, nutrient input or river discharge. The healthiest reefs (highest living coral cover) identified in this study were located at the shelf edge of La Parguera - where communities were dominated by massive species such as the *Montastraea annularis* complex and *Colpophyllia natans*, and plating species like *Agaricia lamarki* in deeper water (25-40 m depth). A shift in species composition occurred on turbid reefs, with a dominance by *Montastraea cavernosa* - and reef-building corals declined in abundance or were absent below 15 m depth. *Acropora palmata* has been dramatically reduced in abundance over the last 20 years but areas of *Acropora palmata* thickets are still present. Some reefs still have fairly extensive populations of *Acropora cervicornis*.

Introduction

Western Atlantic coral reefs have over 60 species of scleractinian corals, but reefs in Puerto Rico are dominated by the reef-building coral taxa, *Montastraea annularis* (complex), *Agaricia agaricites*, *Montastraea cavernosa, Porites asteroides* and *Colpophyllia natans*. These are the major contributors to reef accretion, and are often the most conspicuous corals found in shallow water. In addition to these, *Acropora palmata* and *Acropora cervicornis* often form dense, high relief monospecific thickets; *Acropora palmata* is most abundant from 0-5 m depth in exposed fore reef habitats, while A*cropora cervicornis* occurs from 5-15 m depth on the fore reef and in shallow, protected back reef environments. Although storms and disease have reduced the population of *Acropora palmata* and *Acropora cervicornis*, there are still areas of abundance in southwest Puerto Rico. Since the reef transects used in this paper were run at five meters and below, *Acropora palmata* is not recorded in this paper.

Like most of the world's reefs, the Puerto Rican reefs have shown marked loss of living coral during the past thirty years [pers. observ.] from natural and anthropogenic causes. Rapid rates of human population growth and density in Puerto Rico has led to increased coastal development, dredging and sand extraction in nearshore environments, deforestation for agriculture, and increased discharge of sewage and industrial waste. Some of the consequences associated with increased human pressure include high terrigenous sediment influx, increased nutrient levels, overfishing and habitat modification. In addition, natural threats such as the island-wide mortality of the herbivorous sea urchin, *Diadema antillarum* in the 1980s, coral disease epizootics, bleaching and storm damage have contributed to an overall reduction in coral abundance and cover and increases in fleshy macroalgae.
Puerto Rico has a variety of reef types located on the west, south, and east insular shelf and slope of the Island. These include fringing reefs, bank-barrier reefs and patch reefs. Very general and descriptive surveys were done by

Goenaga and Cintron [1990] and a comprehensive survey of the physical parameters and reefs for much of the island was presented in Morelock, *et al*. [2000] and in Garcia, *et al*. [in press]

For this study, we have surveyed more than 60 sites on the southwestern Puerto Rico shelf during the last 20 years. The present condition of the reefs range from good (more than 20 percent living coral cover, a low incidence of recent mortality, and a high abundance of new recruits) to near total loss (less than one percent living coral).

One factor confounding appropriate management actions is a limited knowledge of the functions and processes controlling reef environments, a paucity of information on the condition of Puerto Rico's reefs, and a general inaccessibility of data sources. A gap analysis needs to be conducted for reefs of Puerto Rico in order to identify what information is available and what types of surveys need to be conducted in order to answer questions that would address management needs. Managers and researchers have the daunting task of compiling and organizing available data and of initiating and completing comprehensive surveys of these reefs. These tasks must be undertaken to identify the most pressing needs in order to protect remaining reefs and restore degraded areas so that future generations may benefit from the environmental and economic services these reefs can provide.

Materials and Methods

In this study, we present data on coral cover, abundance, and condition (coral cover) for reefs located off the west coast (Añasco-Mayagüez Bay and the West Coast Carbonate Platform), southwest coast (La Parguera & Playa Santa, Guánica and Guayanilla) and the south coast (West Ponce reefs). The information presented here draws from a number of previous studies. New information presented in this paper includes baseline assessments conducted in the late 1970s and early 1980s, and quantitative information on coral cover and colony sizes collected in the 1980s and 1990s by the authors. Whenever possible, individual sites were resurveyed in the later 1990s to obtain information on recent changes in composition or cover.

Photoquadrats were used to determine coral abundance and condition and to estimate coral cover. In each location, 30 m long transects are extended parallel to depth contours (Figure 1). A total of 10 quadrats are placed along each transect at 3 m intervals, with each quadrat (70 x 100 cm; 0.7 m^2 area) positioned such that the narrow (70 cm length) side is parallel to the line. Numbered tags are placed next to each coral within the quadrat to assist in identification of the corals (Figure 2). For each quadrat, one diver records the coral species associated with each number. A second diver photographs the quadrat. All quadrats are photographed from a planar perspective at a vertical distance of 1.2 m above the quadrat. This distance is maintained by using a 1.2 m stick. Although variation from true vertical to the surface may introduce cover errors, these are slight. Cover is underestimated because the photo is a planar projection of three-dimensional coral.

Figure 1. Photoquadrat line and frame.

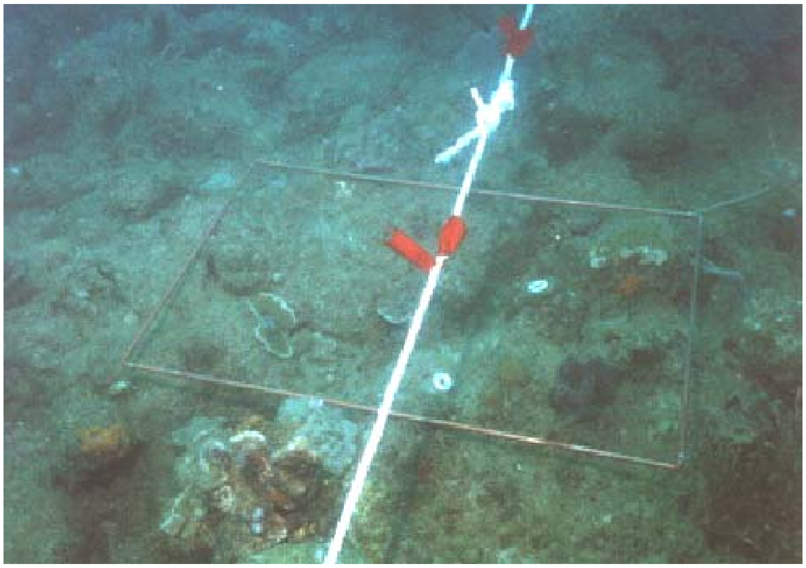


Figure 2. Numbered tags are placed on the coral in the field. Species and number are recorded.

Coral cover is determined for each quadrat using Deneba Canvas that has an area measuring function. Initially, individual corals are identified on the photograph and the perimeter of the coral is marked with a pen. The photograph is then scanned and individual corals are traced on the photograph and measured to determine the area in cm^2 relative to the area of the print (Figure 3). All data are entered into a spreadsheet in order to calculate percent cover by species and total cover for each quadrat and for the total transect, average colony size, and number of colonies.

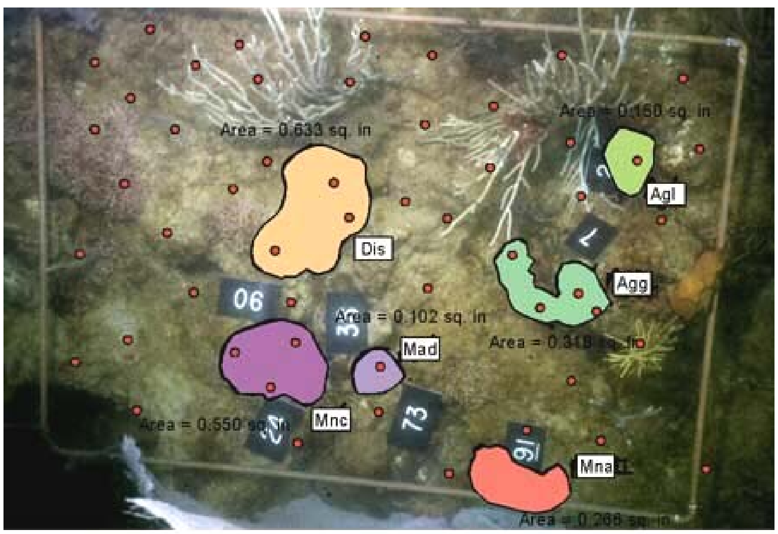


Figure 3. The area of each colony is measured.

In this study, "coral cover" is defined as the amount of the total bottom area occupied by living coral colonies within an entire area that includes sand channels and bare areas.

Whenever possible, corals identified within quadrats were recorded to species level. Although the *Montastraea annularis* group (species complex) have been subdivided into three species as proposed by Knowleton, [1992] many of the surveys used in this paper were made before the introduction of new species. Therefore, the cover is designated the *Montastraea annularis* group and the individual species are not distinguished. Forms or morphotypes of *Agaricia agaricites, Porites porites* and *Meandrina meandrites* were not differentiated. In addition, encrusting colonies of *Madracis* were recorded as *Madracis decactis*. In this study, we only recognized one species of *Stephanocoenia* (*Stephanocoenia intersepta*) and one species of *Dichocoenia* (*Dichocoenia stokesii*). The percent cover by all *Mycetophyllia* species and *Diploria* species was so low that both are recorded only to genera.

Results

The reefs surveyed in this study are divided into emergent reefs (the reef crest is exposed at low tide or within one meter of the surface) and submerged reefs (the shallowest part of the reef is located at a minimum of four meters depth and is never exposed at low tide) as seen in Figure 4.

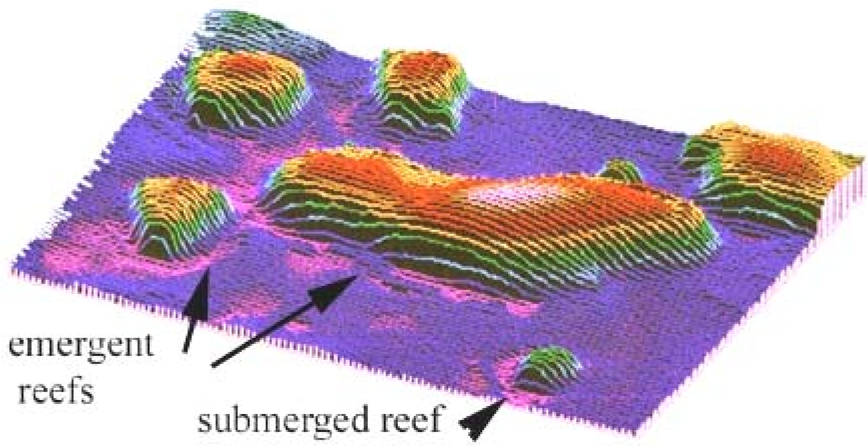


Figure 4. Emergent and submerged reefs.

We divided the insular shelf of southwest Puerto Rico six major reef areas that are unique in reef character and geographic features:

- La Parguera reefs & Playa Santa
- West Coast Carbonate Platform
- Añasco-Mayagüez Bay
- Guánica reefs
- Guayanilla reefs
- West Ponce reefs

As we discuss the individual geographic areas, we see that the width of the shelf and the source of terrigenous sediment influx and sewage discharge differ by regions. The Mayagüez reefs, Guánica reefs, Guayanilla reefs and West Ponce reefs are all narrow shelf platforms. The highest sediment influx from rivers is at Añasco-Mayagüez Bay. These four regions have terrigenous sediments which are easily resuspended. Terrigenous sediment influx and nutrient influx are both highly suspect in reef degradation, but specific literature is limited. Fairly strong cases are made in Acevedo, *et al*., [1989] Cortes and Risk, [1985] and Smith, *et al*. [1981] Specific information on sediment influx and terrigenous sediment cover will be presented for each region.

La Parguera reefs & Playa Santa

The coral reefs at La Parguera have the highest abundance of living coral of all sites included in this survey of reefs. They are discussed first as a standard of "healthy reefs" (more than 20 percent total coral cover) against which the other sites may be compared. The extensive reef system includes both nearshore (inner and outer) and offshore (submerged shelf edge) sites (Figure 5 and 6).

Figure 5. Nearshore reefs

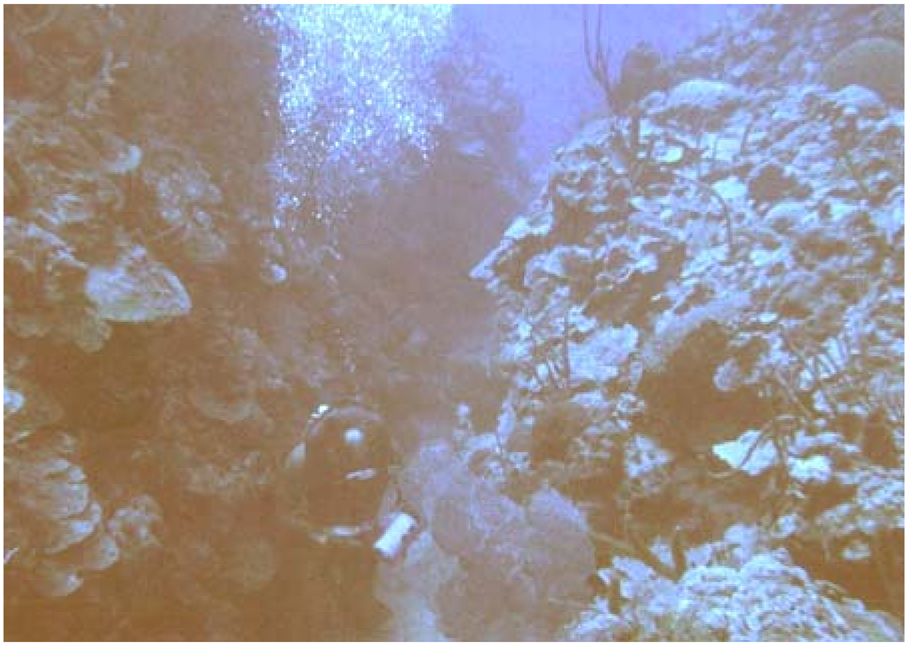


Figure 6. Shelf edge reef at 25 m

Coral reefs are located along a broad carbonate platform that extends up to 15 km offshore (Figure 7), with examples of emergent fringing reefs, bank-barrier reefs and submerged patch reefs. The coastline is fringed by mangroves, with extensive grass beds found in shallow (less than 10 m depth) water, especially around inner reefs.

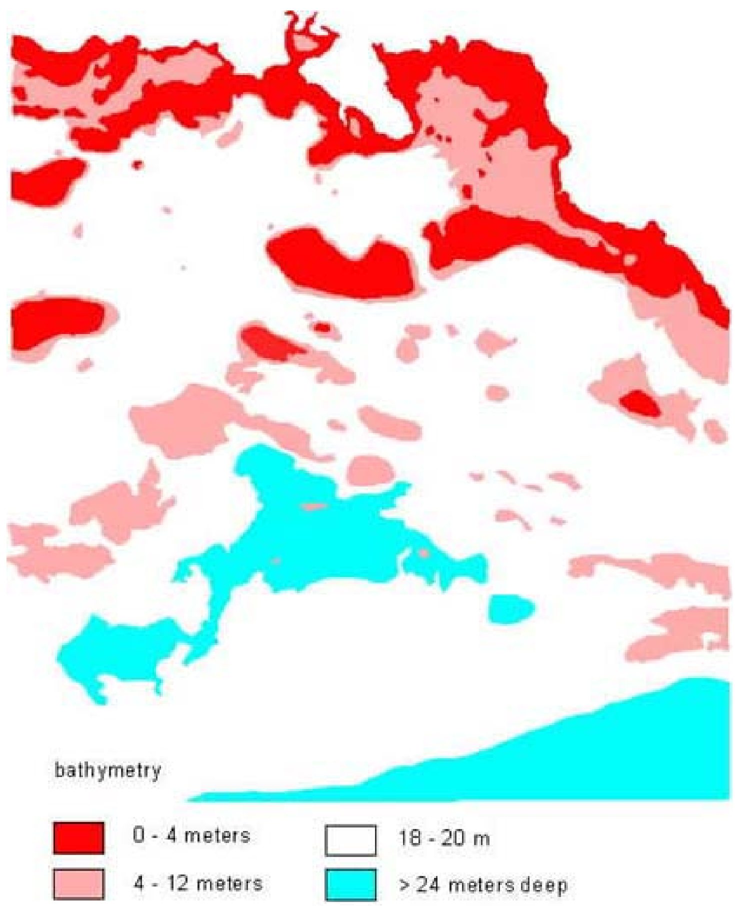


Figure 7. Bathymetry of carbonate platform off La Parguera. More than half of the shelf is 18 to 20 m water depth

The coral reefs at La Parguera have a higher diversity, abundance and cover of living coral than all other sites included in this survey, although these reefs are being degraded from a host of human and natural threats. There is no river discharge and the local sewage discharge is into a mangrove channel which traps most of the effluent close to shore (Figure 8). Sediment composition on the reef tract shows less than ten percent terrigenous sediments (Figure 9). Morelock, et al. 1994

Figure 8. Sewer discharge into mangrove.

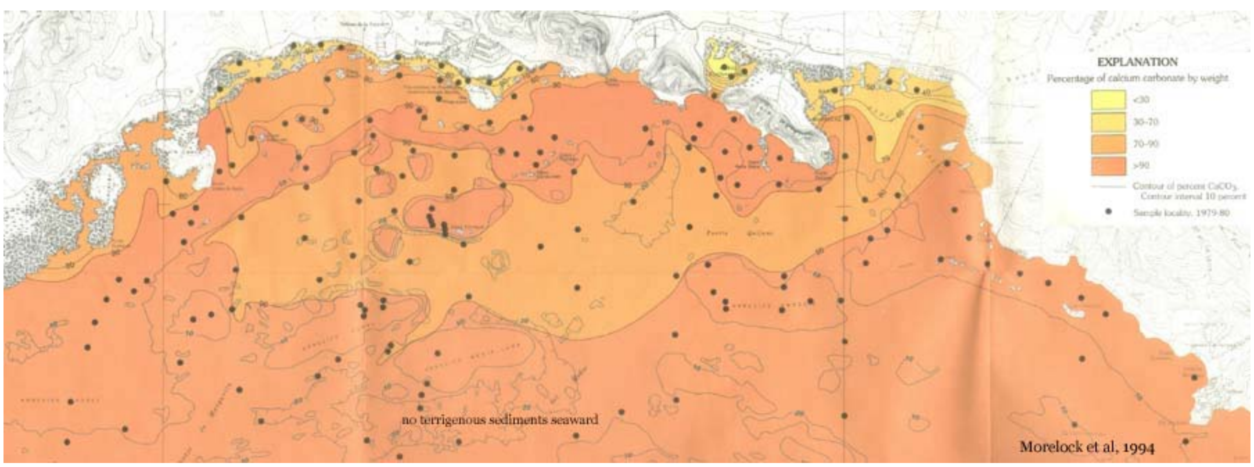


Figure 9. Percent terrigenous sediment (from Morelock, et al., 1994)

However, clear cutting of the hillsides surrounding Parguera and rapid urbanization has contributed to increased sheet run-off of sediments during rainy periods (Figure 10).

Figure 10. Scraping of hillside for urbanization. These cuts may remain several years before construction begins.

In addition, nutrient loading may be an increasing problem, due to the rapid population growth and discharge of untreated sewage, especially from upstream sources (*i.e.*, Guayanilla, Guanica and Ponce). Other factors contributing to an overall decline in reef health include an increased dominance by macroalgae and boring sponges, [Vicente, 1985] possibly associated with nutrient loading, overfishing, a loss of herbivorous urchins, bleaching [Williams and Williams, 1988; Williams, *et al.,* 1987] and coral disease outbreaks. [Bruckner and Bruckner, 1998]

These reefs have been investigated since 1963. [Almy & Torres] The results from earlier studies were published in Morelock, *et al*., [1977] Rogers, [1977] Boulon, [1980] Ramirez, [1992] Morelock, *et al*., [1994] and Torres [1998] Early surveys of general areas of the reef from 1973 [Glynn, 1973] were compared to surveys in 1999 by Firman, *et al.* [1999] Vicente [1994] discussed changes at Enrique Reef over 20 years. Data and comments presented in this section draw from surveys of the coral cover made by the authors. We surveyed these reefs between 1985 and 1999 and present the data in this paper. The reefs are mapped (Figure 11) as either emergent or submerged as defined earlier.

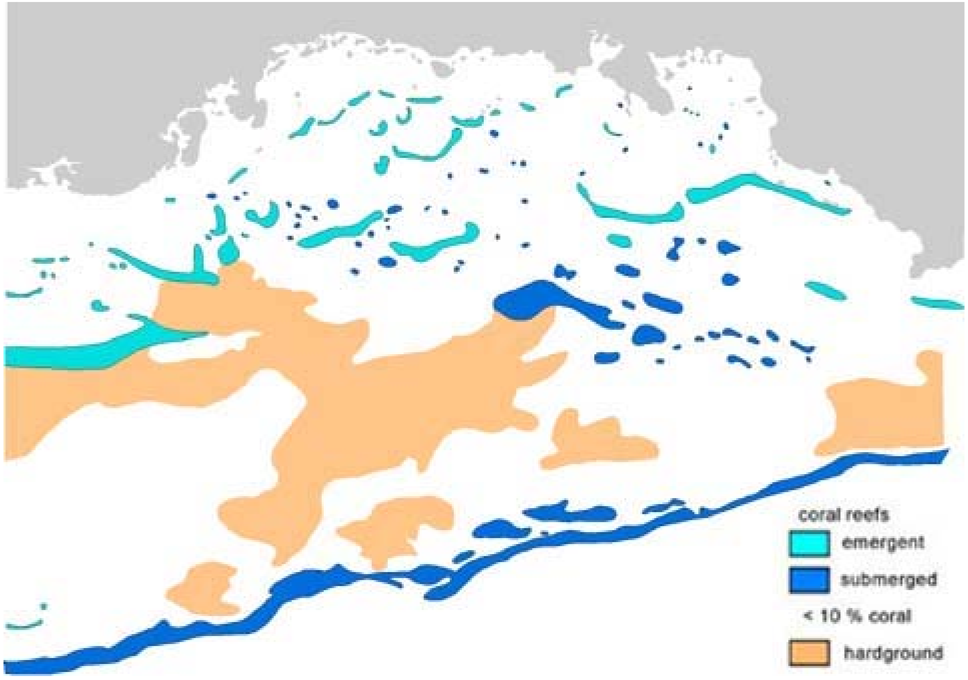


Figure 11. Map of the La Parguera shelf reefs

Emergent reefs on the La Parguera platform had three distinct fore reef zones similar to those observed at Yucatan, [Logan, 1969] Jamaica, [Goreau and Goreau, 1973; Liddell & Ohlhorst, 1987] and Belize. [James and Ginsburg, 1979]

In shallow exposed environments (0-5 m depth), reef communities were formerly dominated by extensive thickets of *Acropora palmata* (Figure 12). This coral was recorded on the fore reef of all outer reefs (Pinnacles, Turrumote, Media Luna, Laurel, San Cristobal, Margarita) and on inner reefs (Enrique, La Gata, Mario), and occasionally occurred in back reef habitats of these reefs, but was rare or absent on turbid, nearshore reefs (Collado, La Conserva, Atravasada).

Figure 12. *Acropora palmata*

Since 1975, the abundance and cover of this coral has been in decline, primarily from hurricane damage, white-band disease and corallivorous mollusks. In most locations, the density has been reduced to less than one colony every 2-5 m, although small patches of 5-10 colonies can still be found. Extensive thickets were still documented on Laurel as recently as August 1998; [pers observ] but a near total loss was documented after Hurricane Georges. The only area identified in the La Parguera reef system where this coral still flourishes is between the east end of Margarita and San Cristobal and on Atrevesado Reef.

In reef environments formerly dominated by *Acropora palmata*, few corals now exist; these include small brain corals (*Diploria* spp.), *Porites astreoides*, and *Millepora* spp., as well as soft corals (*i.e.*, *Gorgonia* spp. and *Psuedoterigorgia* spp.). The coral cover at five meters is mainly species of massive coral (Figure 13) although *Acropora palmata* were abundant on the shelf reefs 25 years ago. *Acropora palmata* was present on the shelf edge reefs 6,000 yBP, but coral growth could not keep up with rising sea level.

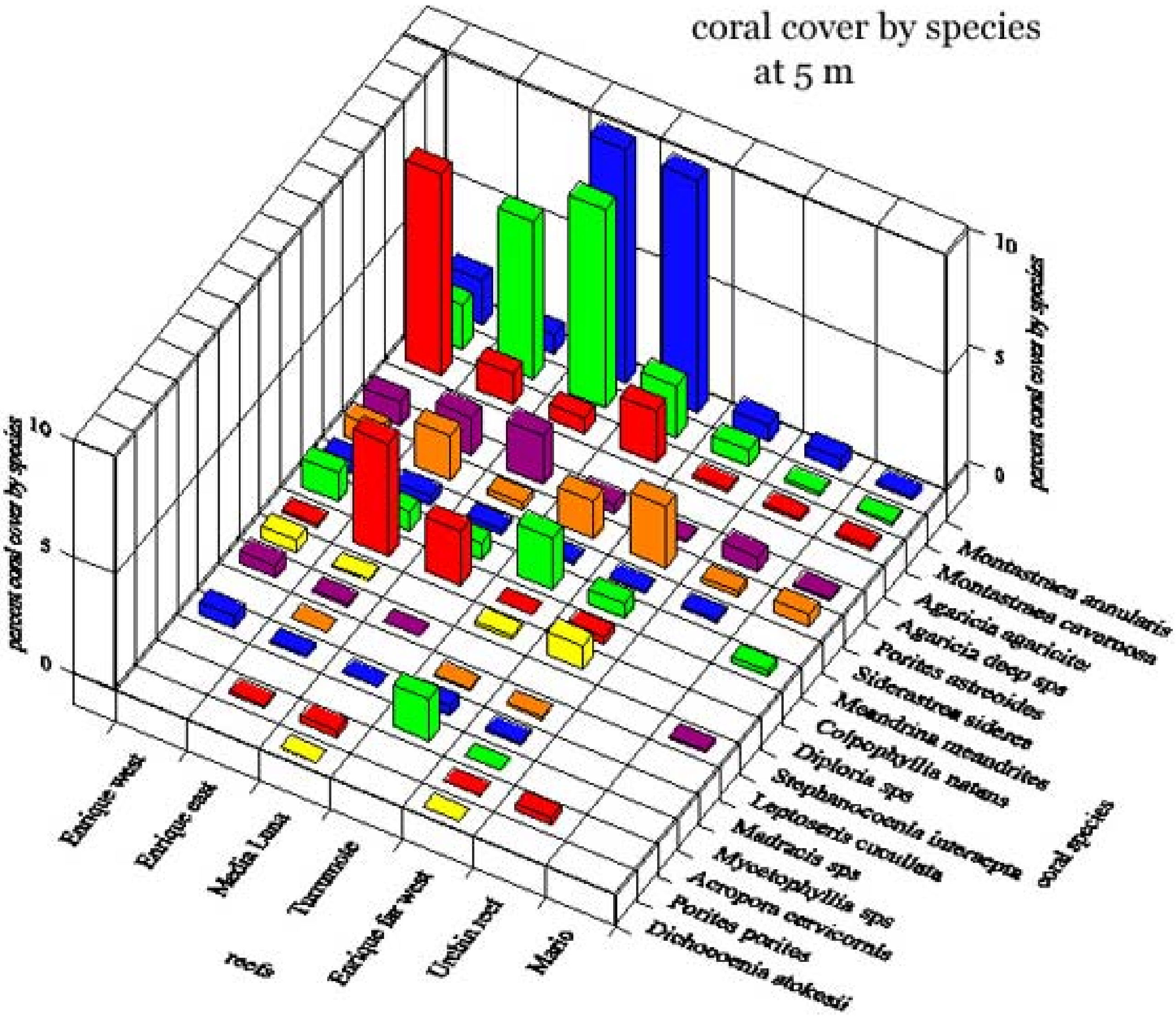


Figure 13. Coral cover by species at five meters water depth.

A break in slope may separate the *Acropora palmata* Zone and the Massive Coral Zone. Coral species in the massive zone (Figure 14) grow on a relatively steep slope and are dominated by *Montastraea, Agaricia*, and *Porites* species (Figure 15).

Figure 14. Massive coral zone

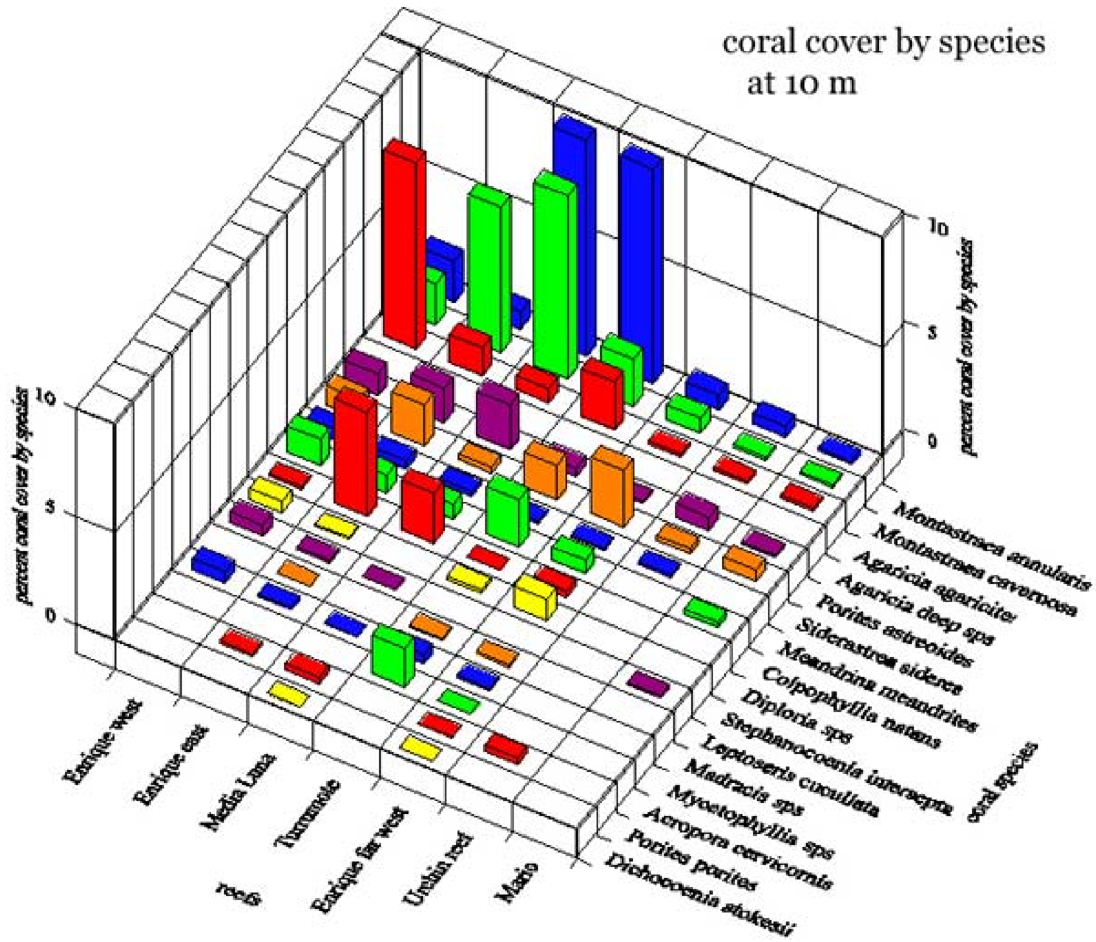


Figure 15. Coral cover by species at 10 m water depth.

The upper part of the zone terminates at 12 to 14 m on the emergent reefs where the lower part of the reef front is covered by a sand and gravel fore-reef talus zone on Enrique and Turrumote reefs. The lower part of the massive zone was measured at the submerged reef southeast of Turrumote reef (Figure 16) and at the submerged shelf-edge reef (Figure 17). The cover at 20 m (Figure 18) was measured at the submerged reef southeast of Turrumote and at the shelf edge.

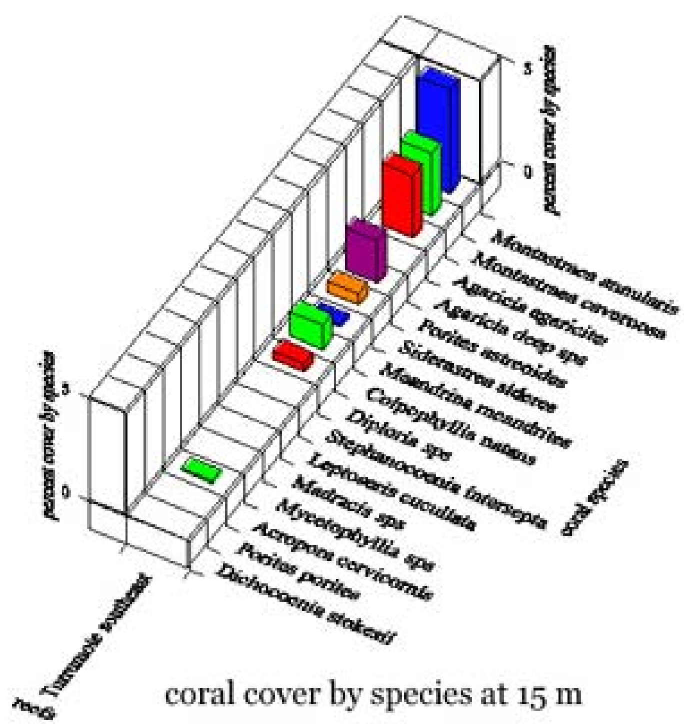


Figure 16. Coral cover by species at 15 m water depth., Turrumote southeast

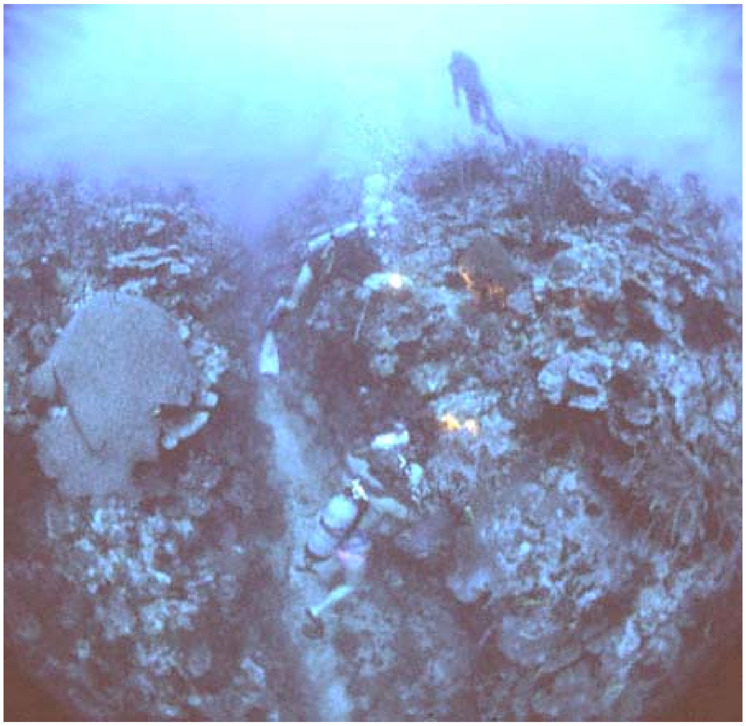


Figure 17. Submerged shelf edge reef

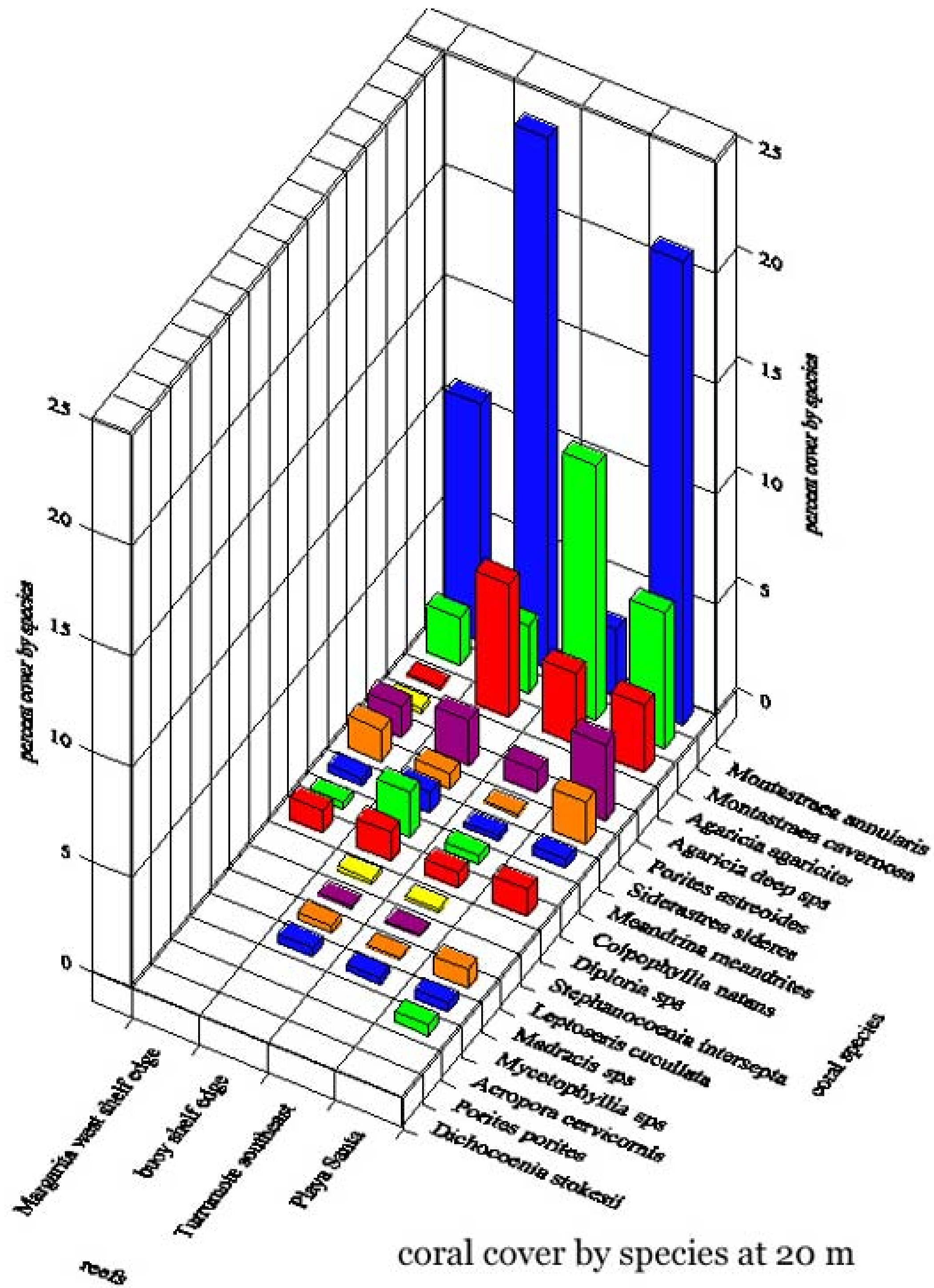


Figure 18. Coral cover by species at 20 m water depth., La Parguera outer shelf and submerged shelf edge reefs

The Buoy site and Playa Santa are similar with dominance by *Montastraea annularis* and high cover by *Agaricia*; but at Turrumote southeast (on the shelf), *Montastraea cavernosa* is dominant with *Agaricia* and *Montastraea annularis* secondary. The cover by species pattern at Margarita west shelf edge is similar to the Buoy and Playa Santa sites, but with less total cover. There is a pattern of reduced coral cover from Playa Santa to the shelf south of Cabo Rojo lighthouse.

Colony morphology changes from the massive rounded heads found in the shallower zones to platy forms (Figure 19) at 22 to 24 m. The composition of the reef community on the insular slope changes and the *Montastraea-Agaricia* coral zone can be distinguished. *Agaricia* species and *Montastraea annularis* dominate the zone as measured at 25 and 30 m (Figure 20 and 21).

Figure 19. Platy coral – Montastraea annularis complex.

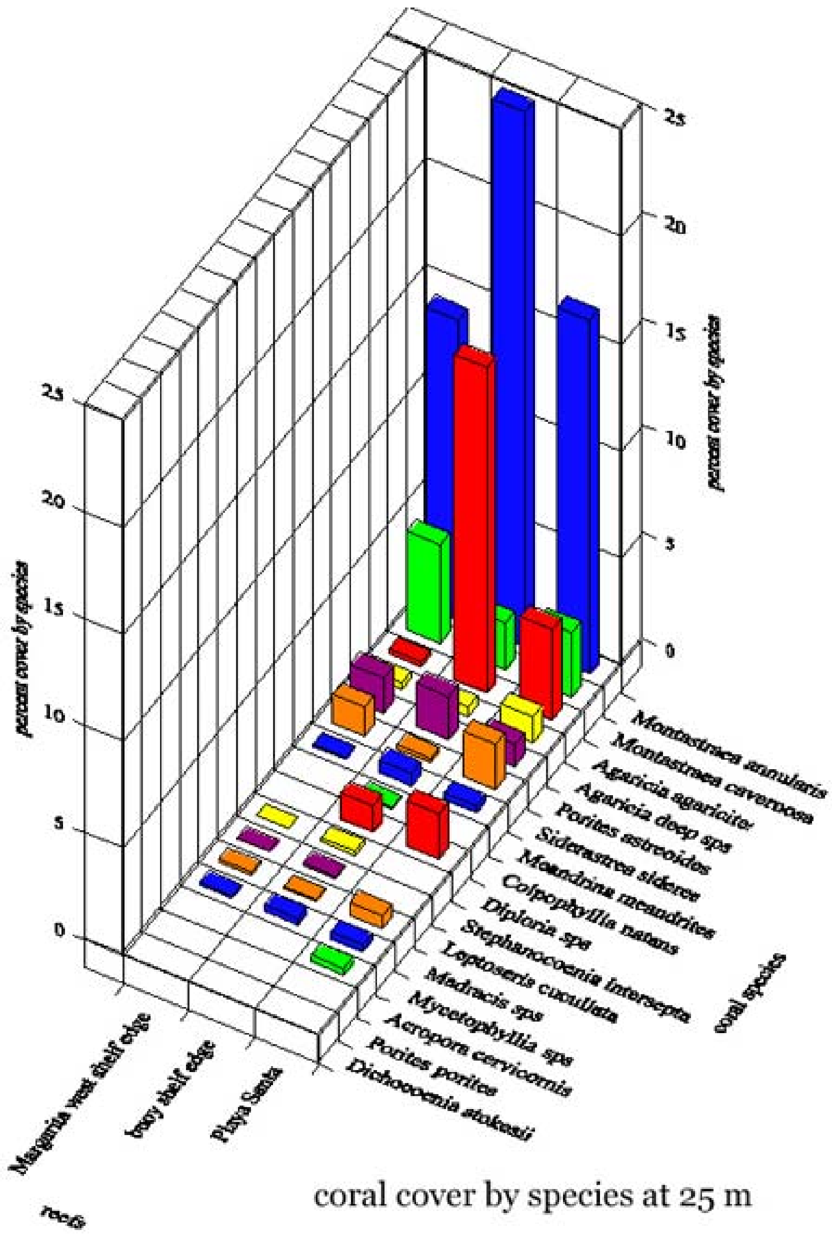


Figure 20. Coral cover by species at 25 m water depth., La Parguera submerged shelf edge reef

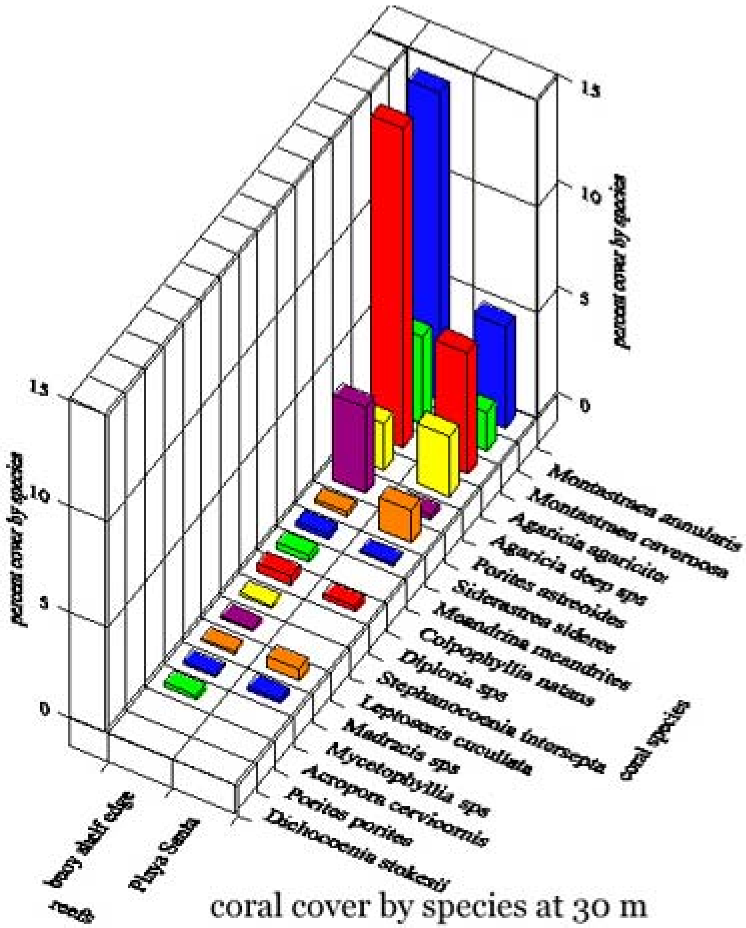


Figure 21. Coral cover by species at 30 m water depth., La Parguera shelf edge reef

The total cover of coral (Figure 22) differs between the nearshore reefs and the shelf edge reefs. The lower cover inshore probably reflects different environmental conditions.

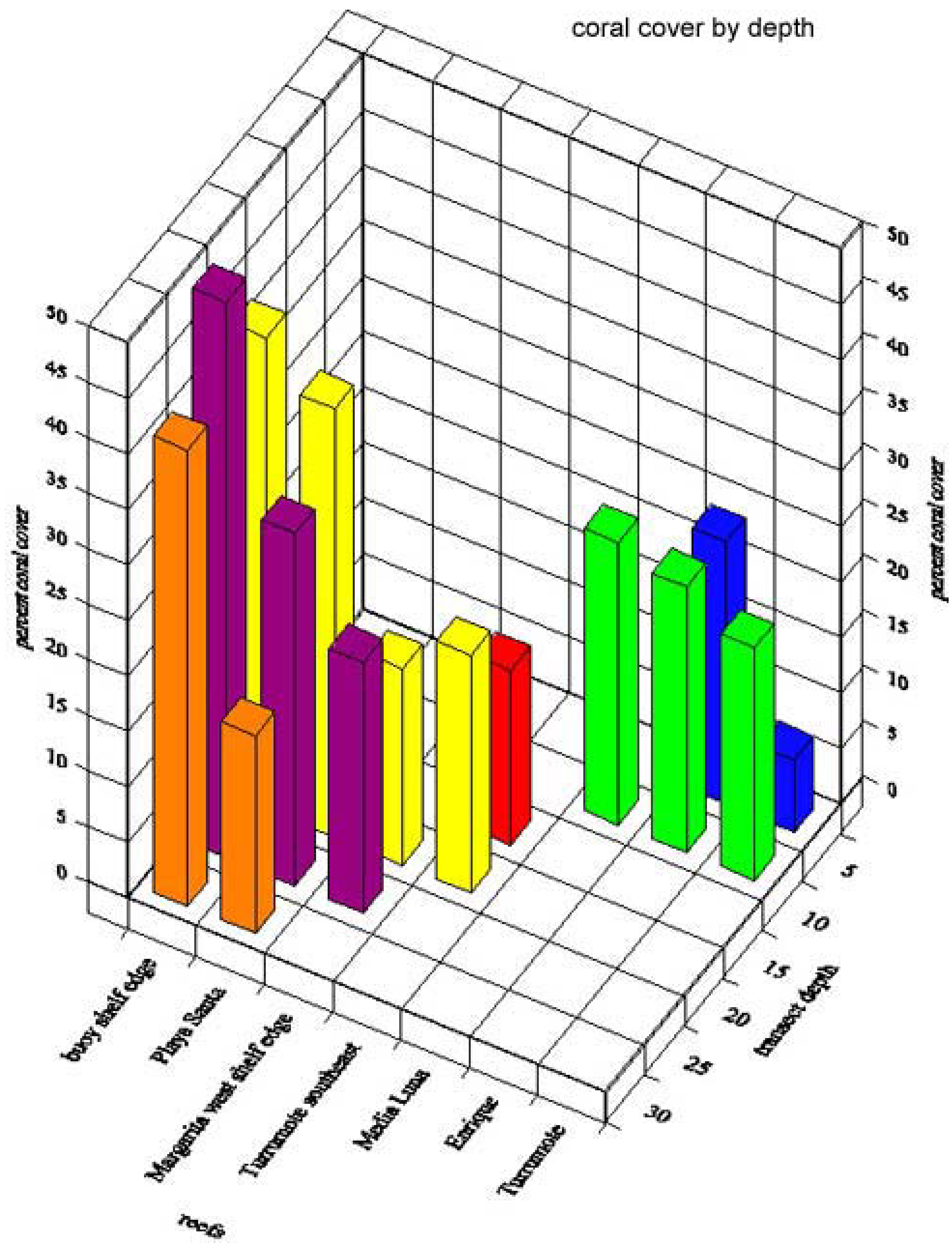


Figure 22. Total coral cover by depth at different reefs

The map view of percent coral cover (Figure 23) on these reefs shows higher cover than at any of the other sites in this report.

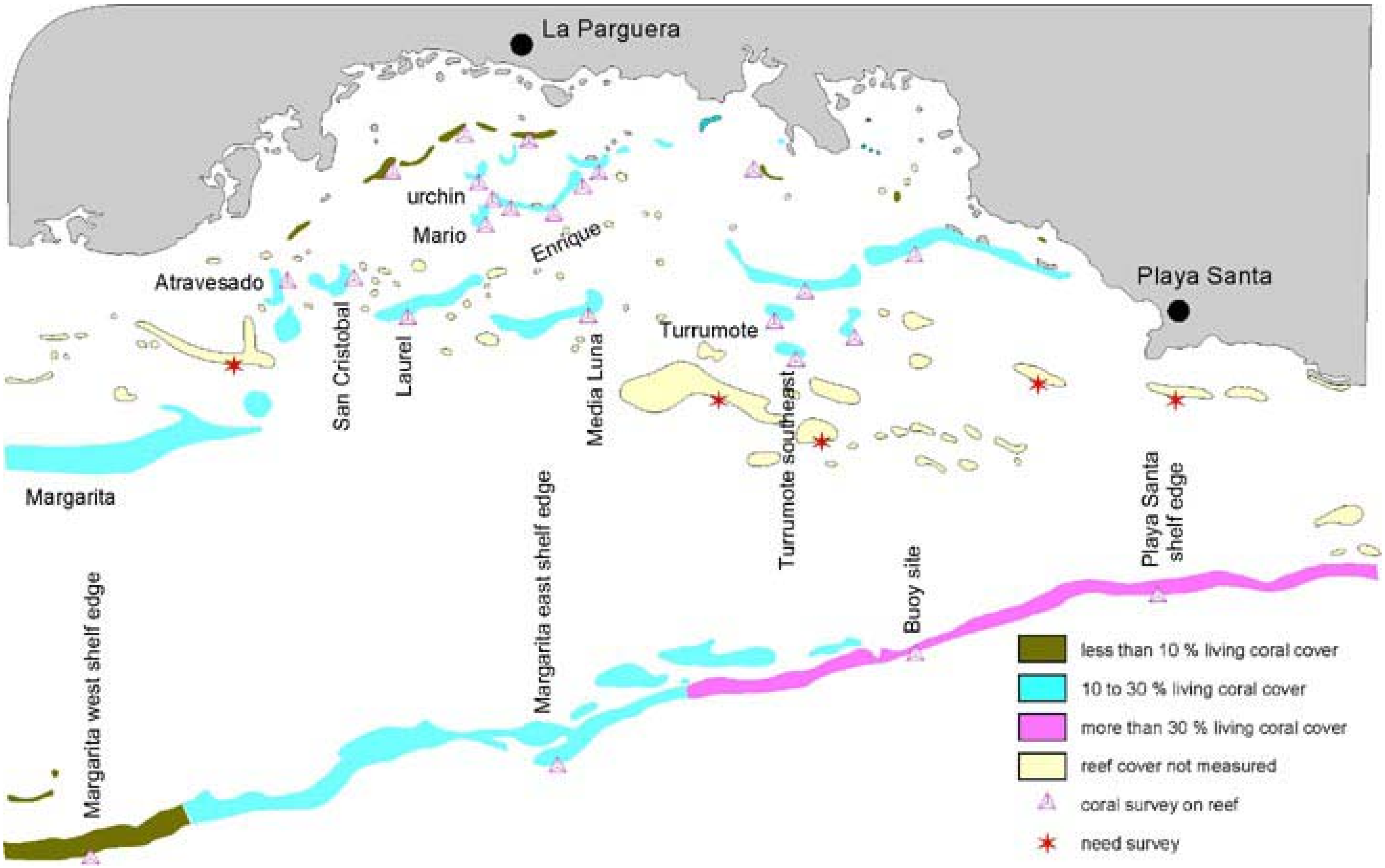


Figure 23. Status of the coral reefs of La Parguera as shown by total percent of living coral surface.

A series of cores drilled into the outer and mid shelf reefs [Hubbard, *et al*., 1996] allow reconstruction of the Holocene reef development history. The outer reef complex is comprised of roughly parallel but discontinuous ridges which are cut by distributaries from the deeper landward trough of the Turrumote Basin. The Holocene shelf edge reefs began 8,000 to 9,000 yBP as *Acropora palmata* growth (Figure 24) on the newly submerged Pleistocene surface. Based on the regional sea-level curve of Lighty, *et al*. [1982] and the local *Acropora palmata* curve (Figure 25), water depths over the reefs were near 6 m, which is beyond the optimum range for branching acroporids but was observed at Los Roques, Venezuela. [Morelock, pers. obv.] The dominantly *Acropora palmata* reefs accreted at rates up to one centimeter per year, maintaining a constant depth below rising sea level.

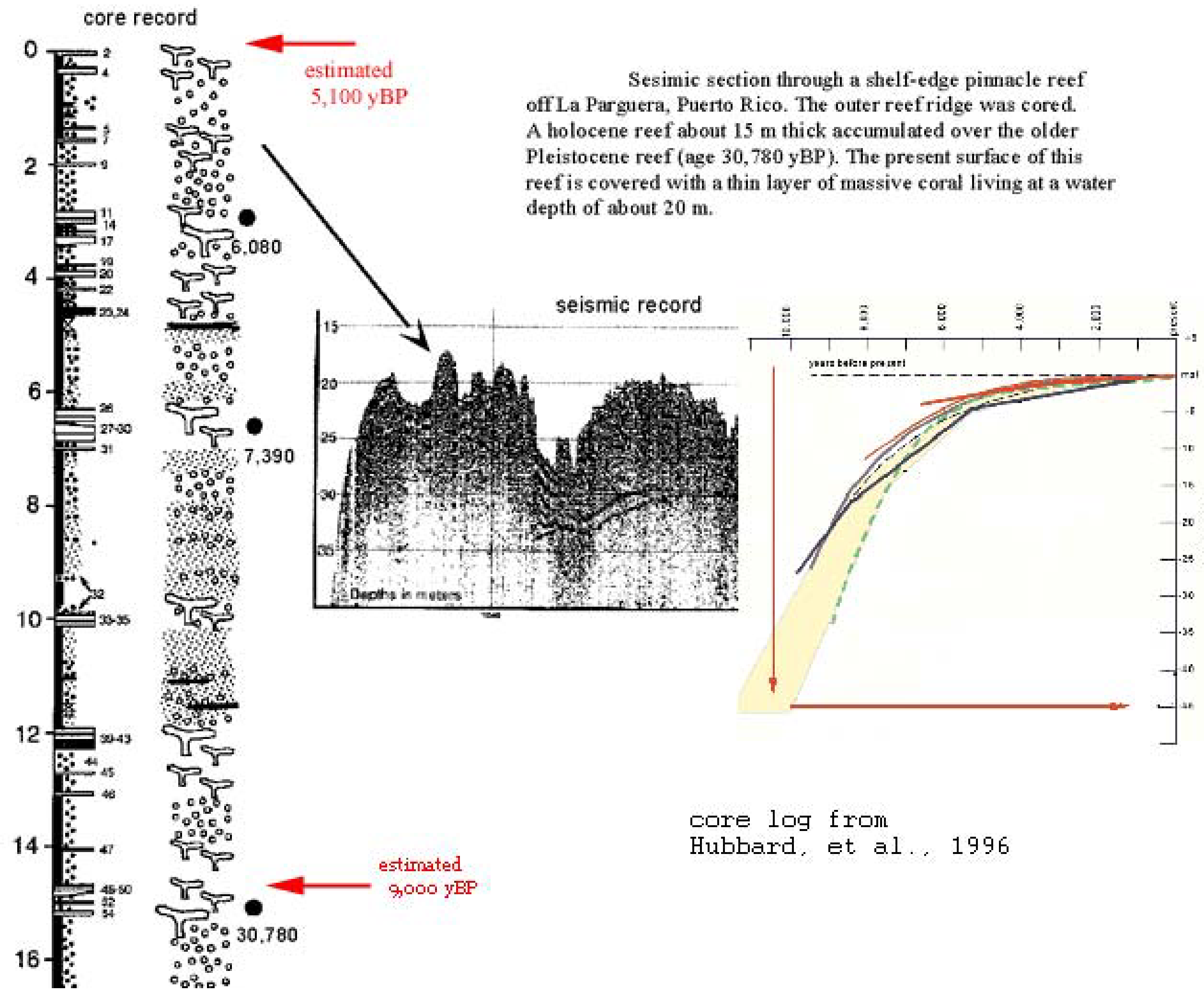


Figure 24. Relict *Acropora palmata* reef at La Parguera shelf edge

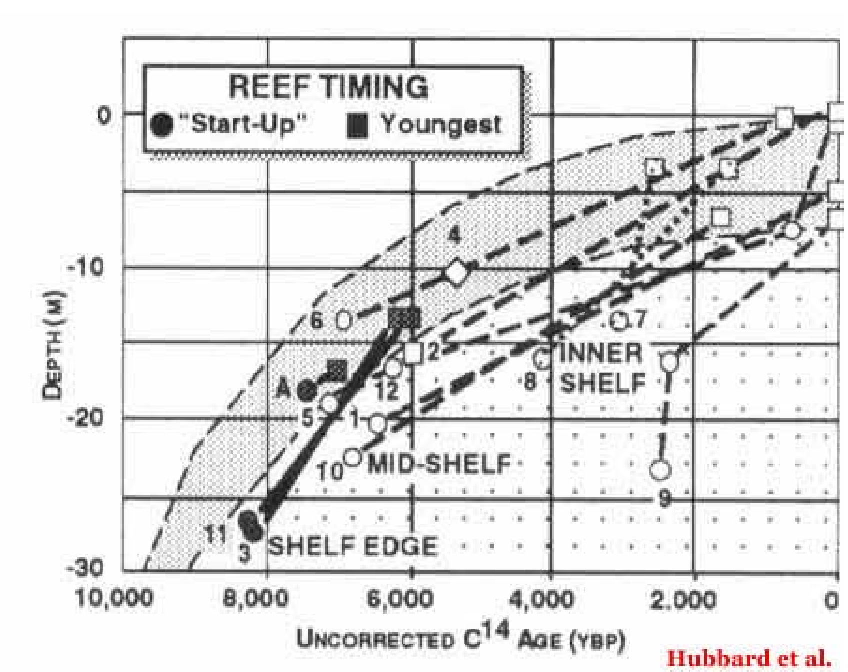


Figure 25. Acrop*ora palmata* time scale for Late Holocene

These coral died off 6,000 yBP and the surface was barren until massive coral began to grow a few hundred years ago. The modern massive coral are a single coral layer dominated by head corals that cover up to 50 percent of the bottom over the relict *Acropora palmata* reef. From the maximum size of massive corals on the La Parguera shelf edge, we assume that this modern "coral carpet" is only one to two hundred years old.

These data are valid only for the La Parguera shelf edge reefs, but if we assume a similar history for the rest of the southwestern Puerto Rico shelf reefs, the modern coral cover is only a thin reef layer lying over a 6,000 year old *Acropora palmata* reef (Figure 26). Coring at Lang Bank off St. Croix, USVI shows a similar history [Hubbard, pers. observ.] which makes the assumption reasonable.

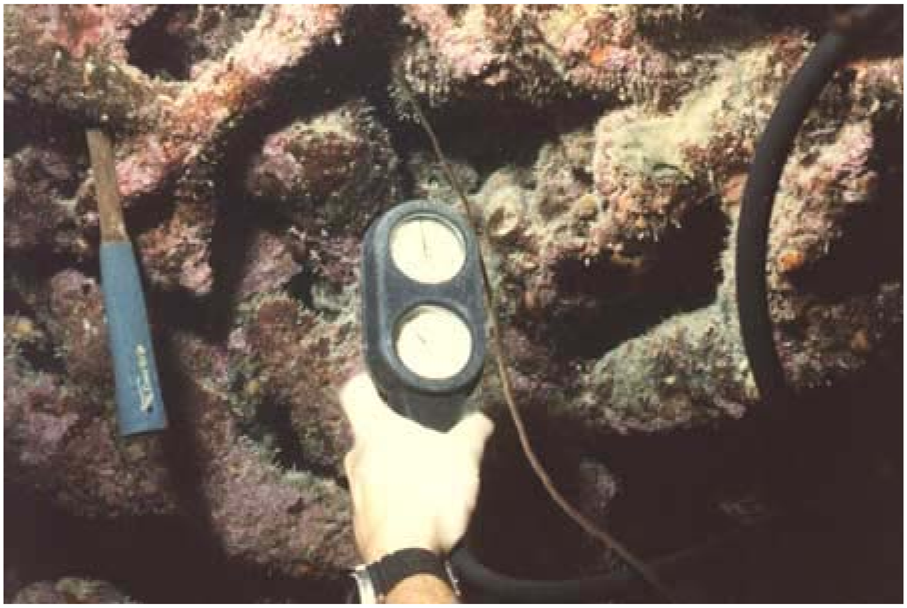


Figure 26. Relict *Acropora palmata* reef on the outer shelf at La Parguera

West Coast Carbonate Platform

The west coast shelf south of Punta Guanajibo is a carbonate platform about 15 km wide. The width of this shelf and the presence of numerous coral reefs on the shelf break and interior shelf are effective in moderating wave energy. The broad platform starts at Punta Guanajibo and wraps around the southwest corner of the Island. Only one paper [Loya, 1976] discusses the reefs on this shelf. Individual reef surveys have been made by Garcia [1999] and by us. The results of our surveys are used in the following discussion.

As at La Parguera, we see two types of reef on this platform (Figure 27).

- the shelf edge reefs at the shelf margin break and
- shelf/patch reefs on the top of this broad platform.

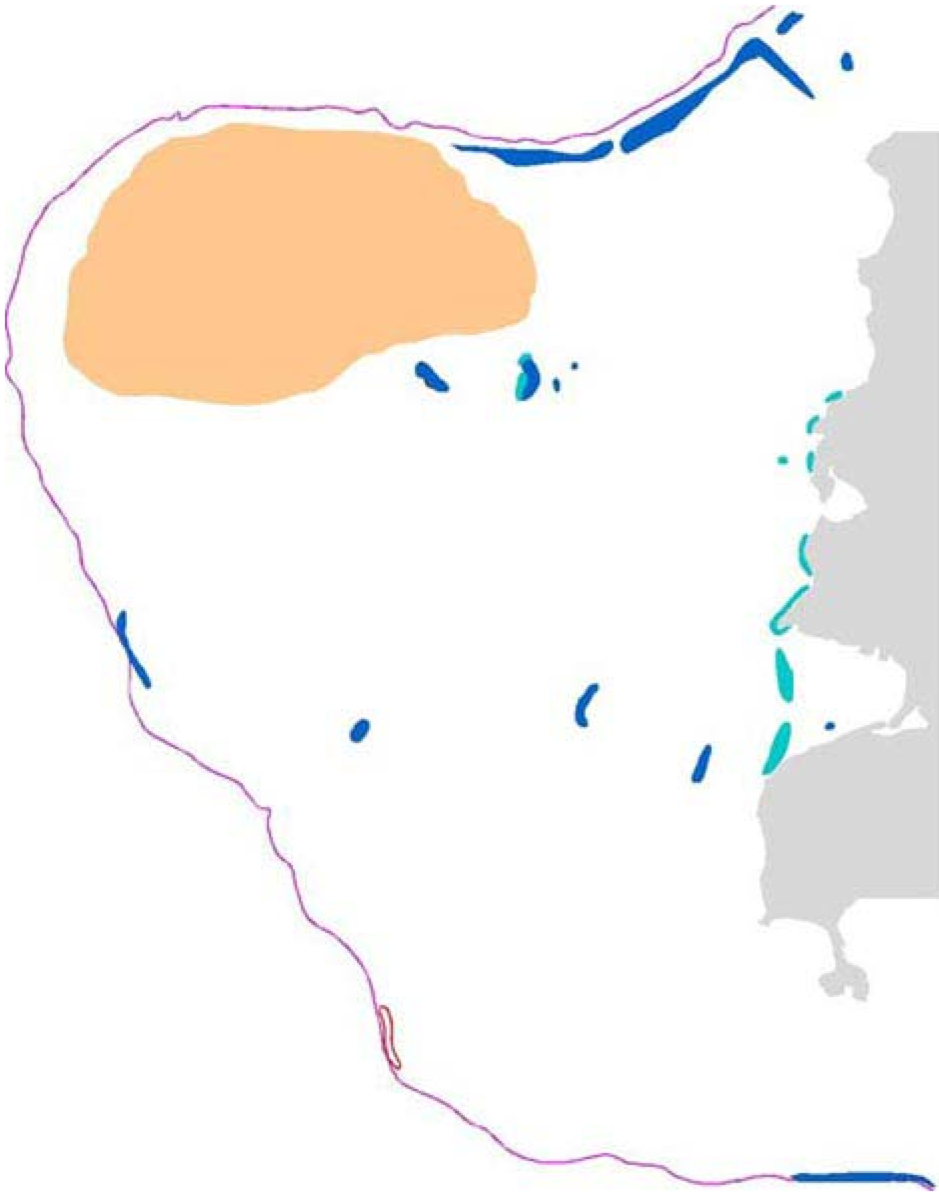
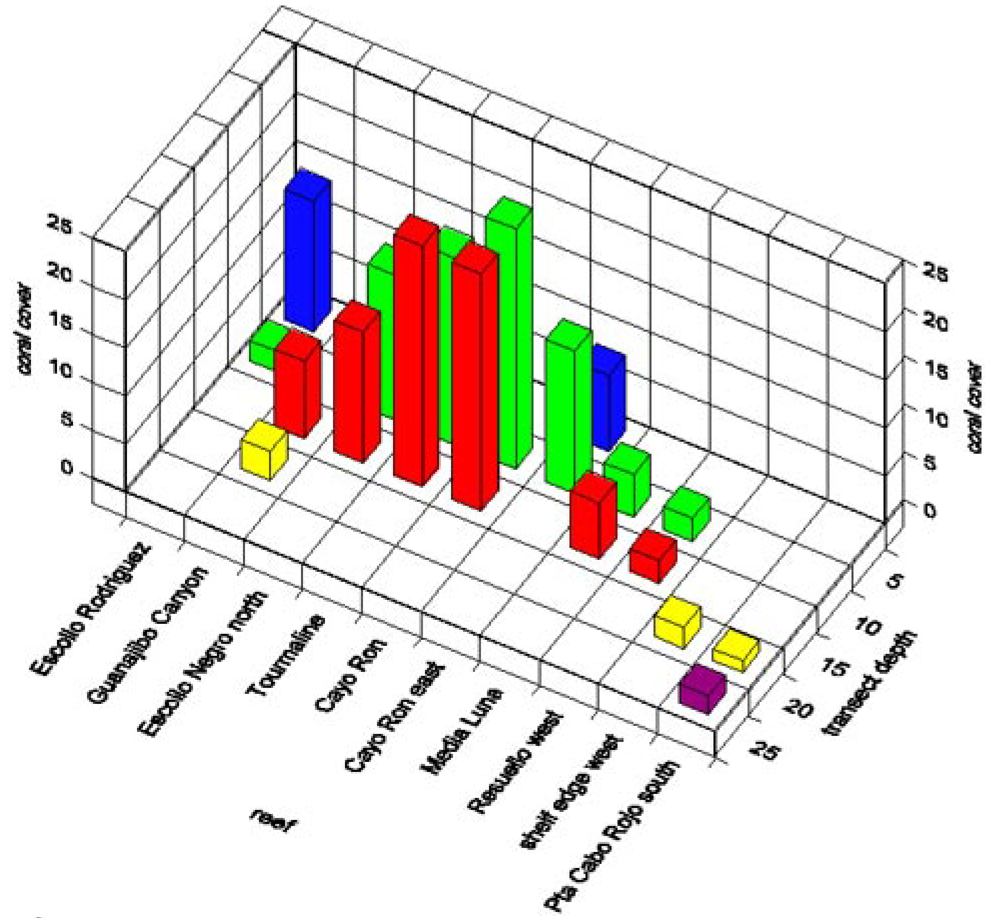
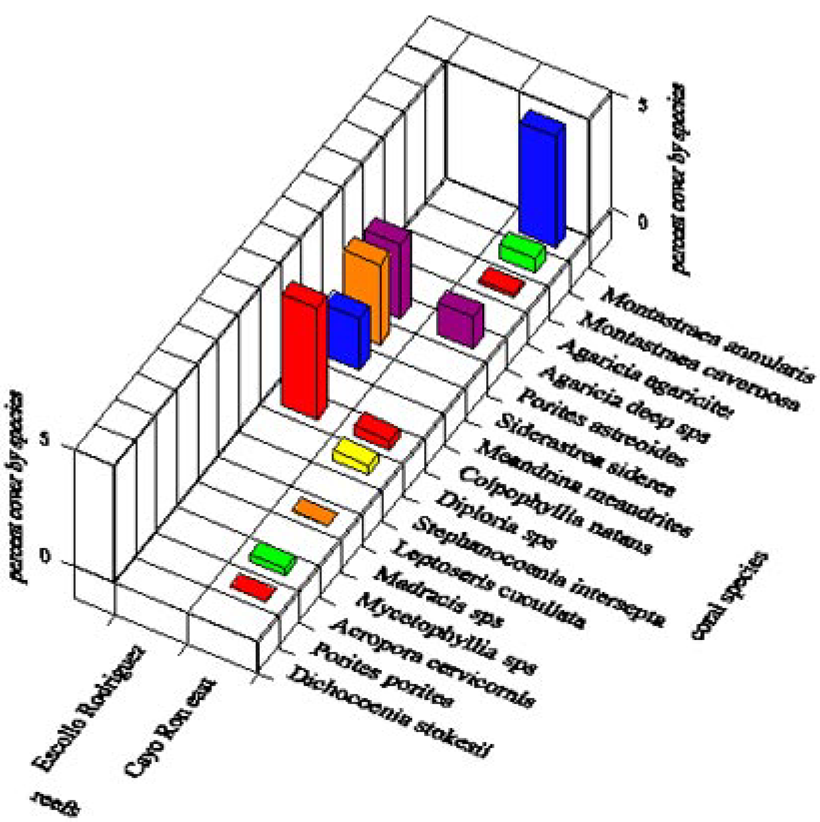


Figure 27. Reefs on the western carbonate platform

The reefs have a zonation pattern similar to the La Parguera reefs but much less coral cover and sparse occurrence of coral reefs on the shelf and insular slope. The *Acropora palmata* Zone is seen on shallow patch and shelf reefs that occur on the interior of the platform. Storm waves have had less effect on the west coast, and there are still large stands of *Acropora palmata*. The seaward slope on the north platform margin is less than at La Parguera and the cover is less. The shelf margin and the northern part of the platform have 15 to 25 percent living coral cover at 5 to 15 m depth (Figure 28). The shelf reefs at Cayo Ron have total coral cover of 24 to 27 percent at 10 and 15 m, but reefs to the south have less than ten percent coral cover at these depths except for the Boqueron Bay barrier reef.

Figure 28. Total coral cover by depth on the west coast reefs





The coral cover by species at five meters was measured at Cayo Ron east and Escollo Rodriguez, two reefs stressed by sediment influx and resuspension of fine grained sediments (Figure 29). *Montastraea annularis* was dominant on Cayo Ron east. Escollo Rodriguez had about the same amount of cover by *Colpophyllia natans, Meandrina meandrites, Siderastrea siderea* and *Porites asteroides* – the only coral present at five meters.

Figure 29. Coral cover by species at five meters water depth

The *Montastraea annularis* group dominates the ten meter level (Figure 30) on the shelf and platform reefs on the northern part of the platform. The 15 m level (Figure 31) has less than ten percent cover by any species and total coral cover is reduced. The most common species were *Montastraea annularis* and *Montastraea cavernosa*.

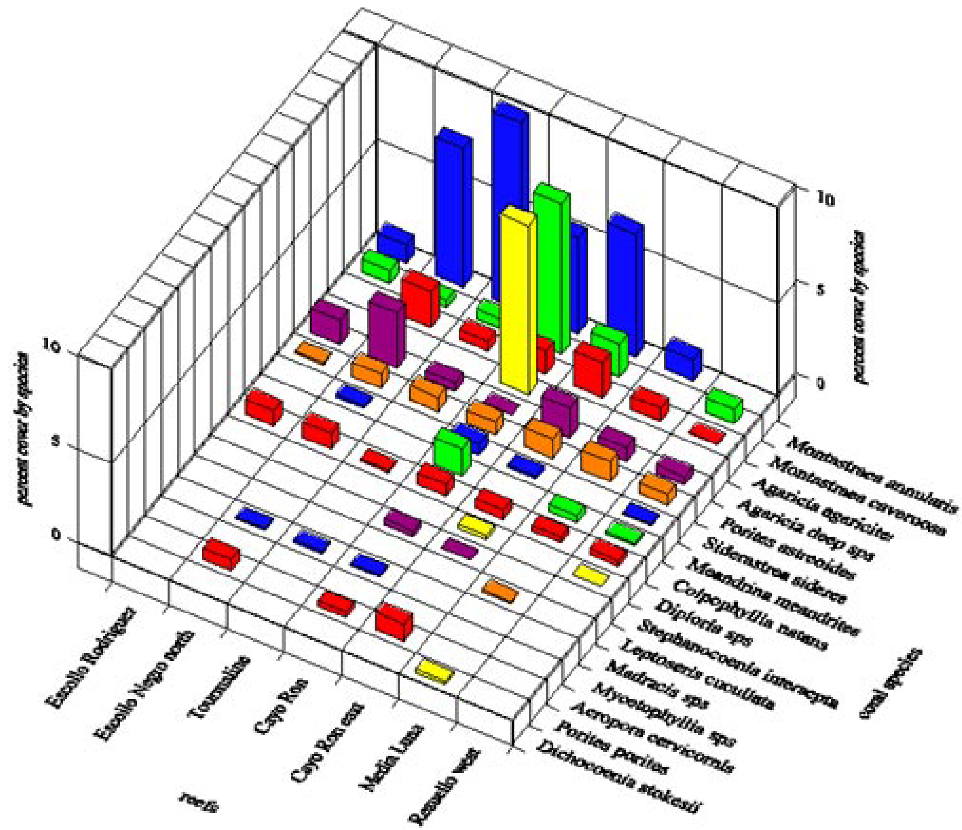
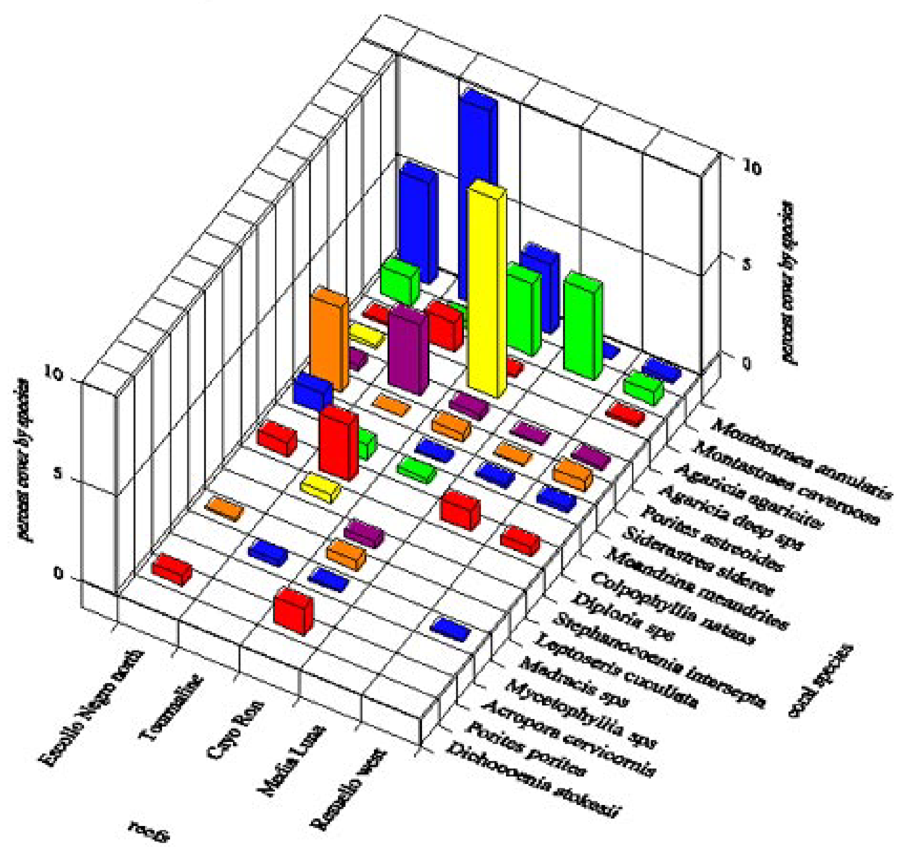


Figure 30. Coral cover by species at 10 m water depth.

Figure 31. Coral cover by species at 15 m water depth.



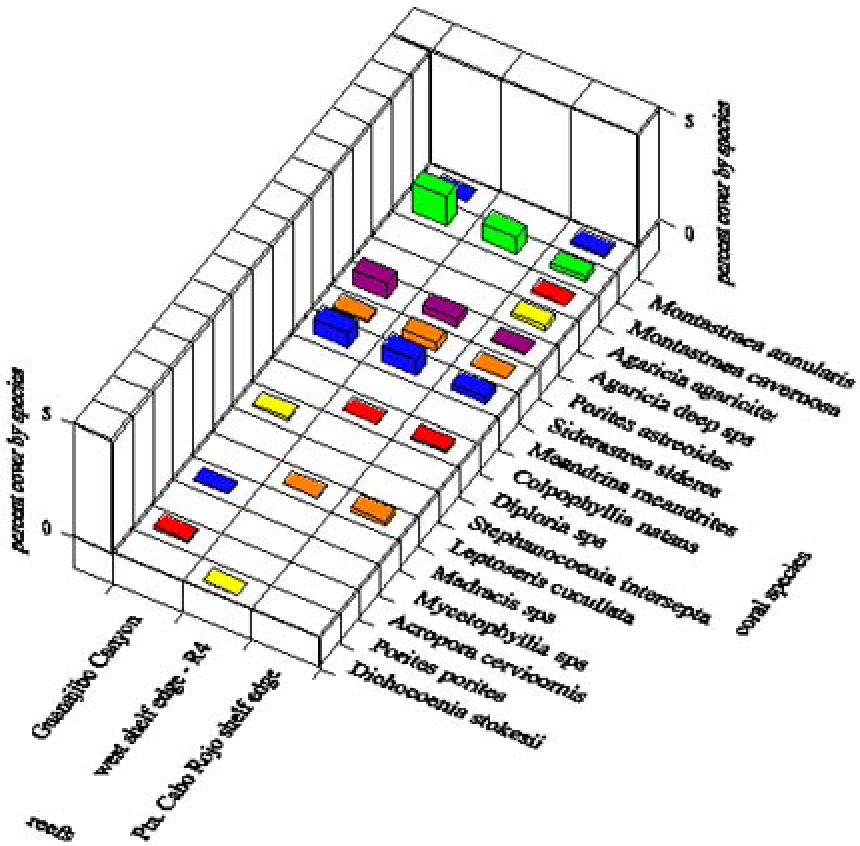


Figure 32. Coral cover by species at 20 m water depth.

The 20 m level, measured on the shelf slope (Figure 32), had very low coral cover with no coral of the fourteen species present dominating. If we assume the same history as at La Parguera for the shelf edge reefs off Boquerón and Punta Cabo Rojo, something has prevented the colonization of these areas and they are presently hard grounds. Both shelf edge sites (Boquerón west R4 and Punta Cabo Rojo shelf edge) are in clear water far from shore and show no effects of increased nutrient or sediment load. Some other factor such as strong currents causing a lack of larval recruitment must be acting in what is still a natural environment. The shelf edge of this platform has consistently higher currents than any other part of Puerto Rico. [pers. obv.] Both areas had almost no coral larval recruits (juvenile).

The mapped view of coral cover on the reefs (Figure 33) shows that the status (cover on the reefs and density of reefs on the platform) of these reefs is much less than at La Parguera, even though the environmental stresses (sediments, nutrients, storm waves) should be low.

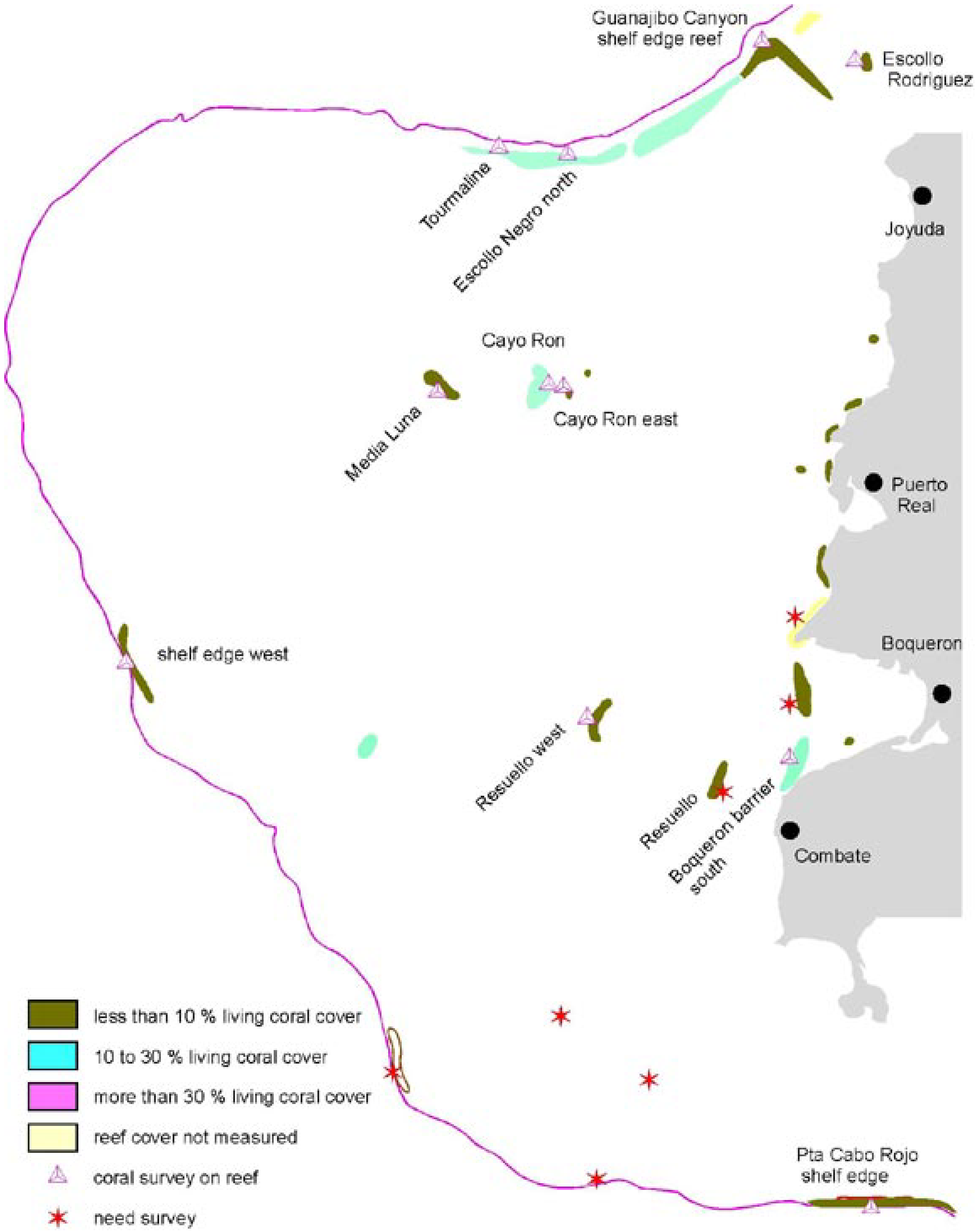


Figure 33. Status of the coral reefs of the west carbonate platform as shown by total percent of living coral surface.

Some of the shelf reefs had thick accumulations of *Acropora palmata* with almost total canopy cover by the overlapping fronds of the coral in 1995. Observations in 2001 showed a loss of more than half of the *Acropora palmata*.

Añasco-Mayagüez Bay

From Punta Jiguero to Punta Guanajibo the shelf is narrow (Figure 34), but coral reefs at the shelf break and on the interior reef platform add a degree of roughness that attenuates wave energy and redirects its path. Because of the narrow shelf and sediment influx from three rivers, the waters across Añasco and Mayagüez bays are turbid and deposition of fine grained sediments on the coral reefs is high (greater than 10 mg/cm^2/day). Although this is a lee shelf, high wave action during storm conditions results in considerable resuspension of the terrigenous sediments of the basin between the reefs and the shoreline (Figure 35). The physical parameters, including water clarity were measured by Cruise, *et al*. [1994] and Garcia, *et al*. [1998]

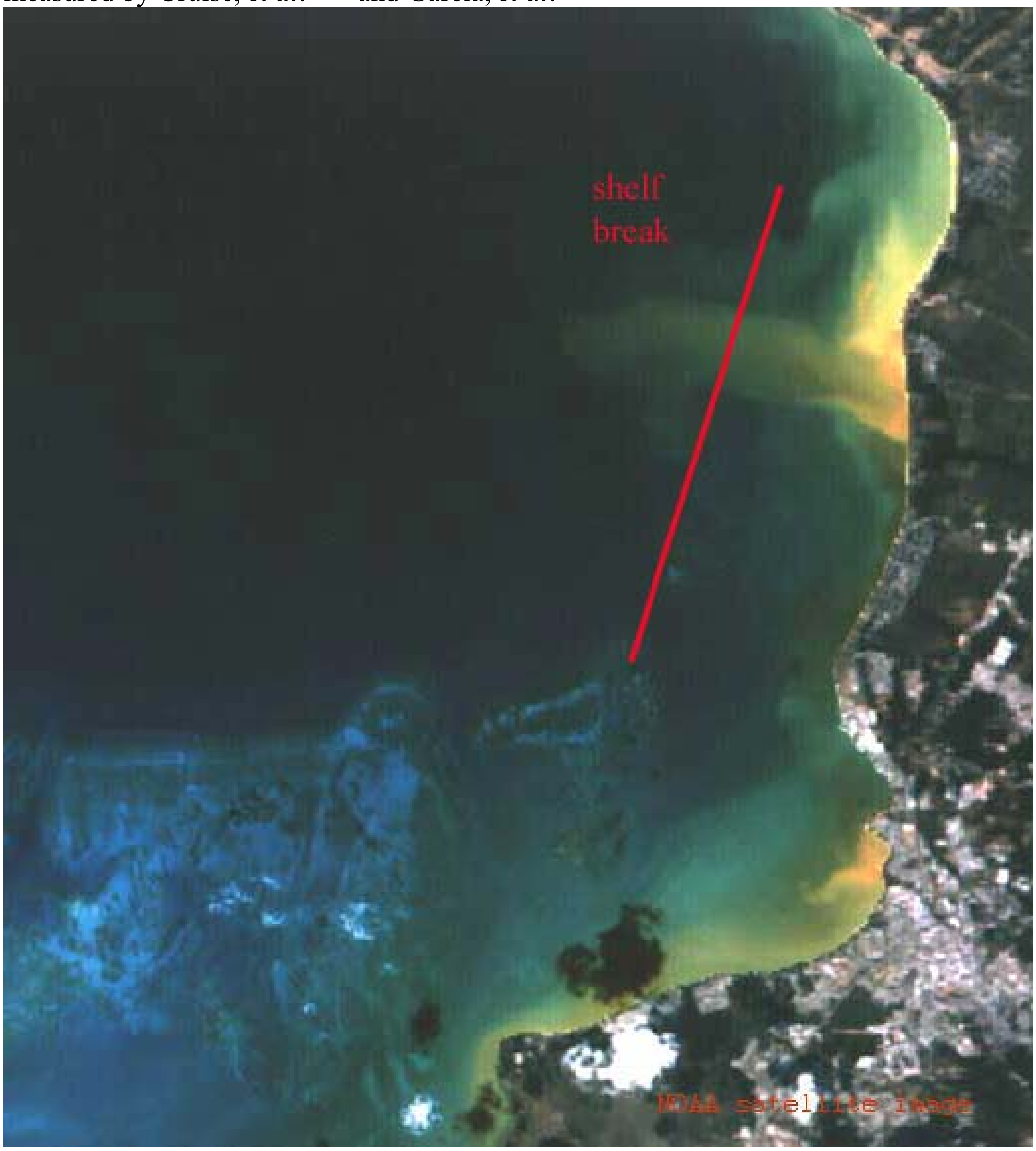


Figure 34. Mayagüez-Añasco shelf – NOAA satellite image

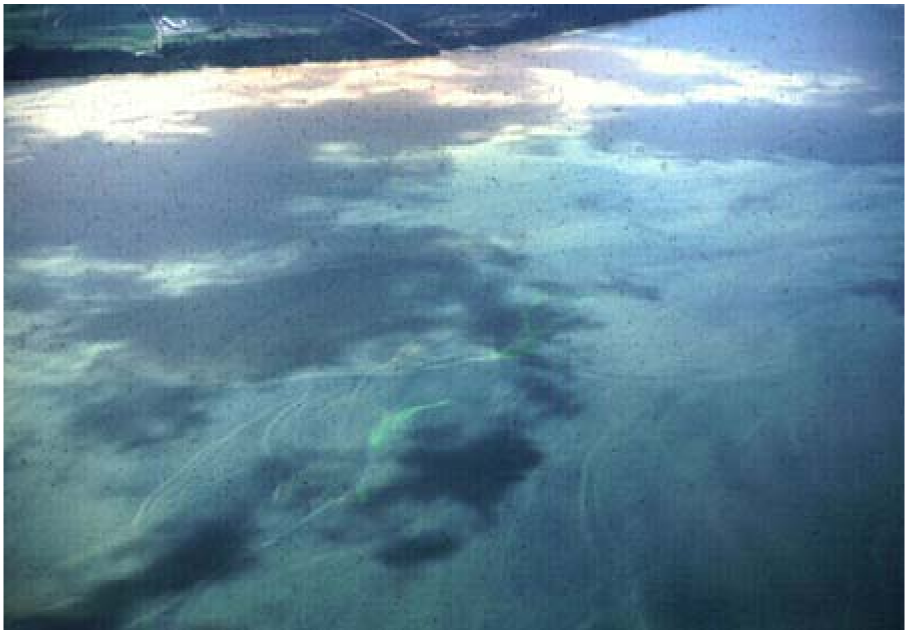


Figure 35. Turbid water of Añasco Bay

The shelf between Punta Jigüero and Punta Cadena has no sediment influx from rivers and is clear of the plume of sediments from the Añasco River. Despite having a more favorable environment than the Añasco reefs, coral is almost absent from this part of the shelf. No shelf edge reefs were found during our investigation, and in discussions with local divers, no one has found coral reefs on the shelf break.

As sea level rose, the higher topography of the shelf on either side of the Añasco, Yagüez and Guanajibo river channels was colonized by reef corals along with several inshore highs which were probably remnants or former beach lines. These areas were flooded less than 10,000 years ago, and sea level approached its present position about 5,000 yBP. This was a fairly rapid rise of sea level that must have been accompanied by relatively high erosion and turbidity as the shoreline eroded creating conditions in which coral growth and reef accretion were restricted.

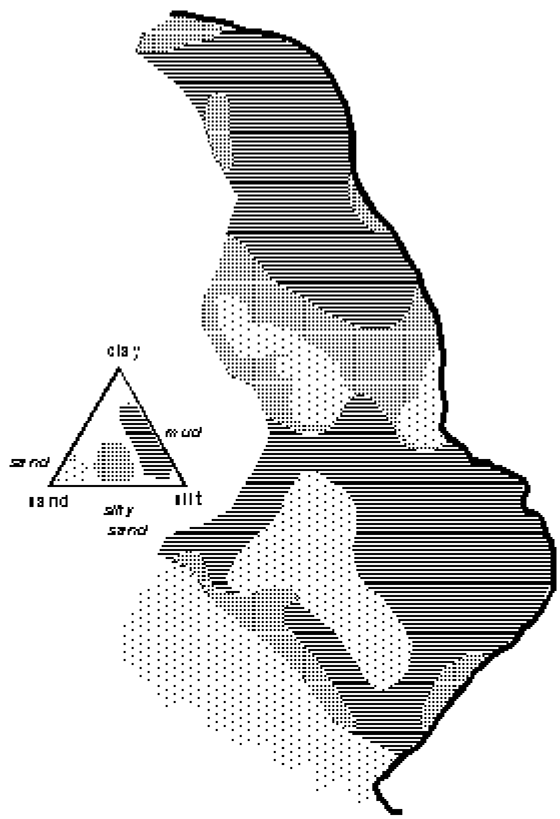


Figure 36. Grain size facies for Mayagüez-Añasco bays

Grab samples have been collected in several studies of this area [Morelock, *et al.*, 1983; Webb, *et al.*, 1994] and the results of the grain size analyses (Figure 36) show that the coarsest sediments are associated with the shelf edge reefs and patch reefs. These are carbonate sediments, and shell material in the gravel size makes up as much as half of some of these sediments. The carbonate sources are the reefs, which are present as bathymetric highs.

The sediment facies mapped by Morelock, *et al*. [1983] shows a large area of fine-grained terrigenous sediments in both bays (Figure 37). Additional sediments are derived from discharge of the three local rivers and during periods of high rainfall, the bays are very turbid. Sediment resuspension is a common occurrence.

The reefs at Añasco-Mayagüez have been studied in more detail than the rest of the western shelf area. The results from earlier studies of this shelf were published in Morelock, *et al*. [1983] and Webb, *et al*. [1994] More recent investigations (1996-1997) are presented in this paper, including detailed studies at Manchas North, Manchas Exteriores, Manchas Interiores, Algarrobo, Manchas Grande and Escollo Rodriguez. All of the reefs are submerged except at Algarrobo and Escollo Rodriguez (Figure 38).

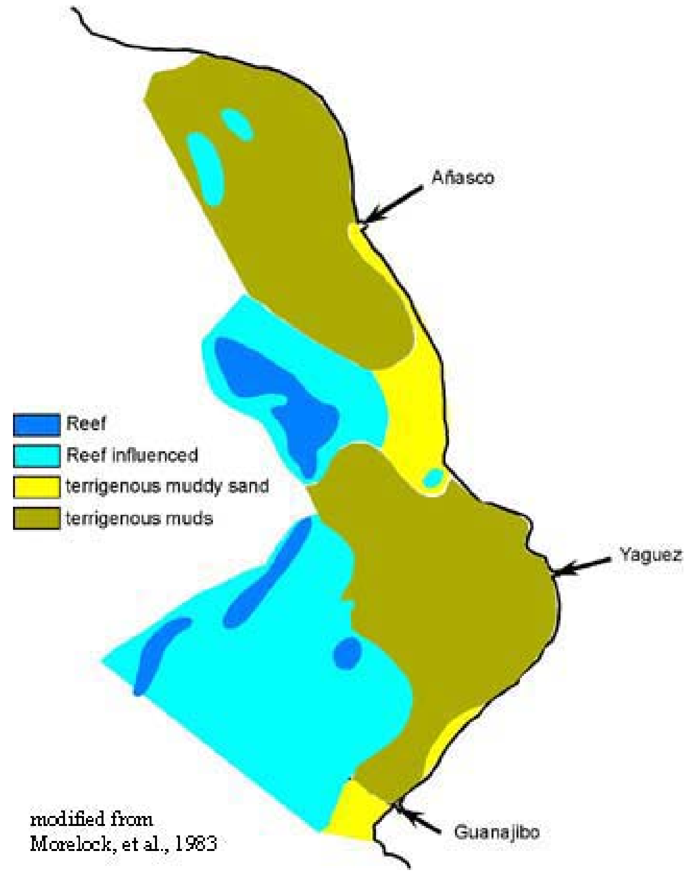


Figure 37. Sedimentary facies Mayagüez-Añasco bays

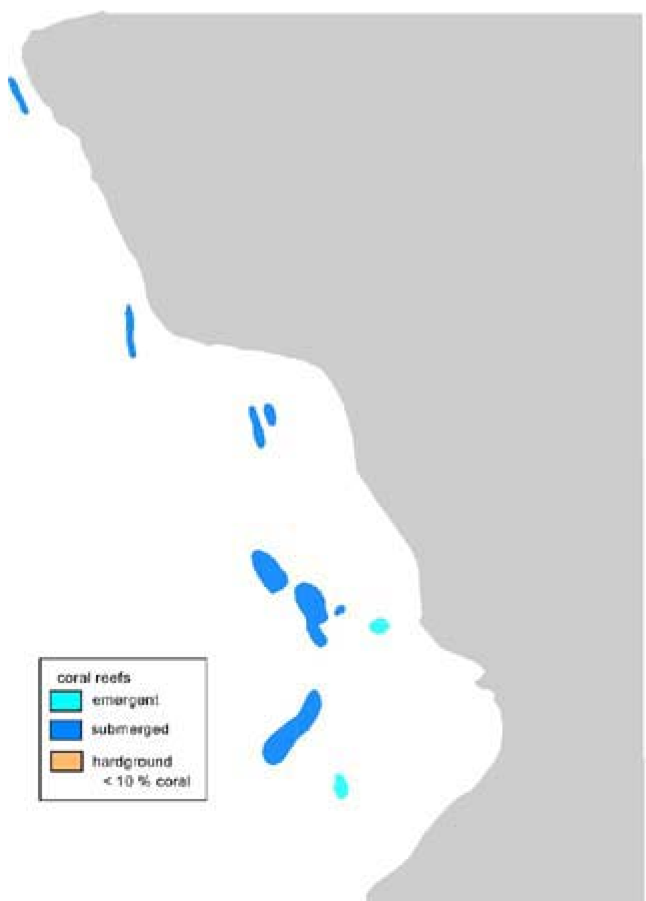


Figure 38. Coral reefs at Mayagüez-Añasco bays

Coral reef condition is described in terms of coral community, abundance and coral cover (Figure 39). Even though the shelf is narrow at Añasco, the shelf edge reef at Manchas Interiores 7 has relatively high coral cover (Figure 40). The other parts of the shelf edge reef have less than 10 percent coral cover.

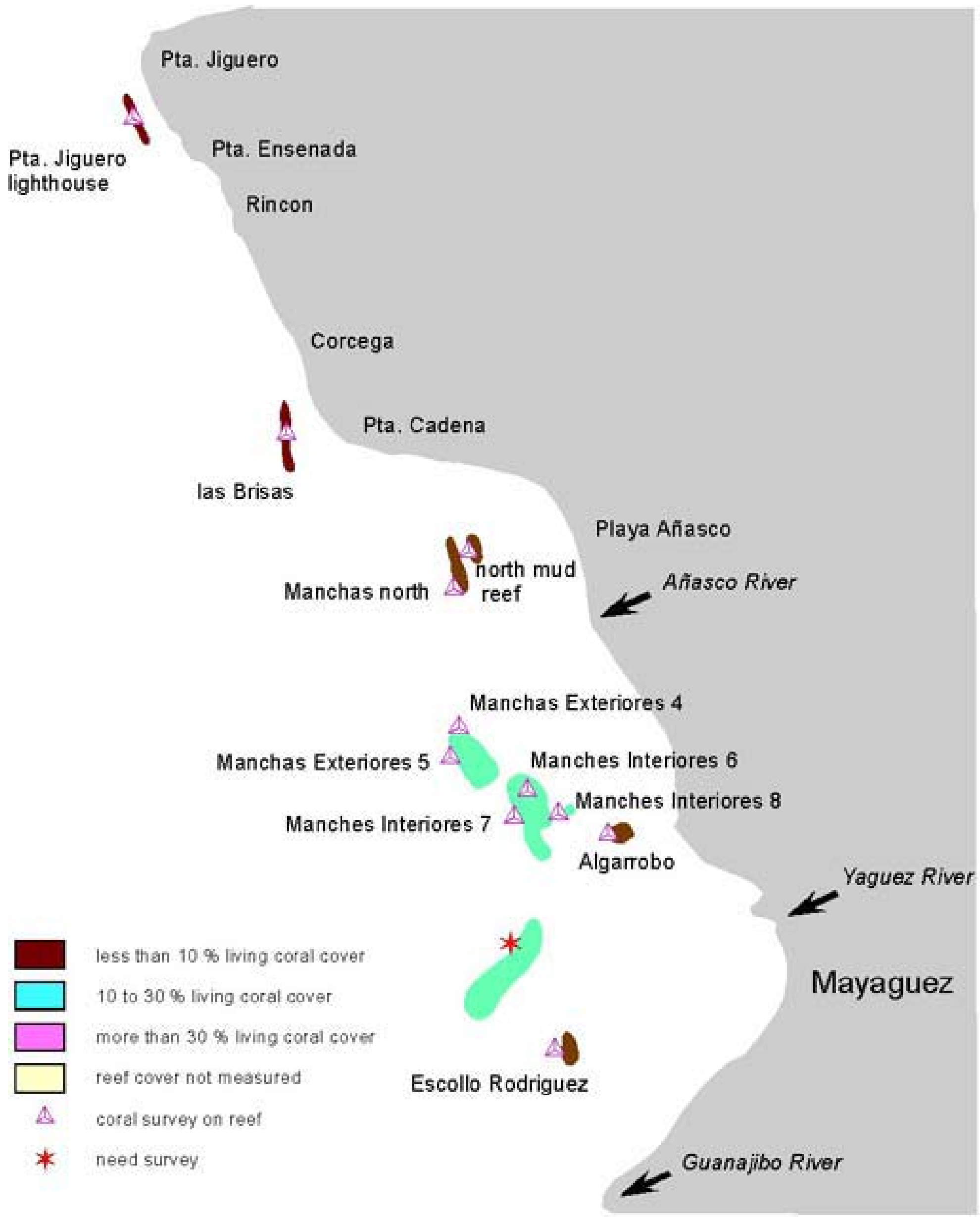


Figure 39 Status of the coral reefs of the Mayagüez-Añasco bays as shown by total percent of living coral surface on each reef.

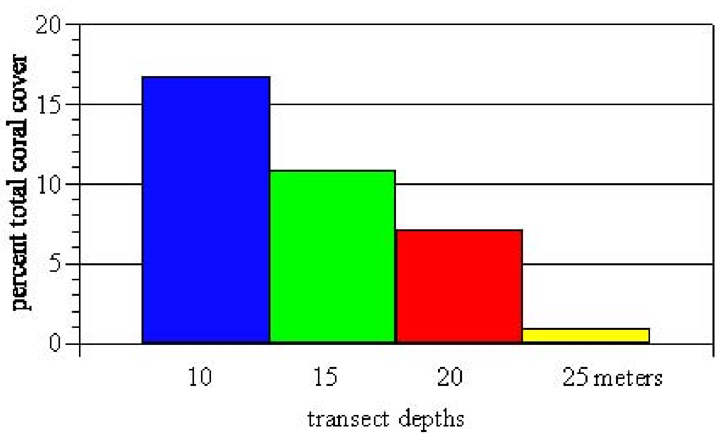


Figure 40. Total coral cover by depth for Manchas Interiores 7

Reef building corals were found on all reefs investigated. Live coral occurred to 27 m depth on shelf edge reefs south of Añasco Canyon and to 14 m on the Manchas North reef. The highest cover was observed on the shallowest part of the shelf edge reefs (Figure 41). The total coral cover shows a rapid decrease with depth. The reefs varied in live coral cover from less than 1 percent at Algarrobo Reef to over 17 percent at Manchas Interiores 7, with the best developed reefs on shelf edge sites farthest from the Añasco River and the ship channel.

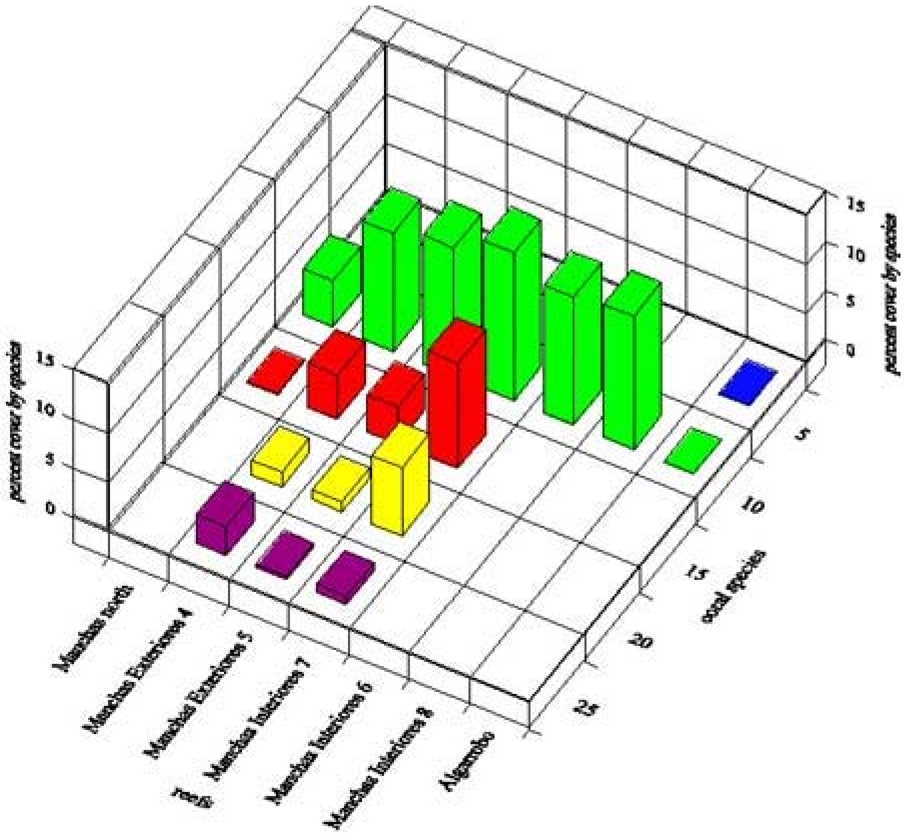


Figure 41. Total coral cover by depth on Mayagüez-Añasco reefs

Colpophyllia natans, Diploria strigosa, Montastraea cavernosa and the *Montastraea annularis* group are the most conspicuous corals on the shelf edge buttresses. Coral masses are separated by narrow sand channels that serve as conduits for the transport of sediments downslope.

The shelf edge reef north of Añasco Canyon has been severely impacted by chronic (virtually continuous) sedimentation (Figure 42). Visibility was poor (2 m) and a layer of fine silt covered the reef substrate. No live coral was found below 14 m, and only 4.7 percent cover was measured at 10 m. The community was dominantly the *Montastraea annularis* group, *Montastraea cavernosa* and *Agaricia* species with the size of an individual coral colony typically less than 10 cm (Figure 43).

Figure 42. High sediment impact, Manchas North reef

Figure 43. Individual colonies in the coral community of Manchas North at 10 m

Although sediment influx has been low, the Punta Jigüero to Punta Cadena shelf had only two coral reefs. Both reefs had low coral cover by flattened colonies. Many of these are one meter across (Figure 44). Almost no *Montastraea annularis* were present. Dominant corals on both reefs were *Porites asteroides, Colpophyllia natans* and *Diploria* species (Figure 45).

Meandrina meandrites were common on the eight meter deep Punta Jigüero reef, but absent on the five meter deep las Brisas reef.

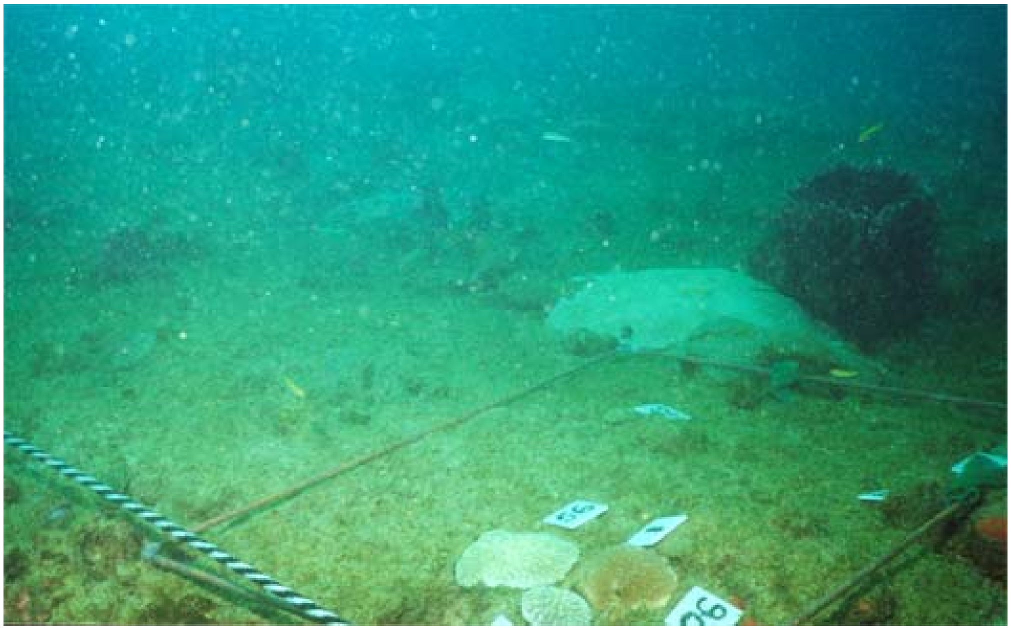


Figure 44. Flat heads of coral at the Punta Jiguero lighthouse reef. Some of these are over one meter diameter

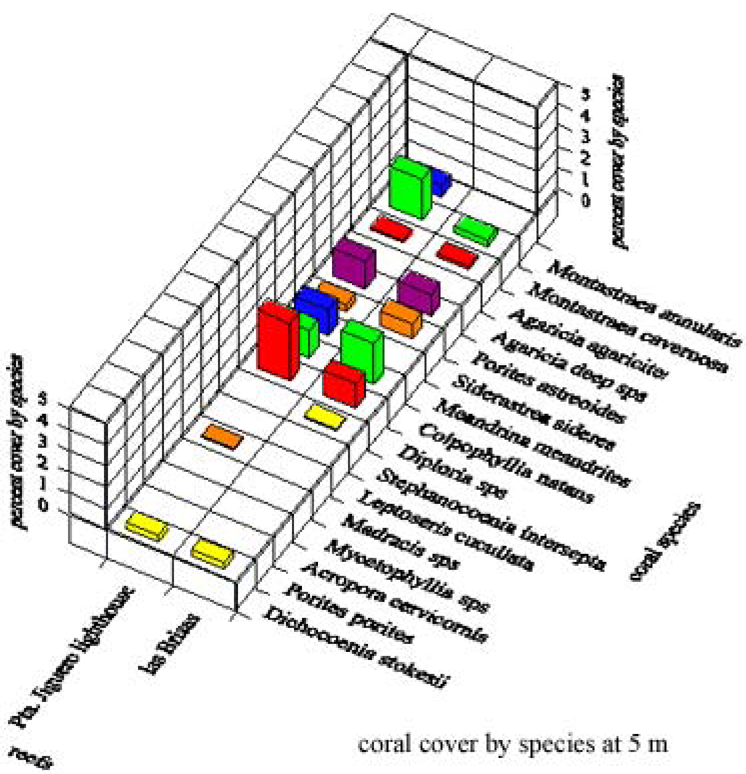


Figure 45. Coral cover by species on the Ríncon reefs.

On the shelf edge reefs of Manchas Exteriores and Manchas Interiores, maximum coral development was at 10 m (Figure 46). *Montastraea cavernosa* was the dominant coral in the 10 m community in terms of abundance and cover. *Montastraea annularis*, *Agaricia agaricites, Porities astreoides* and *Colpophyllia natans* were significant members of the community.

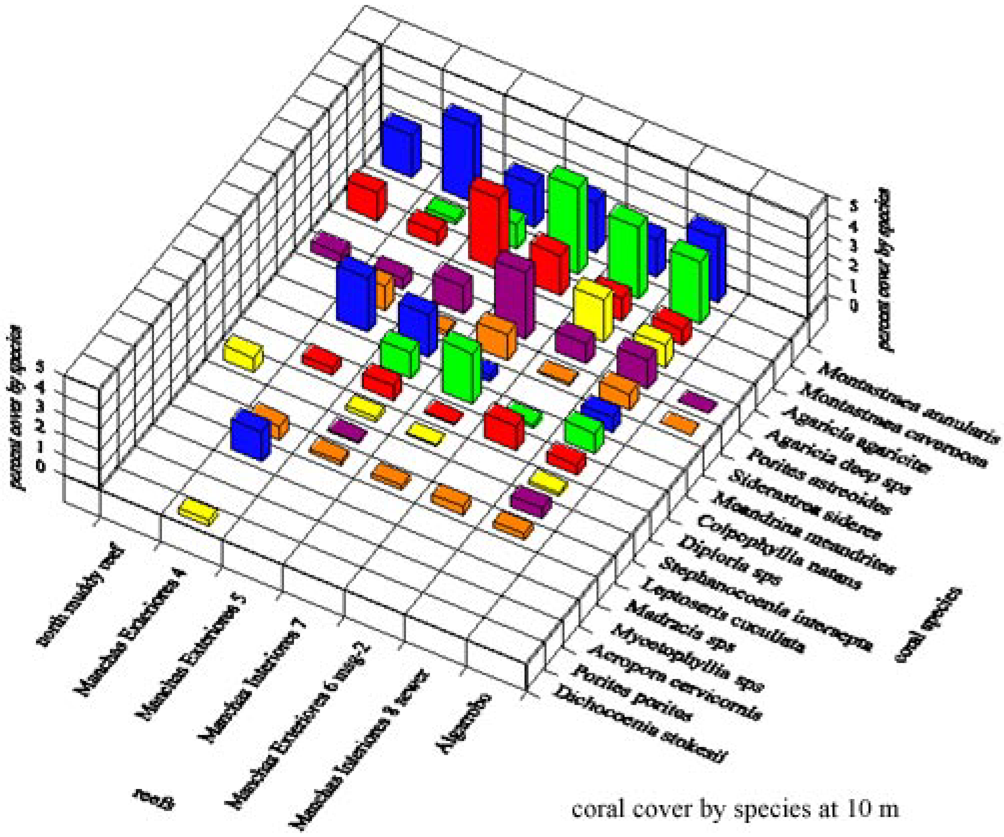


Figure 46. Coral cover by species at 10 m water depth.

The shallow reef platforms on Manchas Exteriores and Manchas Interiores had fewer coral species and a more dense gorgonian assemblage when compared with the shelf edge reefs. On these reefs, the major coral groups included plating corals (*Agaricia* and *Leptoseris*) and massive species (*Montastraea cavernosa, Diploria strigosa* and *Porites astreoides*) which are all species tolerant of sediment influx and turbid low light conditions. [Acevedo, et al., 1989] These reefs are all relatively low in coral cover, but at Manchas Interiores 8 which is the closest reef to the Mayagüez sewer outfall, the coral colonies show less cover by species.

Sites in Añasco Bay (Figure 47) are influenced by Añasco River water (nutrients from agriculture and sewage), the Mayagüez outfall (nutrients from sewage) and the Mayagüez tuna canneries (nutrients from tuna waste). These nutrient sources appear to have affected local reef areas for a long time. Algal turf was prevalent at all shallow sites. Deep reefs were covered with a fine layer of silt, which may prevent settlement of algal spores.

The impact of nutrient loading was most pronounced on Algarrobo Reef (Figure 48). Surveys performed during previous years (while tuna plant effluent was still being discharged into the Bay) demonstrated a high cover of *Bryopsis* algae. Although *Bryopsis* was less prevalent after 1997, this algae may have out-competed corals through shading, competition for space with adults and by preventing sexual coral recruits from becoming established. While this reef is shallow and currently lacks a major canopy, recolonization by reef-building corals may be prevented by distance from other reefs and the high abundance of turf algae limiting settlement sites.

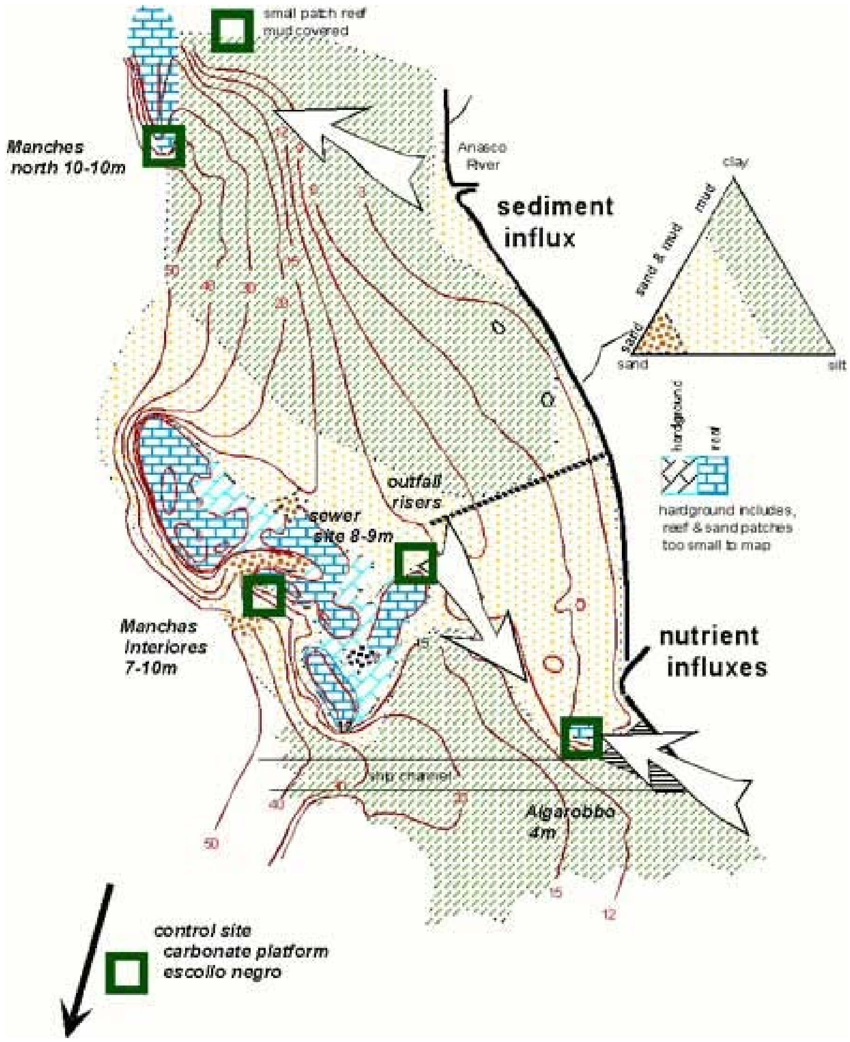


Figure 47. Sediment and nutrient influx sources for Añasco Bay

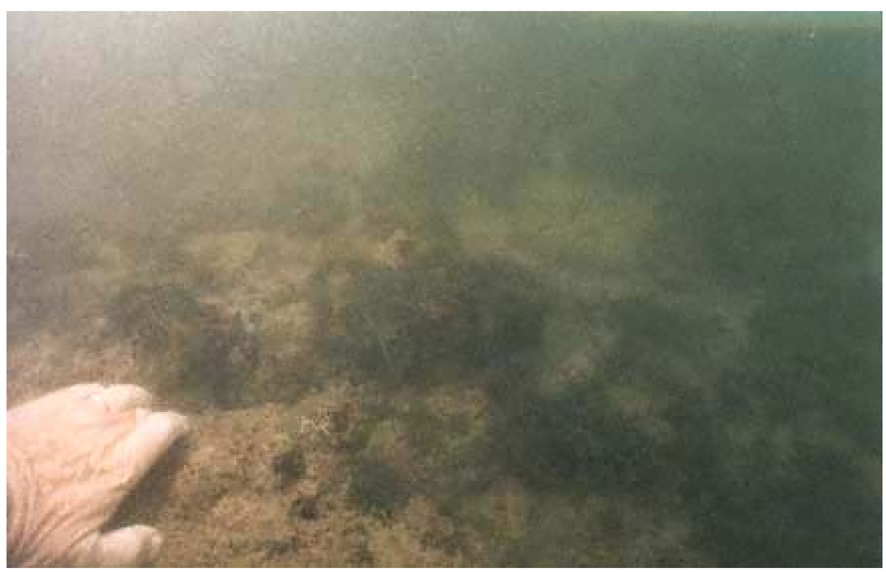
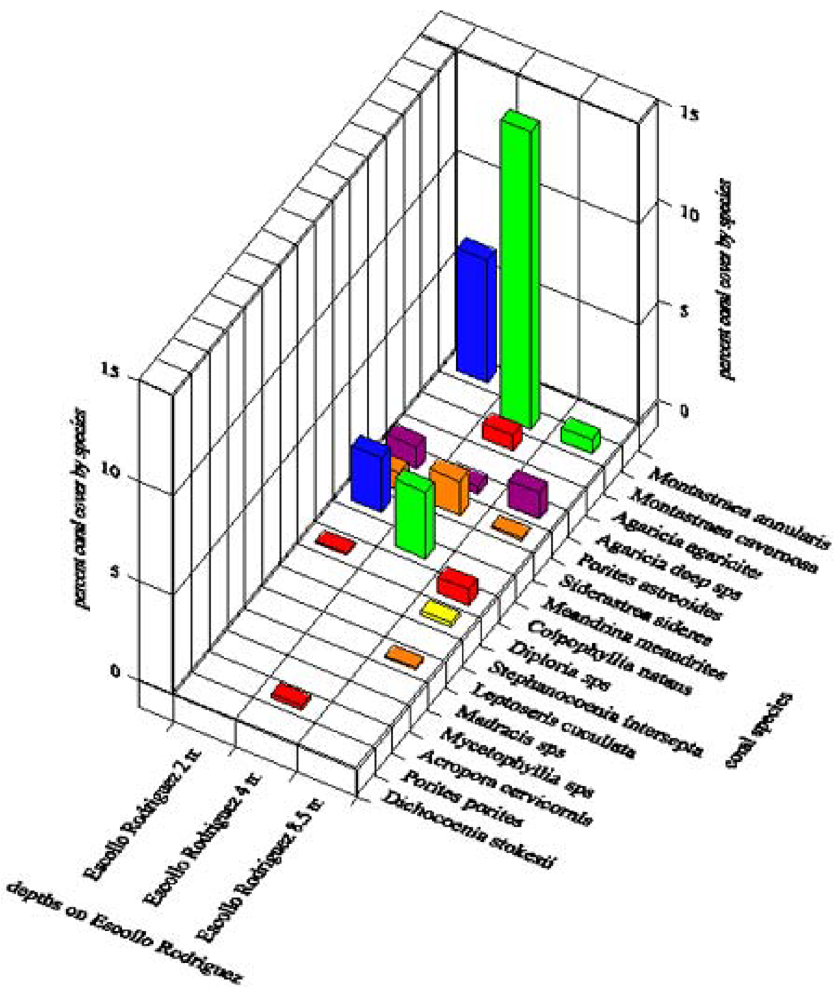


Figure 48. *Bryopsis* on Algarrobo reef

The diversity and abundance of invertebrates on Algarrobo was low. Coral species included *Porites astreoides, Diploria clivosa, Meandrina, Siderastrea* and *Scolymia*. Because few coral were present, a visual examination of the bottom for 60 m was made observing two meters to each side of a guide line. This resulted in finding 15 coral colonies which were measured. The calculated cover for the 240 m^2 area was 0.012 percent. Observations showed about one coral every four meters. All were less than 10 cm diameter, and many were riddled with worm tubes. Many dead *Acropora palmata* fragments were lying on the bottom but no live *Acropora palmata* were present.

Escollo Rodriguez reef has been heavily impacted by sediments from the Guanajibo River and sediment resuspension on the reef (Figure 49).

Figure 49. Plumes of sediment from the Guanajibo River move across Escollo Rodriguez during high rainfall conditions.



The reef ends before the ten meter level with very low coral cover at 8.5 m (Figure 50). Cover at four meters is surprisingly high, with cover primarily by *Montastraea cavernosa* (Figure 51). Although no *Montastraea annularis* are present at four meters, this species is more than half the total coral cover at two meters.

Figure 50. Coral cover by species by depth on Escollo Rodriguez reef.

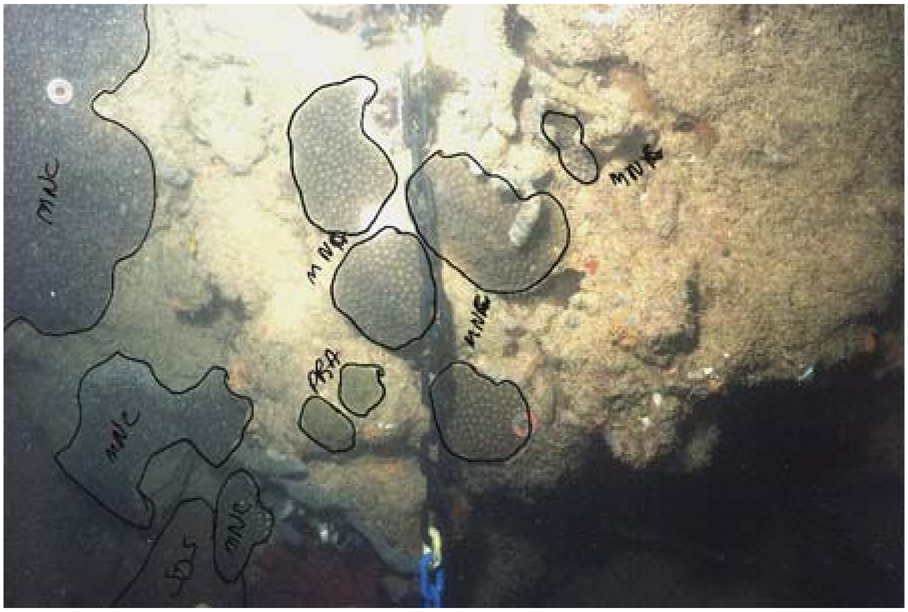


Figure 51. Flat, relatively large colonies of *Montastraea cavernosa* are common at four meters depth on Escollo Rodriguez

Meandrina meandrites was common at 15 m depth on the Manchas Exteriores and Manchas Interiores shelf edge reefs (Figure 52). This coral had wide depth distribution with small colonies, including new recruits, occurring to 25 m. The *Montastraea annularis* group, *Montastraea cavernosa, Porites astreoides* and *Agaricia agaricites* were the dominant corals at this depth.

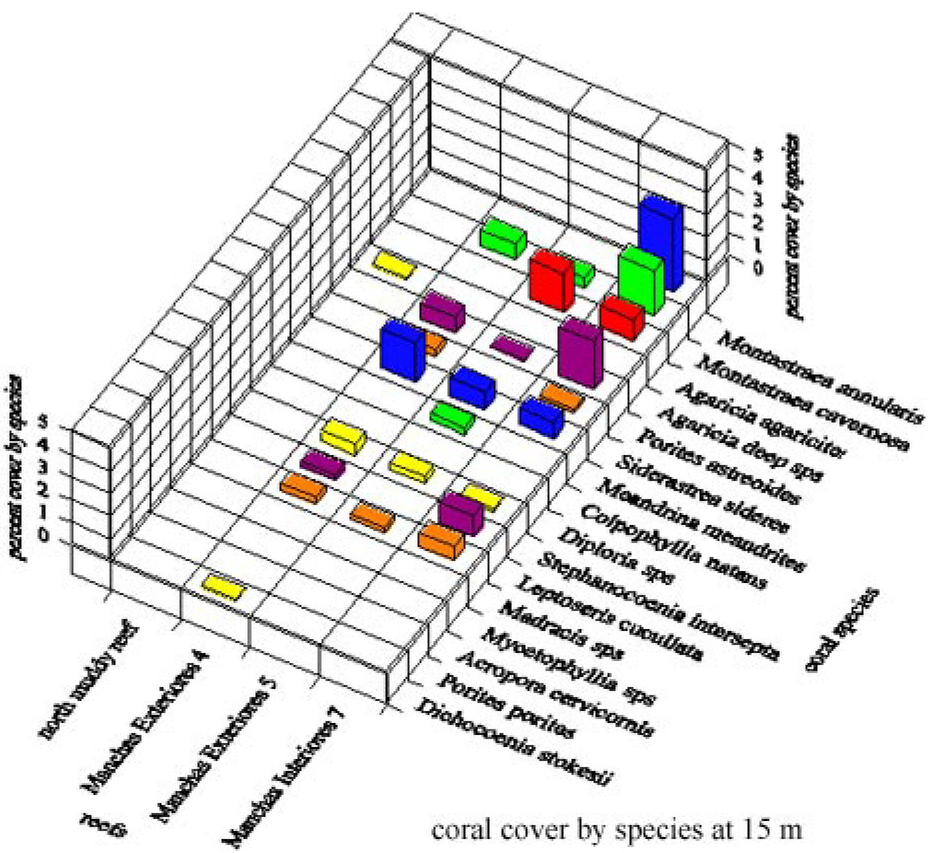


Figure 52. Coral cover by species at 15 m water depth.

Below 15 m, species composition at the shelf edge shifts to a community consisting primarily of plating species. Dominant corals at 20 m included *Montastraea cavernosa, Agaricia, Madracis, Stephanocoenia, Leptoseris, Meandrina meandrites* and *Meandrina*. *Stephanocoenia* was the most abundant coral on horizontal surfaces from 15 to 25 m as a small (3-5 cm) flattened crust (Figure 53).

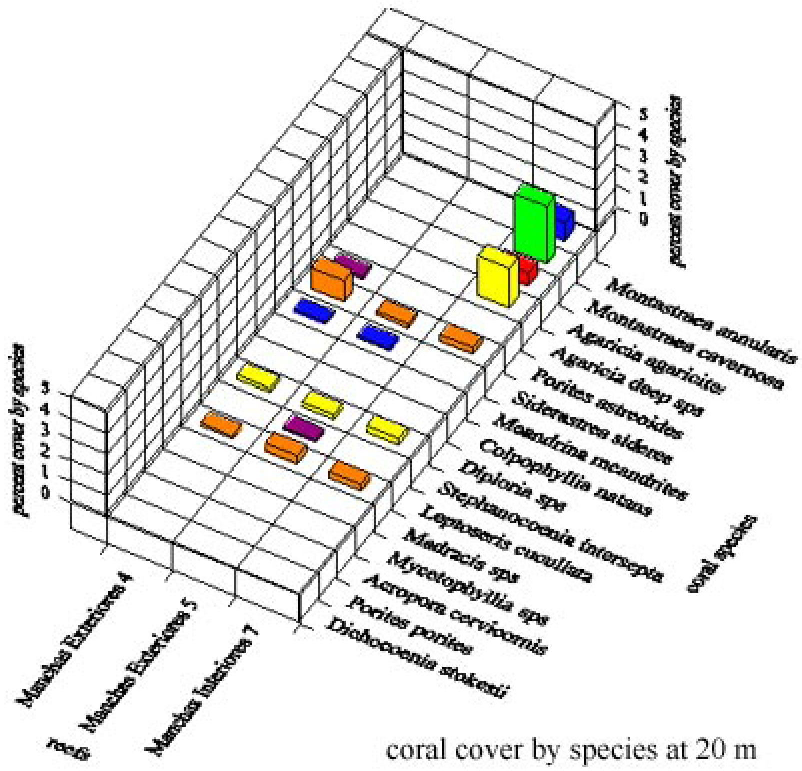
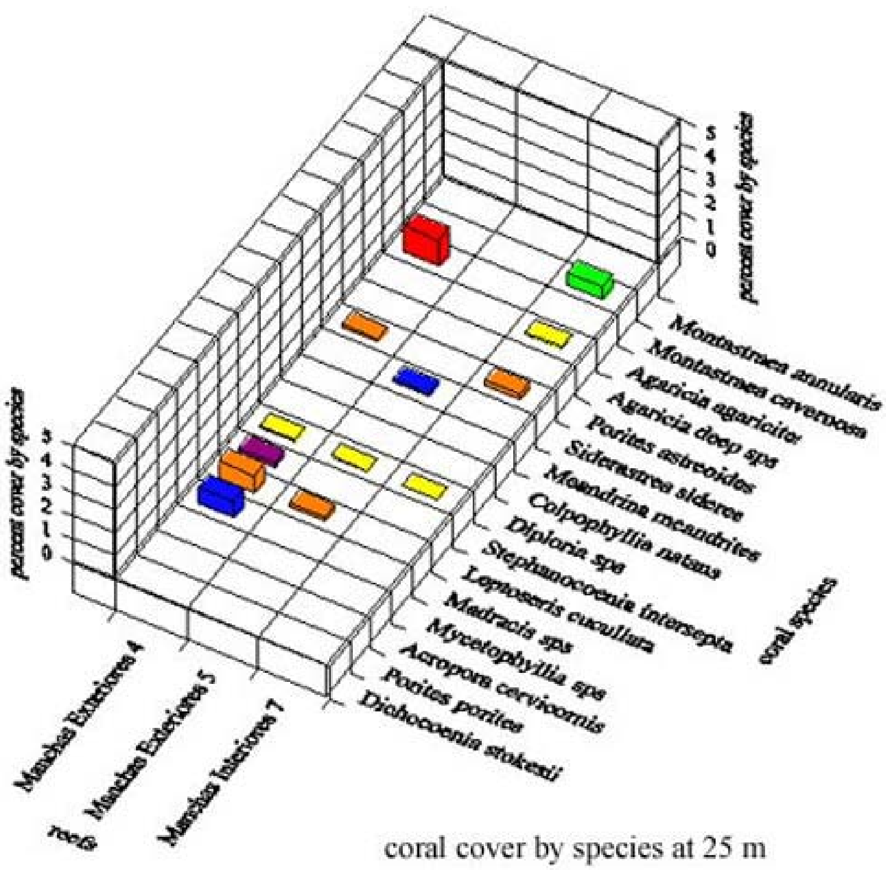


Figure 53. Coral cover by species at 20 m water depth.



At and below 25 meters (Figure 54), the bottom was muddy but large isolated boulders were found. The plating corals *Agaricia* and *Mycetophyllia* were observed on vertical surfaces of these boulders to a depth of 27 m. Although both species are patchy in their distribution, their large size contributes significantly to total cover. *Montastraea cavernosa* and *Siderastrea siderea* were the other common coral.

Figure 54. Coral cover by species at 25 m water depth.

Guánica reefs

Guánica is the first site east of La Parguera. Coral reef transects have been run at four sites. Coral cover was greater than at Guayanilla, but less than at La Parguera (Figure 55). Coral cover, species numbers, and diversity are low in the reef system in front of Guánica Bay. There was not an increase in total percent cover, diversity, and species numbers with distance from the sediment source but an opposite trend in which cover and diversity decreased with distance.

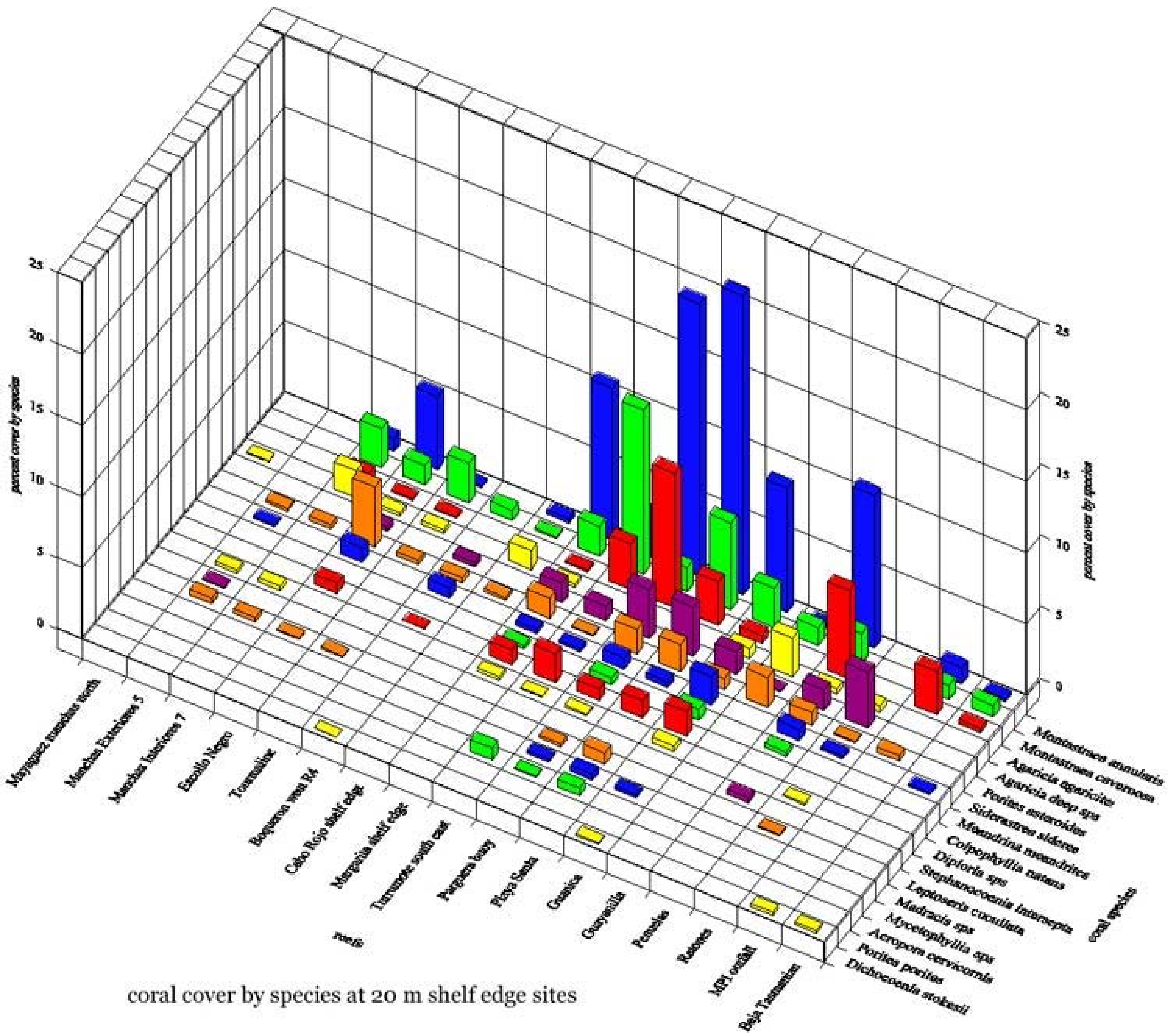


Figure 55. Coral cover by species at all shelf edge sites at 20 m water depth

Both shelf and shelf edge reefs are present at Guanı́ca (Figure 56). The number of species, and diversity have declined over the last ten years and the reef map shows relatively low coral cover at all sites (Figure 57).

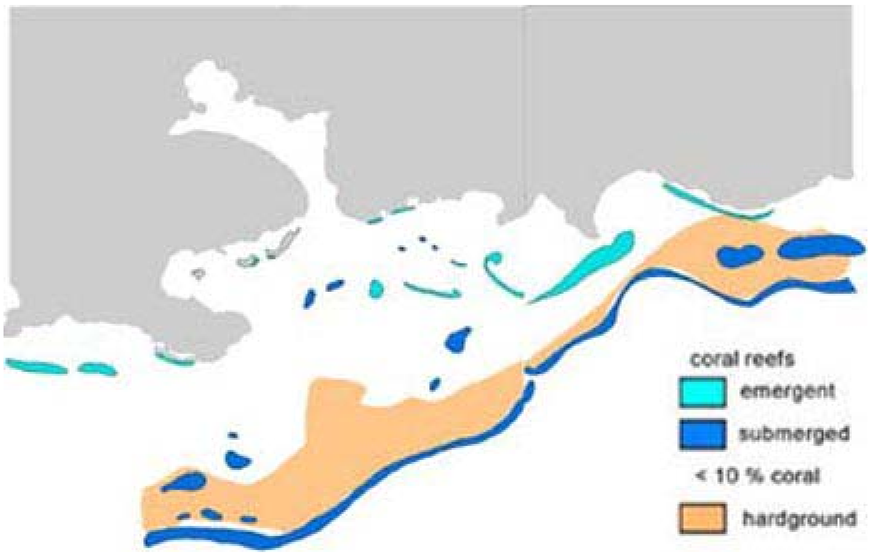


Figure 56. Coral reefs at Guanica

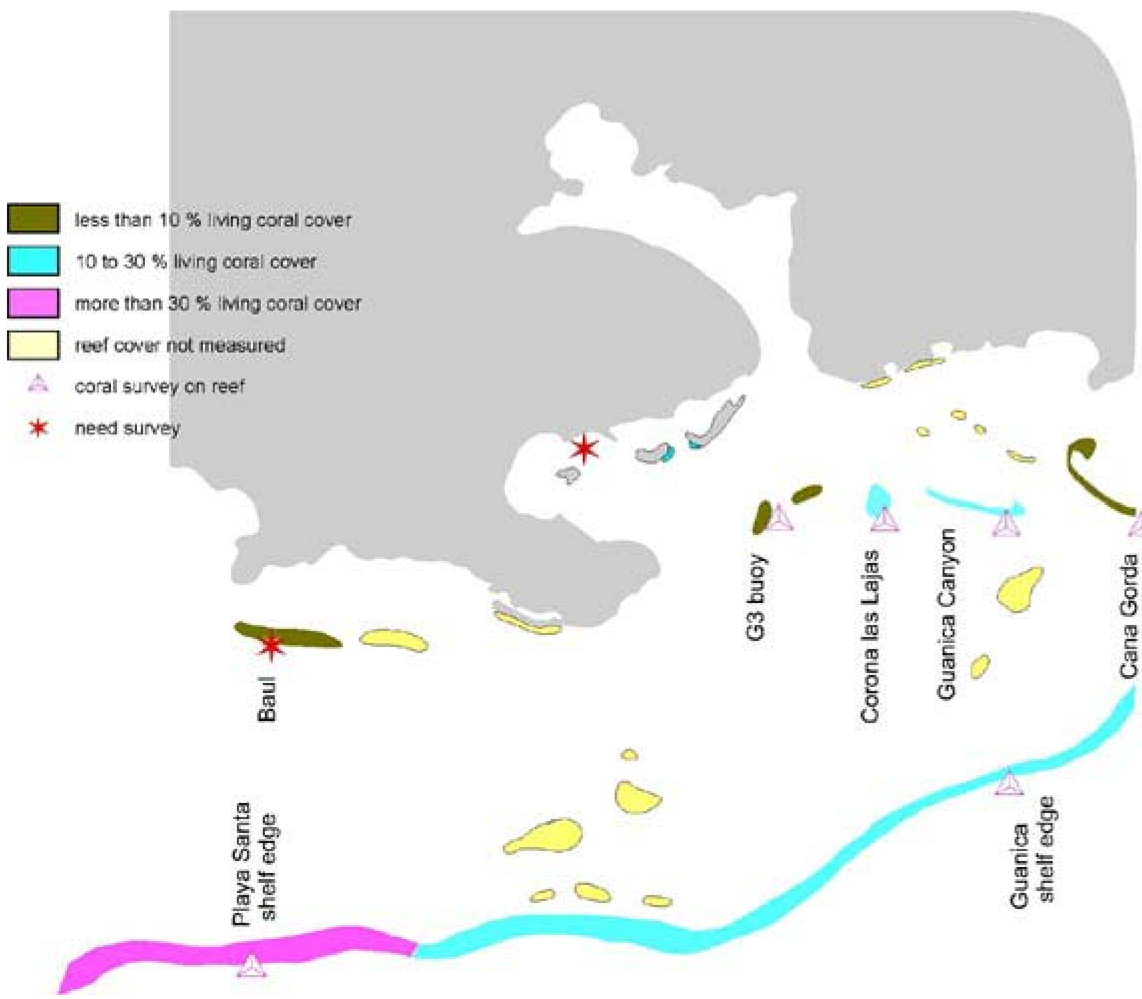
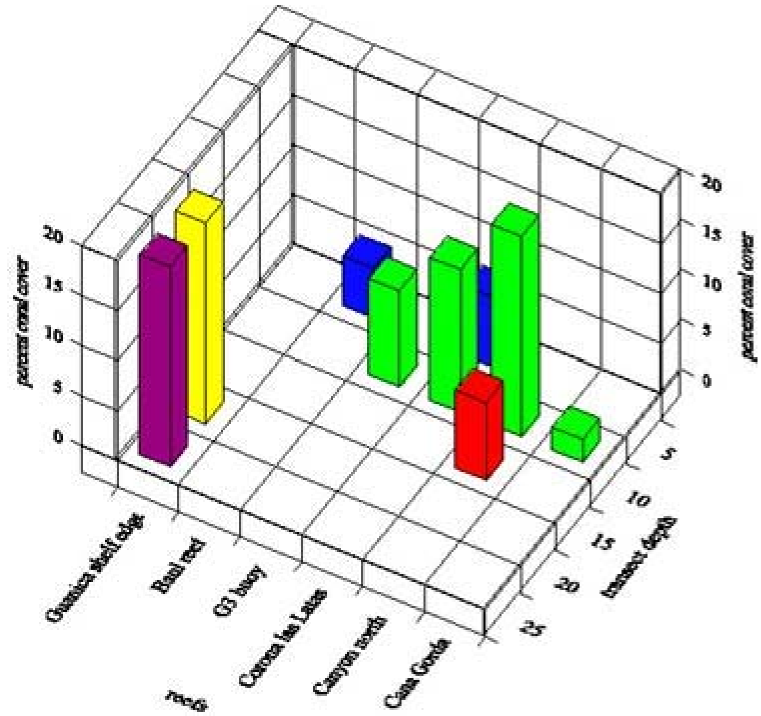


Figure 57. Status of the coral reefs of Guanica as shown by total percent of living coral surface.

The total coral cover on the reefs was less than 10 percent for the shelf reefs and about 20 percent on the shelf edge reefs (Figure 58). The lowest coral cover on a shelf reef was at the Caña Gorda reef and the highest total coral cover was at the g3-buoy which is the site closest to the terrigenous mud source.

Figure 58. Total coral cover by depth on Guaníca reefs



The total number of species at 10 m at each shelf site was low with a different species being dominant at each site (Figure 59). *Montastraea cavernosa* was the dominant species at the g3-buoy, the dominant coral at the Canyon North site was *Montastraea annularis*, and at the Caña Gorda, *Porites astreoides* was dominant.

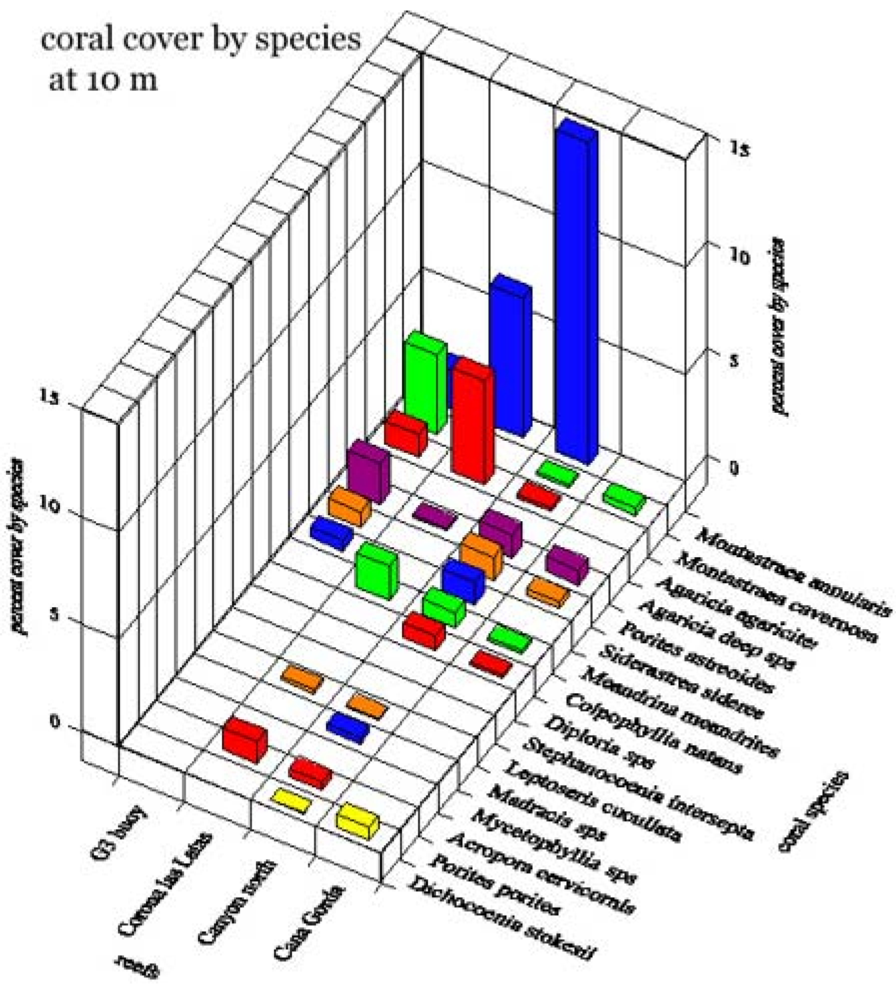


Figure 59. Coral cover by species at 10 m water depth.

The Canyon North site showed a marked decrease in total coral cover from 1988 to 1999 from 14.2 percent to 8.4 percent. A significant decrease in the percentage of *Porites astreoides, Siderastrea siderea, Meandrina meandrites, Colpophyllia natans*, and *Diploria strigosa* was found. The number of species found in each area remained the same.

The pattern of cover on the shelf edge reefs was less than at La Parguera (Figure 60), but still a reasonable amount of cover and species diversity.

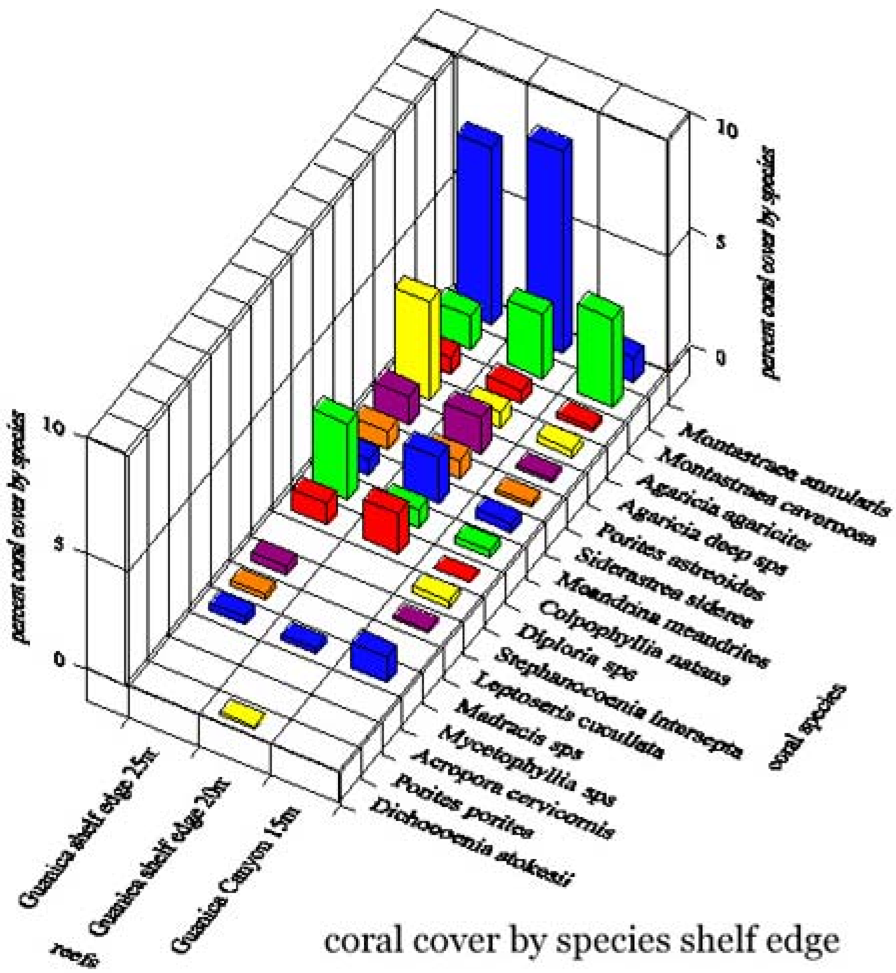


Figure 60. Coral cover by species on the shelf edge reefs, Guaníca

Guayanilla reefs

This was a resort diving area until the 1970's when construction of a refinery complex created an almost permanent turbid water environment. Results from earlier studies of these reefs were published in Morelock, *et al*. [1979] Data and comments presented in this section draw from this source and data collected during surveys from 1985 to 1999.

The three sedimentary environments on the insular shelf of the Guayanilla and Tallaboa canyons (Figure 61) are the relatively bare rock and reefs (Figure 62) on the shelf platform and the muddy sediment-floored submarine canyon floors. Sediments in the mud facies are resuspended by ship traffic in the Guayanilla and Tallaboa canyons. The present Guayanilla and Tallaboa bays are turbid-water areas with Secchi visibilities of less than three meters.

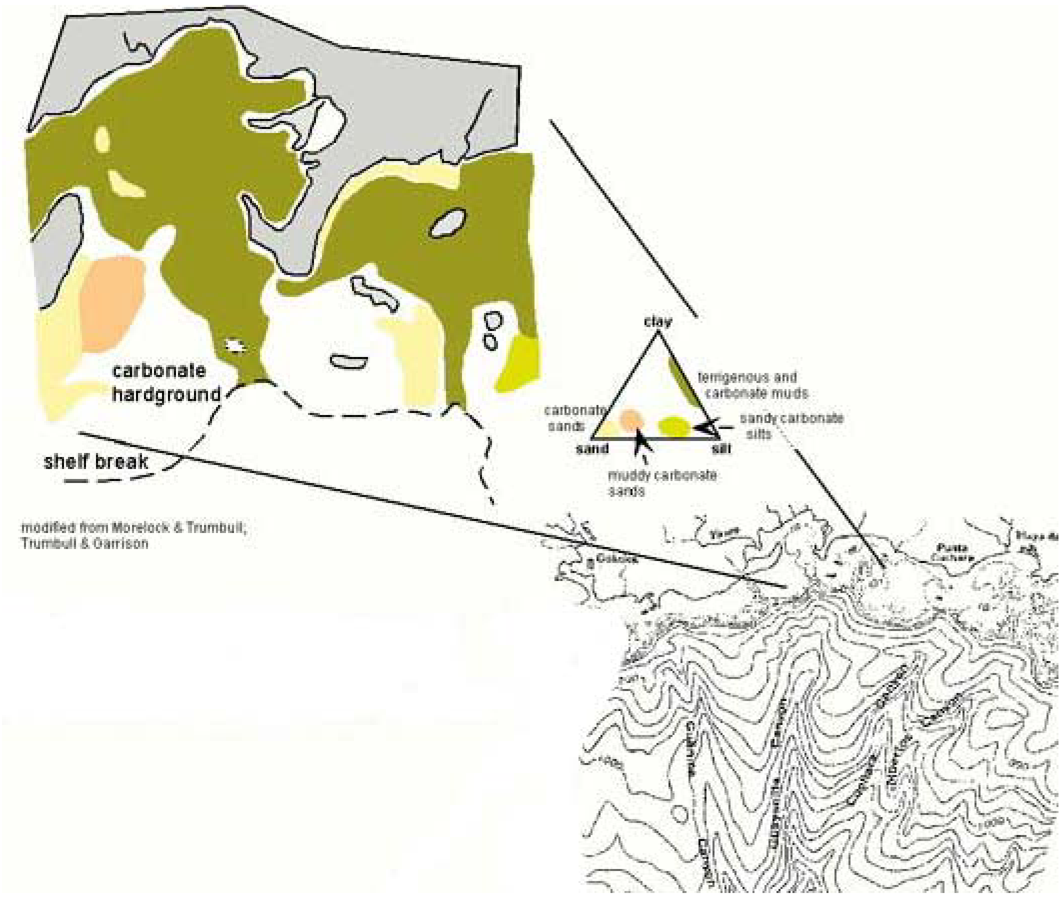


Figure 61. Guayanilla Sedimentary environments

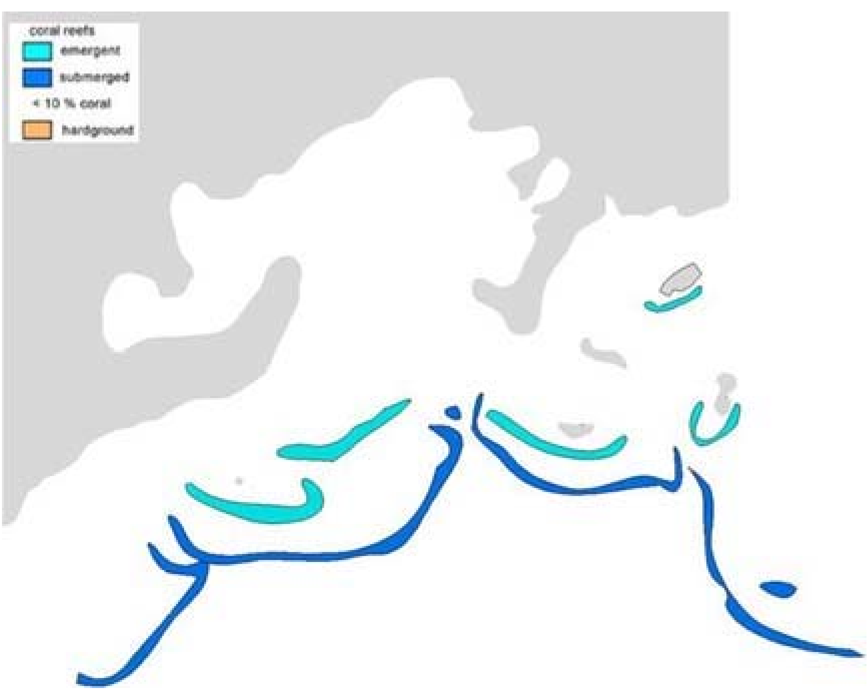


Figure 62. Coral reefs at Guayanilla

Modern reef growth is limited to areas of hard bottom with bathymetric relief. Larges areas of dead coral heads (Figure 63) suggests that until very recent time, coral growth was far more vigorous than in the present environment. Rock surfaces of dead coral colonies show that development of the reefs probably followed the same pattern as at La Parguera. Reefs are now restricted to shallow-water areas at the open shelf edge. Little of this reef growth is thriving, and the community ecology of the reef resembles a much deeper-water assemblage. Patch reefs that were present in the bay areas are now shoal mounds of rubble covered with grass beds.

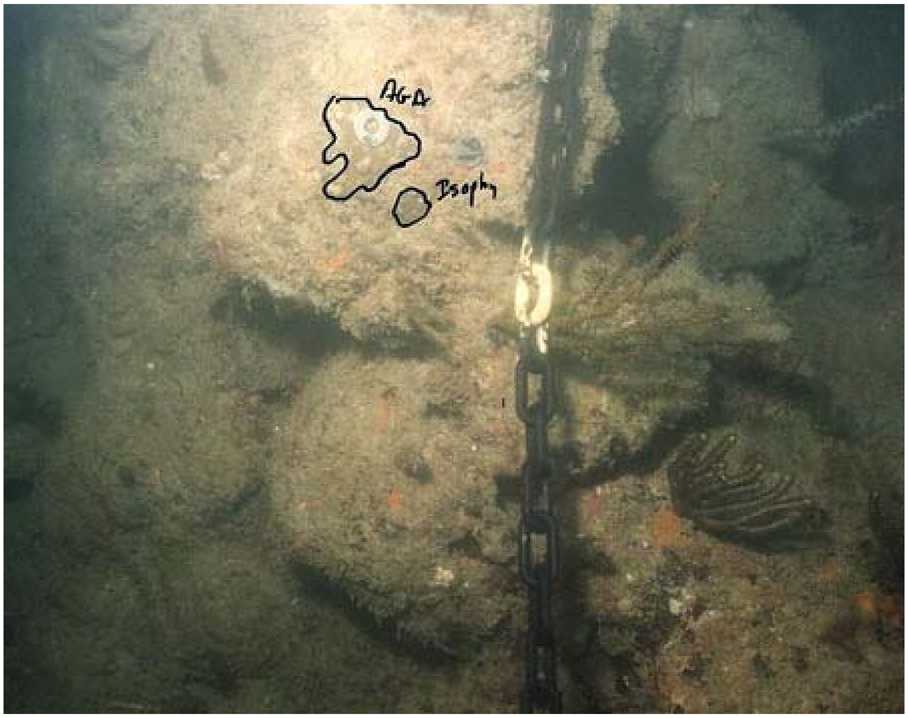
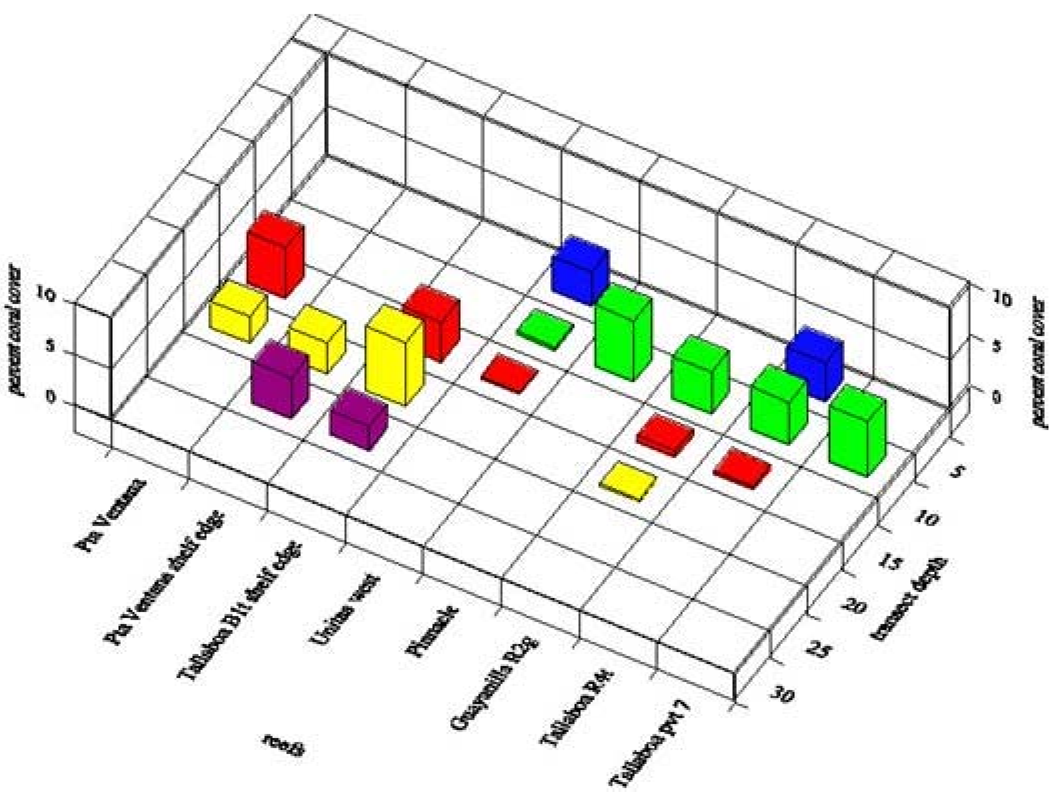


Figure 63. Rock surface formed by dead coral colonies

Figure 64. Total coral cover by depth on Guayanilla reefs



The surveys show the reduced living coral cover that occurs with increased sediment stress beyond the normal condition(Figures 64 and 65). The eastern wall of Punta Ventaña canyon shows a total coverage of five percent living coral at 15 m and only 2.5 percent at 20 m. All depths for these reefs have less than six percent living coral cover. At several of the sites, there is no living coral below 10-12 m.

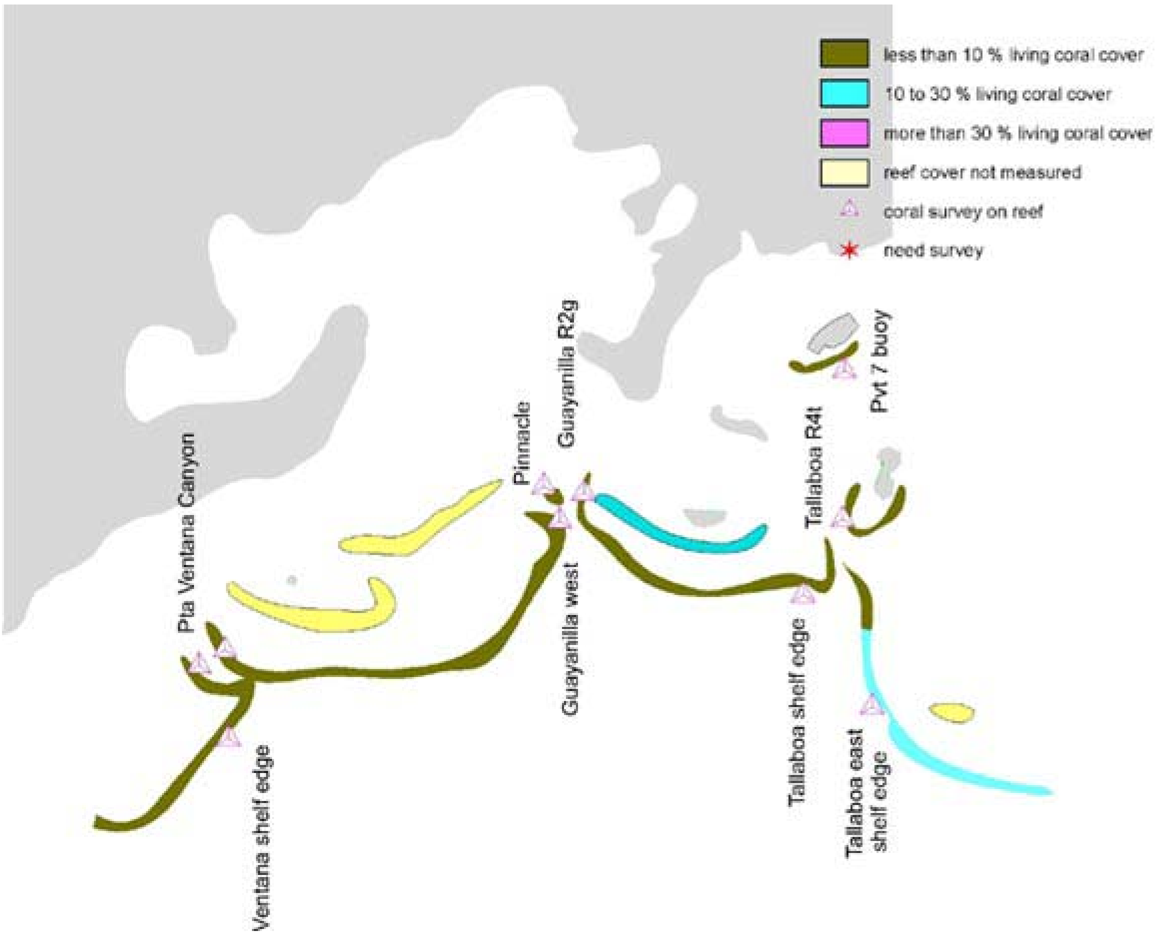


Figure 65. Status of the coral reefs of Guayanilla as shown by total percent of living coral surface.

The five meter (Figure 66) sites in Guayanilla and Tallaboa bays have very low coral cover and a very limited number of species. Relict reefs in the inner bays are now covered with *Thalassia*.

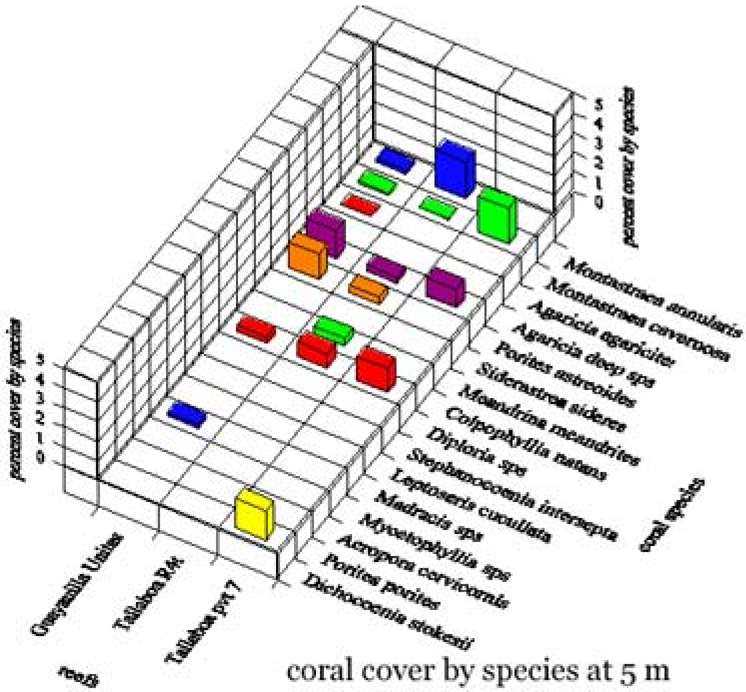


Figure 66. Coral cover by species at five meters water depth.

At 10 m (Figure 67), the shelf reefs showed a marked increase in the dominance of *Montastraea cavernosa*, compared to the same depth zone at Turrumote Reef (La Parguera); it is three to six percent cover or more than half of the living coral present. The number of species has been reduced, with only five species having more than one percent cover on the transects. The *Montastraea annularis* group are present but comprise only a small part of the coral cover.

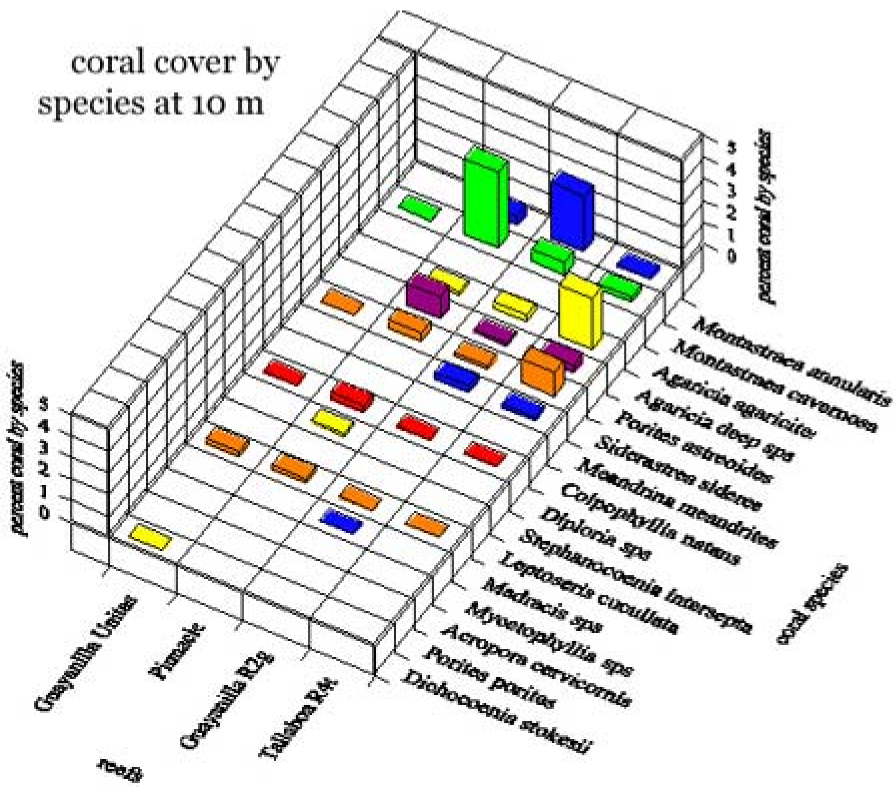


Figure 67. Coral cover by species at 10 m water depth.

There are distinct changes in the ecology of the submarine canyon and shelf edge reefs at 15 m, 20 m and 25 m (Figures 68, 69 and 70). The coral community shows elements of both the massive coral zone and the deeper-water platy zone. The dominant coral was now *Montastraea cavernosa*, with *Montastraea annularis* and *Agaricia agaricite*s lower in abundance. There was an increase in *Siderastrea siderea* abundance, and the shape and growth of *Agaricia* was modified to a platy form attached to vertical surfaces. These changes reflect sediment stress and lowered light level adaptations of the community. The coral system is now living close to the limits of tolerance.

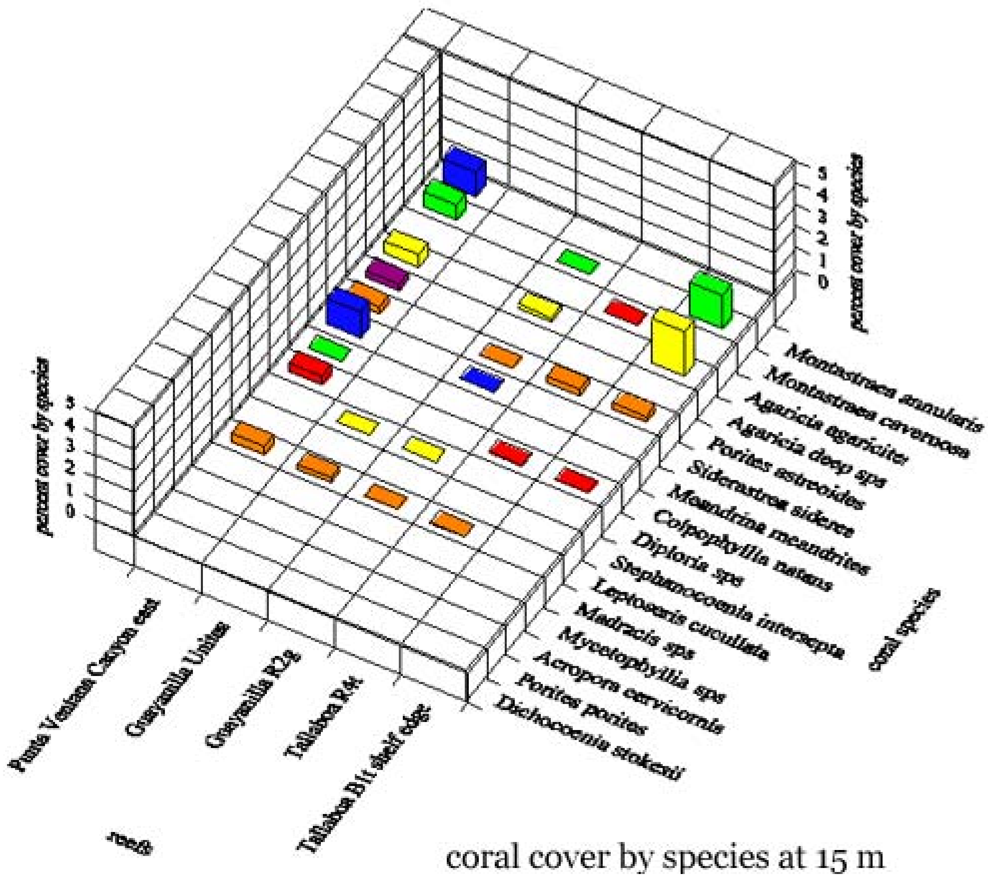


Figure 68. Coral cover by species at 15 m water depth.

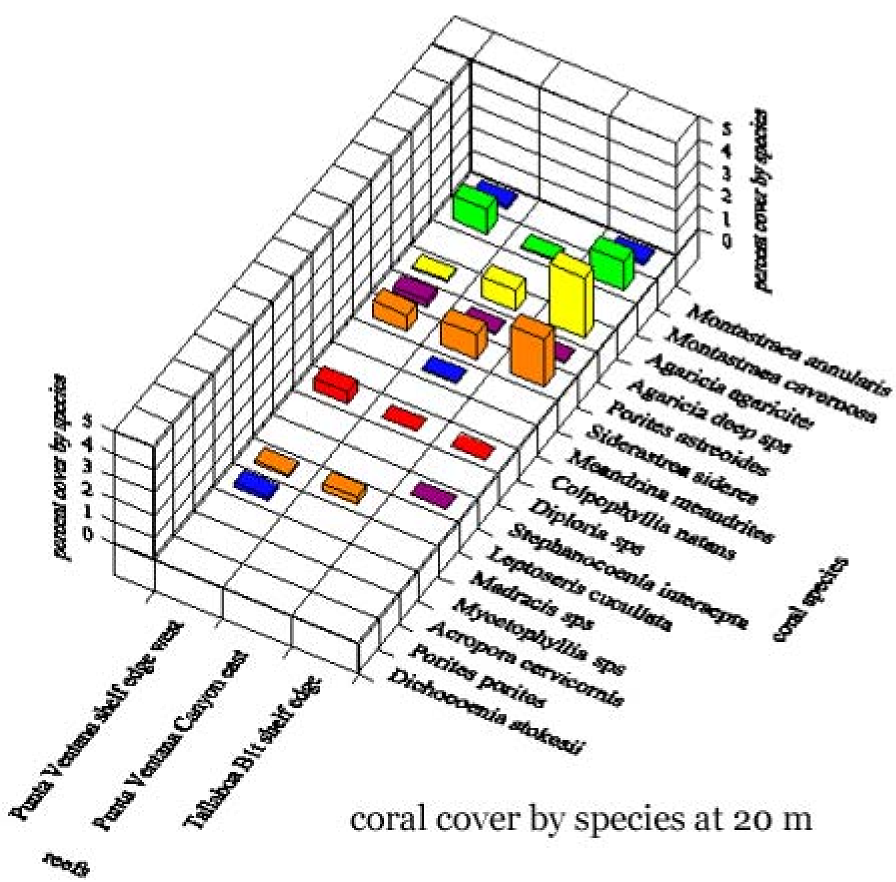


Figure 69. Coral cover by species at 20 m water depth.

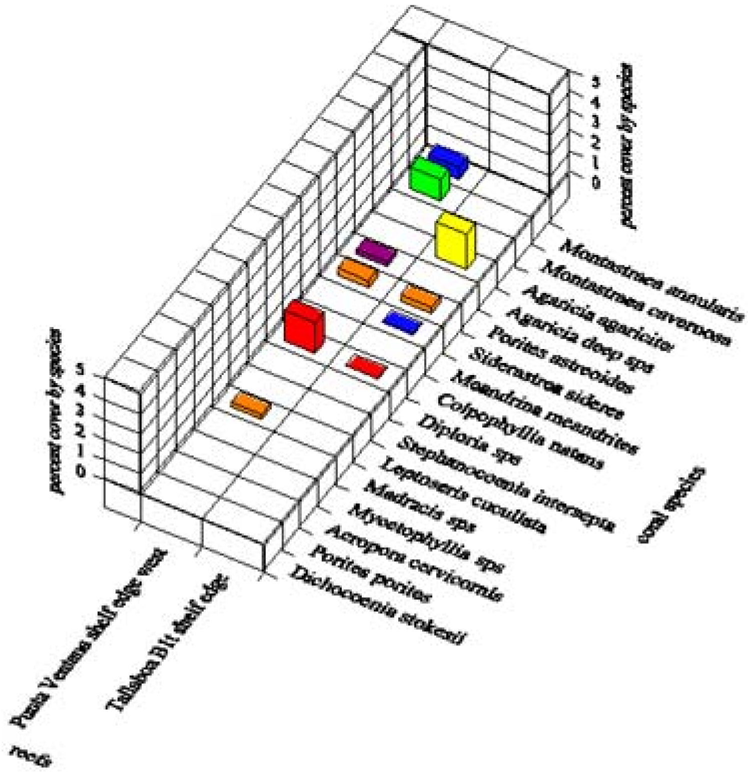


Figure 70. Coral cover by species at 25 m water depth.

West Ponce reefs

The coral reefs west of the Baja Tasmanian carbonate platform and the Ponce Submarine Canyon (Figure 71) are affected by westward-moving terrigenous sediment plumes. The only emergent reefs are in front of Cayo Ratones and south of Isla Cardona. The only areas with appreciable living coral are the shelf edge reefs. These reefs were studied in 1987-1988. The results were published in Acevedo, *et al*. [1989] Data and comments presented in this section draw on this source and surveys made during an investigation of the benthos for the Ponce deep water sewer outfall. [Morelock, *et al.,* unpub. report]

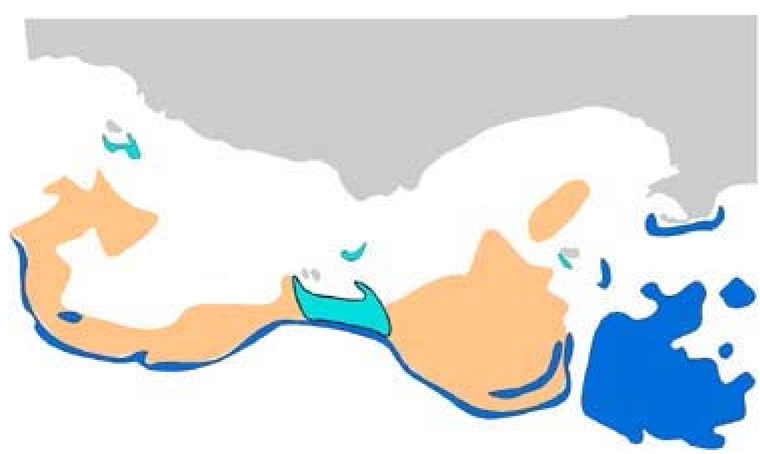


Figure 71. Coral reefs at west Ponce

The carbonate platform is separated from the shoreline by the Ponce Basin which extends west of Ponce Harbor and grades northward into the nearshore zone. Sediments in the Ponce Basin (Figure 72) are poorly sorted terrigenous silts and clays with small amounts of carbonate mud and sand that have been carried in from surrounding areas and have accumulated in low-energy, deeper-water conditions. Similar sediments floor the Ponce Submarine Canyon. The fine-grained sediments are resuspended by wave action and ship traffic causing underwater visibility of less than one meter. pers. obs. The resuspension develops a sediment plume that is transported by currents, carrying fine sediments over the West Ponce reefs. Acevedo, et al., 1989

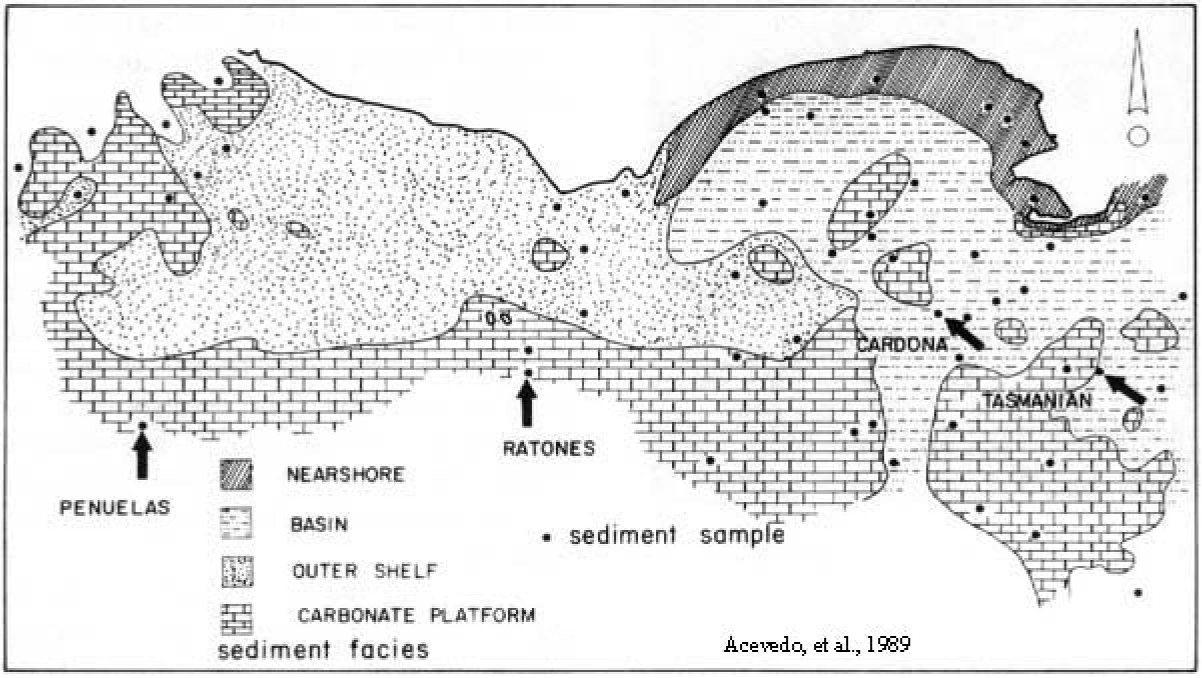


Figure 72. Sediment facies west Ponce. The Basin sediments are sandy muds and muds.

The platform is an area of hard carbonate pavement with thin carbonate sands and small reefs. The water is generally turbid with Secchi disc readings of less than 5 m. The shallow shelf reefs had very low coral cover and the least sediment-tolerant specie, *Acropora palmata*, is not present (Figure 73).

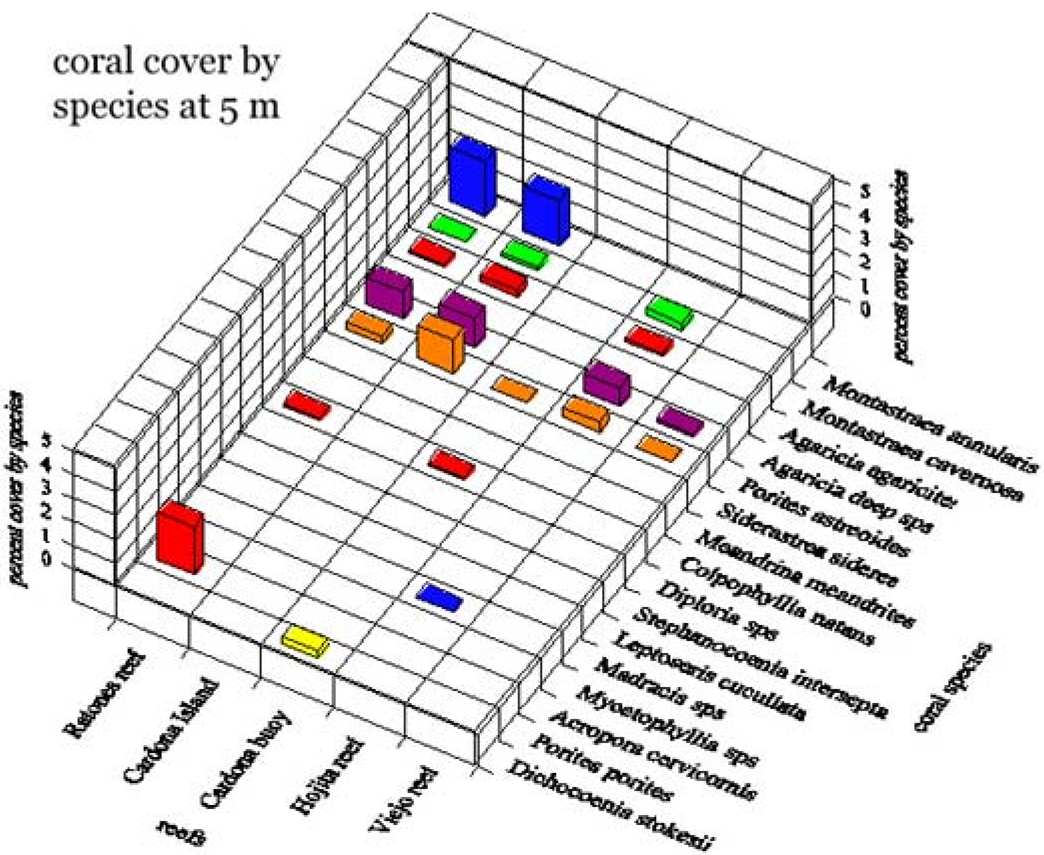


Figure 73. Coral cover by species at five meters water depth.

Below five meters, the reefs had large amounts of fine-grained terrigenous sediments. The coral cover and diversity on the reefs has been severely reduced by chronic sediment stress. The total coral cover is drastically reduced at depth in relation to the other reefs. A striking effect of terrigenous sediment influx is increased turbidity and loss of light, which results in shifting of the zonation and an upward migration of zone depths (Figure 74). Hallock and Schlager, 1986

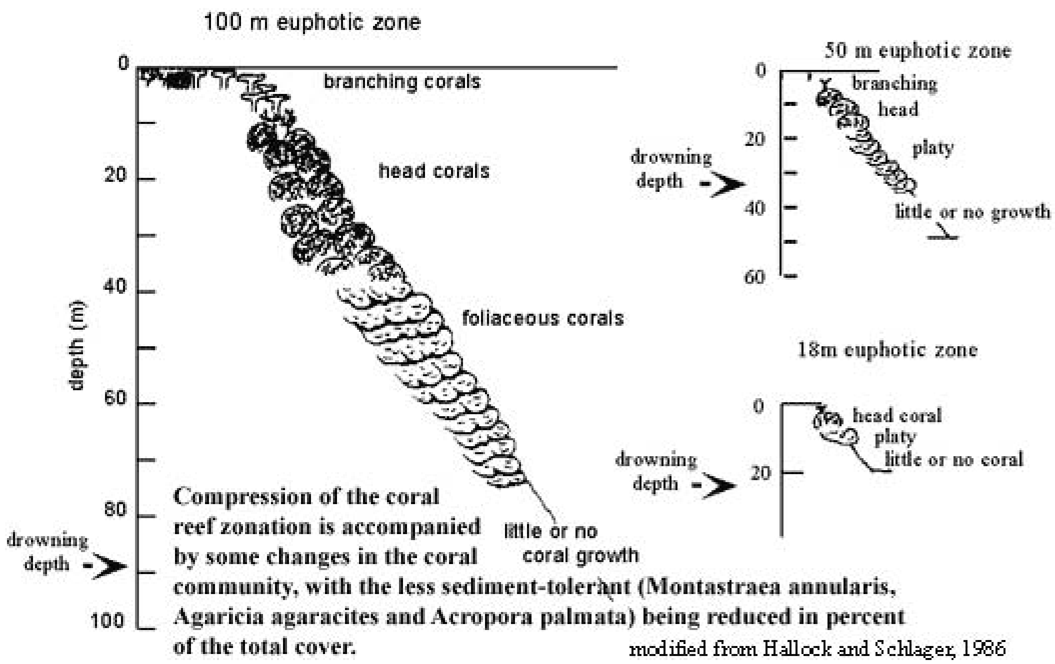


Figure 74. Compression and changes in reef front zonation caused by water turbidity. Modified from Hallock and Schlager, 1986

Loss of light is critical to the deeper coral assemblages, and a chronic increase in turbidity will move the lower limit of coral growth to shallower depths. This is reflected by a marked change in the reef-front zonation with depth (Figure 75). A compression of the depth zonation is accompanied by changes in coral species domination, which is directly related to individual species tolerances for sediment stress. Both loss in total coral cover and a shift to slower growing coral species were seen in the reefs between the Ponce Canyon and Cayo Ratones Reef.

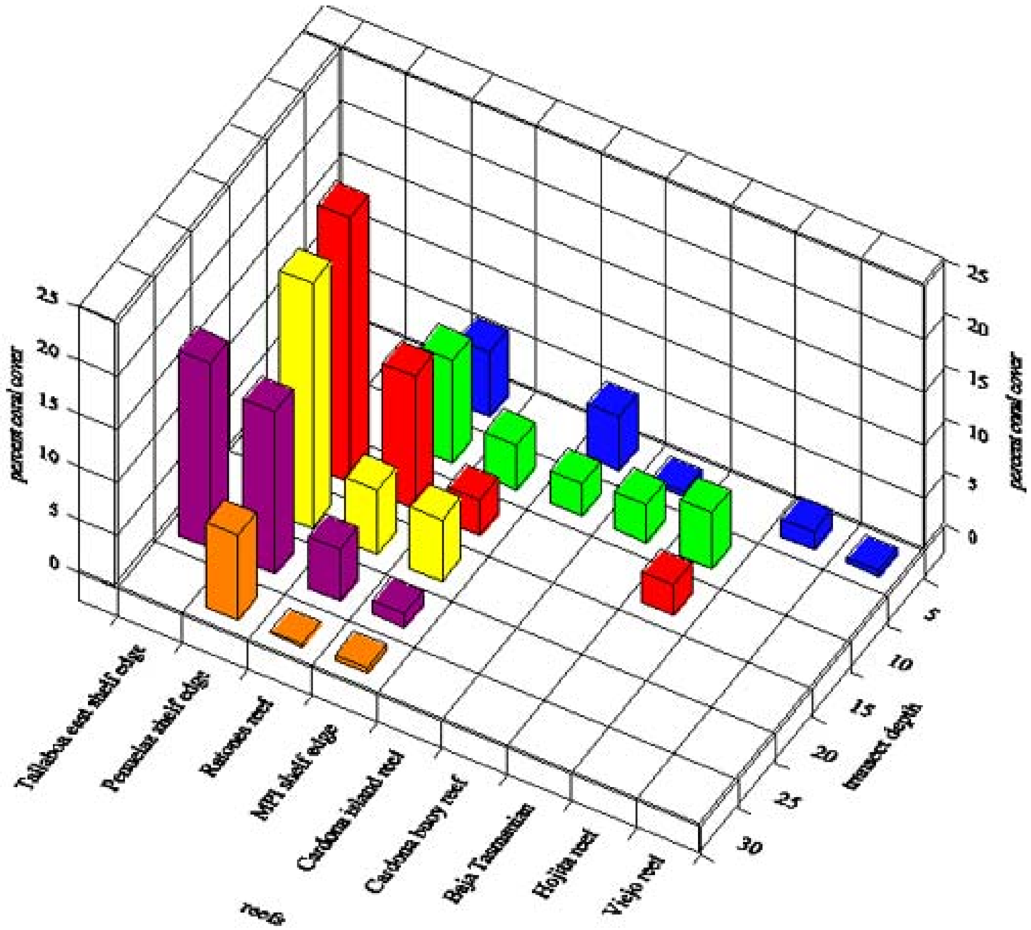


Figure 75. Total coral cover by depth on west Ponce reefs

Coral cover was reduced near the source of terrigenous sediment influx. As we move westward from the source of the sediment plume, the effect on the coral cover is reduced (Figure 76). Past Cayo Ratones Reef, the reefs at Peñuelas are much less affected, and coral cover at all depths is more like the reefs at La Parguera (Figure 77).

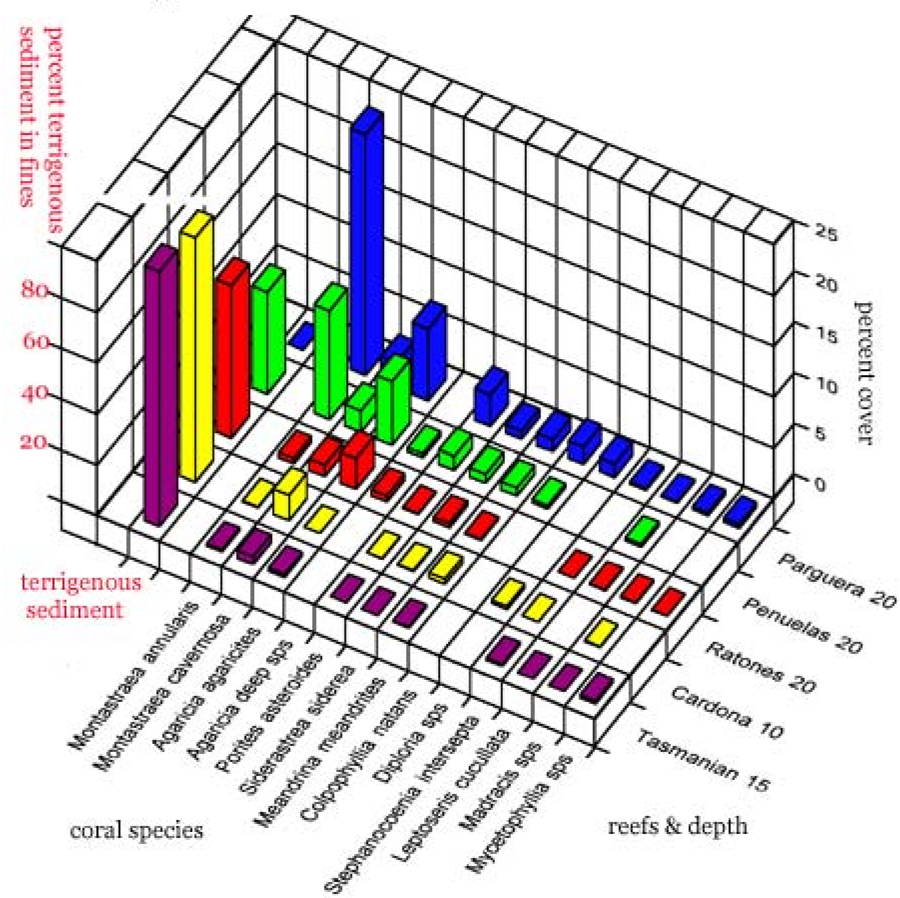


Figure 76. Living coral of the species Montastraea annularis and Agaricia agaricites increase in cover with reduced amounts of fine grained terrigenous sediments

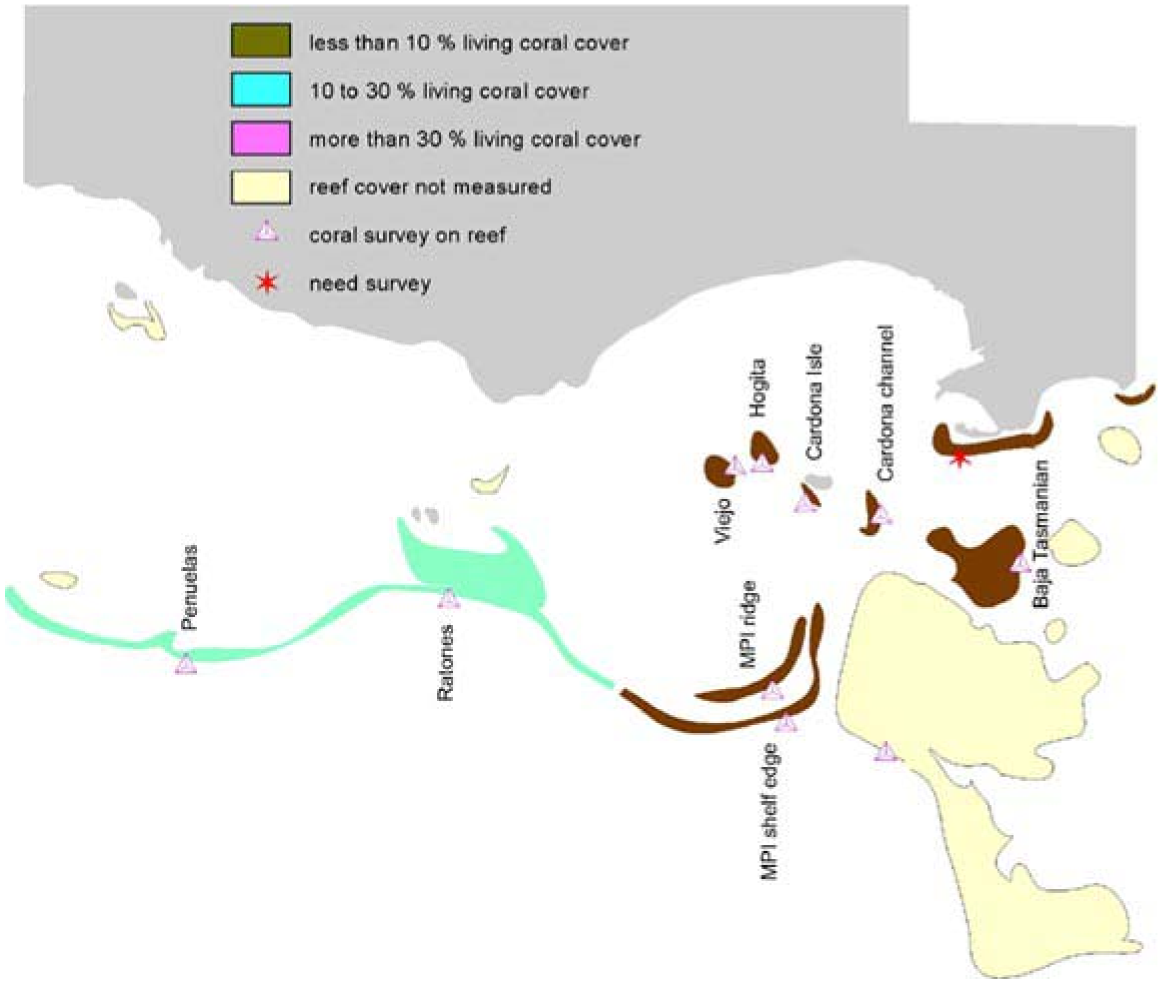


Figure 77. Status of the coral reefs of west Ponce as shown by total percent of living coral surface.

A maximum of 18 species of corals were recorded at 10 m depth (Figure 78). Of these, only seven species were more than 0.5 percent cover (by species) on the eastern reefs. *Montastraea cavernosa* was dominant at 10 m. This coral is one of the most sediment-resistant species of the scleractinian corals. [Lasker, 1980; Loya, 1976] The total cover of *Montastraea cavernosa* is not significantly different from values at La Parguera, but the reduction or absence of other coral species changes the relative abundance and reinforces the conclusion that *Montastraea cavernosa* is highly tolerant to a long-term sediment stress condition. No living corals were found below 12 m at Cayo Cardona.

A deep-water coral, *Agaricia lamarcki*, was found at 15 m on Bajo Tasmanian and Ratones (Figure 79), suggesting that the light levels were greatly reduced. The deeper reefs all have low coral cover and rapid attenuation of cover with depth. The values for *Montastraea annularis* and *Agaricia agaricites* decreased significantly with increased sediment conditions. The main loss in total cover was reduction in cover by *Montastraea annularis*. The cover by *Montastraea cavernosa, Siderastrea siderea, Porites astreoides, Colpophyllia natans*, and *Meandrina meandrites* was not significantly different between sites. Cayo Ratones showed changes in coral cover related to sediment stress, but less than at Cardona. *Montastraea cavernosa* dominates the coral cover except at Peñuelas where the zonation is more normal.

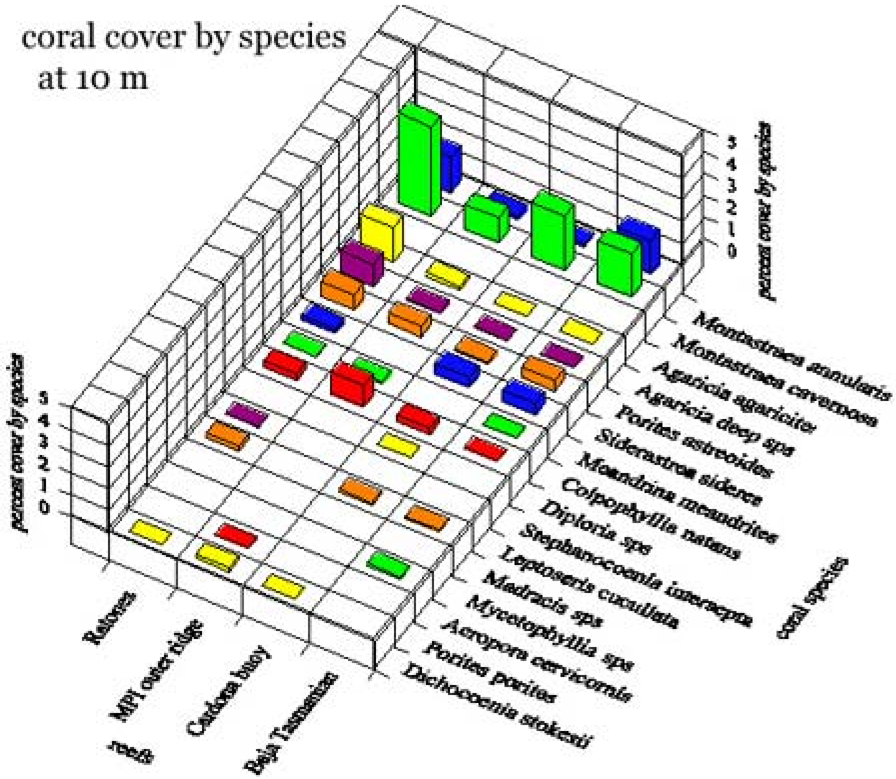


Figure 78. Coral cover by species at 10 m water depth.

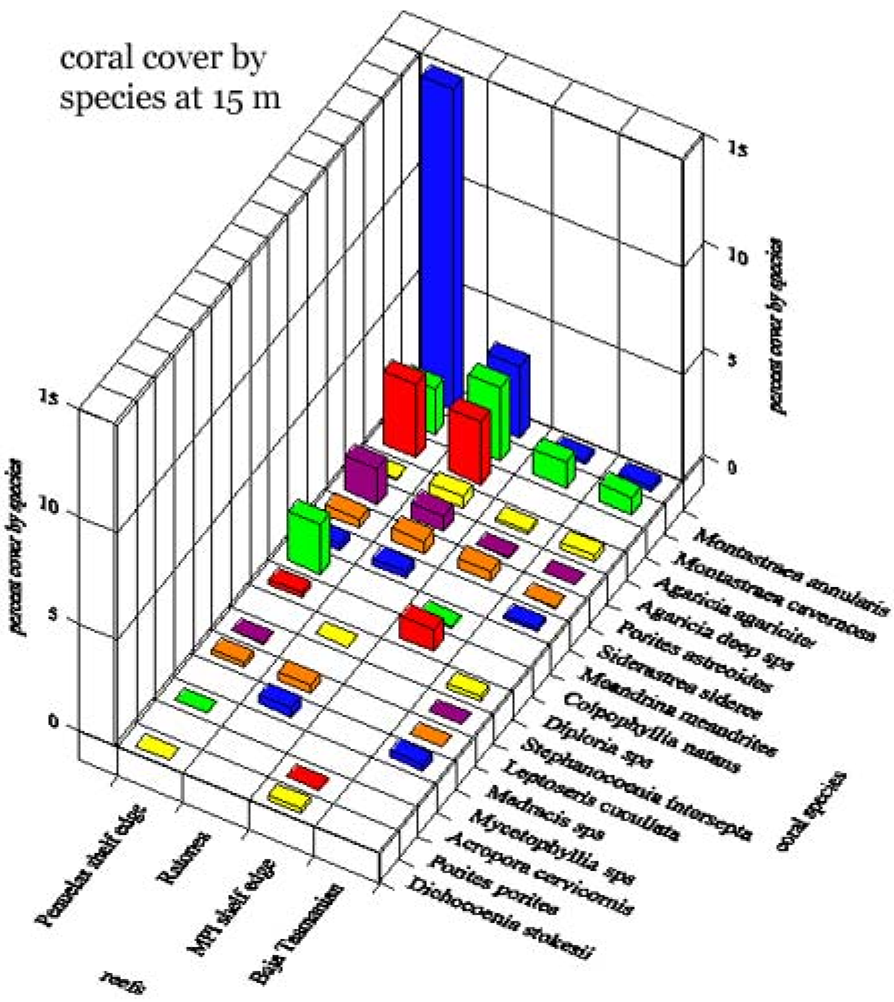


Figure 79. Coral cover by species at 15 m water depth.

Below 15 m, wave action does not remove all of the fine sediments. The combination of depth and turbidity causes light reduction with consequent cover reduction. A platy coral assemblage was dominant at 20 m and deeper (Figure 80). A hummocky topography was formed by dead coral heads covered with a sediment-algae mat.

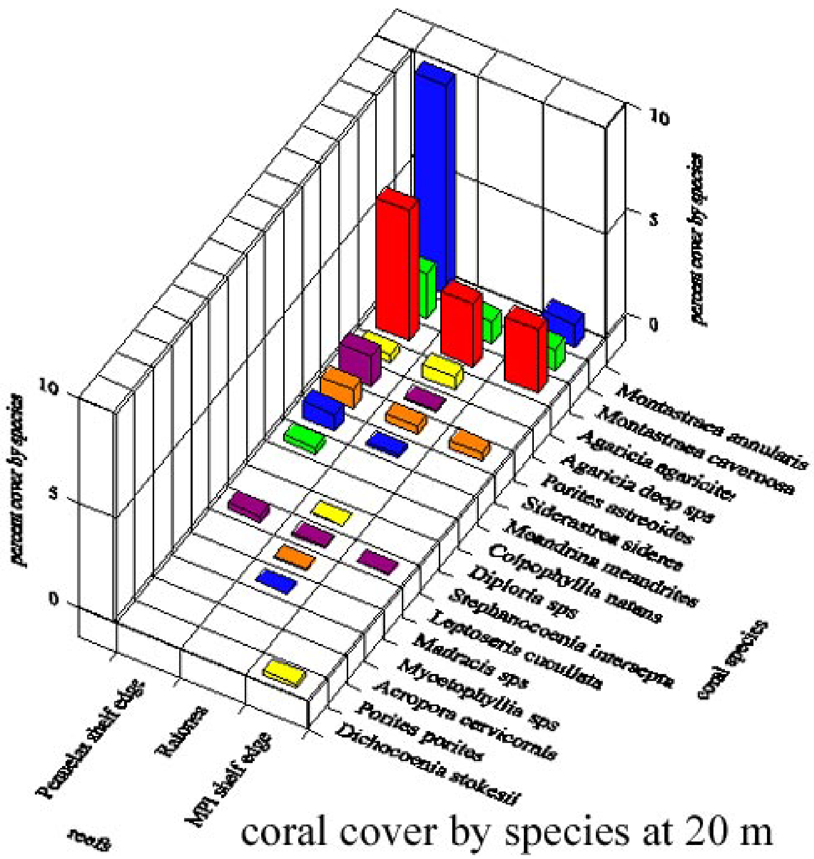


Figure 80. Coral cover by species at 20 m water depth.

At 25 m (Figure 81), few coral species were present in the eastern reefs, with only *Agaricia lamarcki* common. The number of colonies was low, but the size of each colony was large with some approaching one meter diameter. These grew on vertical surfaces of the boulders easing sediment removal. The Peñuelas reefs had higher cover but dominance was skewed to *Agaricia* species at the Tallaboa east site and *Montastraea cavernosa* at the Peñuelas shelf edge site.

Only two species (*Agaricia lamarcki* and *Madracis decactis*) were found at 30 m on Ratones (Figure 82) which had total coral cover of only 0.2 percent. The MPI site had six species but only 0.8 percent total cover. To the west, the reef at Peñuelas had 8.0 percent total cover at 30 m from eight species, but most of the cover (7.2 percent) was *Agaricia* species. If we compare this to the cover at La Parguera where total cover is 41 percent, we see the dramatic effect that sedimentation has produced. The La Parguera 30 m level is definitely in the *Montastraea-Agaricites* zone with dominance by these two species, and cover is high. The hummocky topography continues to more than 40 m at Ratones showing that there was once good coral development – probably similar to La Parguera – on this reef.

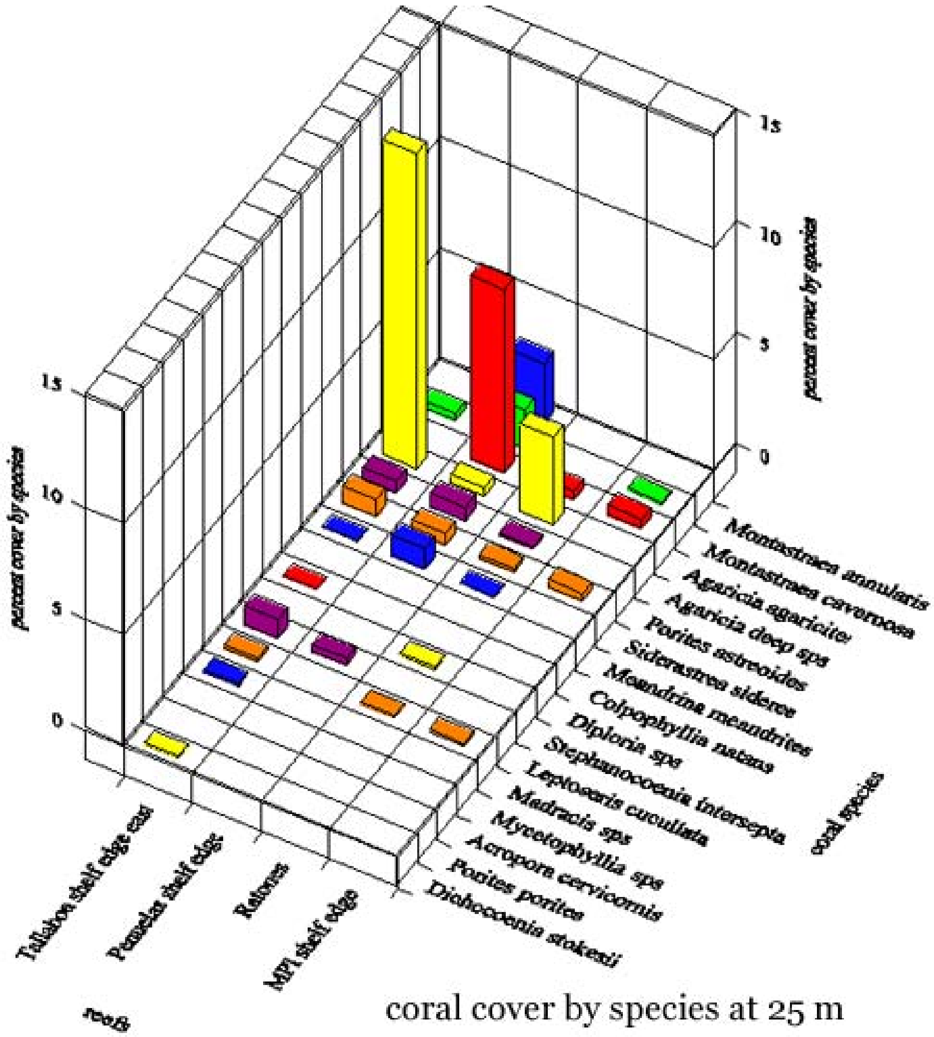


Figure 81. Coral cover by species at 25 m water depth.

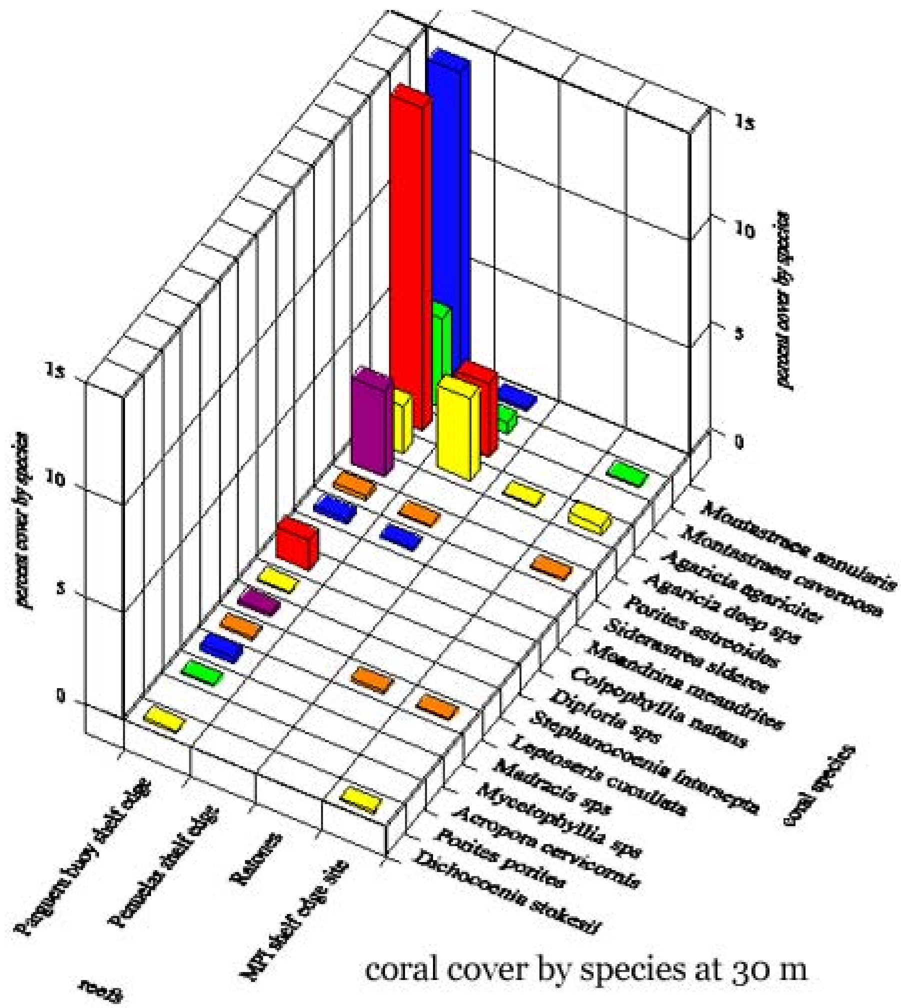


Figure 82. Coral cover by species at 30 m water depth.

These reefs showed an absence of many species that normally extend to depths of 25 or 30 m. The reduced light levels resulted in domination of the community by deeper fore-reef coral. Tolerance of individual species to sediment particles is probably another factor in the final coral species assemblage. Continued stress has reduced the total cover and the number of species. The reefs with high sediment input showed decreased coral species diversity and percent cover. Sediment-resistant species tolerated this adverse environment and their percent cover remained relatively constant.

Discussion

The southwest part of Puerto Rico, reaching from Añasco to Ponce, has three broad carbonate platforms and two areas of very narrow shelf. The three platforms - Boquerón, La Parguera and Peñuelas - have very little river sediment influx and the bottom sediments are calcareous. The shelf at Añasco-Mayagüez has three river discharges and the Guánica-Guayanilla-west Ponce shelf also has river discharge; they have large terrigenous sediment facies with common resuspension of fine grained terrigenous sediments.

High sediment influx, resuspension and turbid water conditions at Añasco-Mayagüez and Guánica-Guayanilla-West Ponce have resulted in low coral cover on the reefs (Figure 83). At the surveyed sites, the bottom is hard dead coral rock which indicates that these once had cover comparable to that on the platforms of Boquerón, La Parguera and Peñuelas. It is therefore a reasonable assumption that much of the insular shelf and slope of southwest Puerto

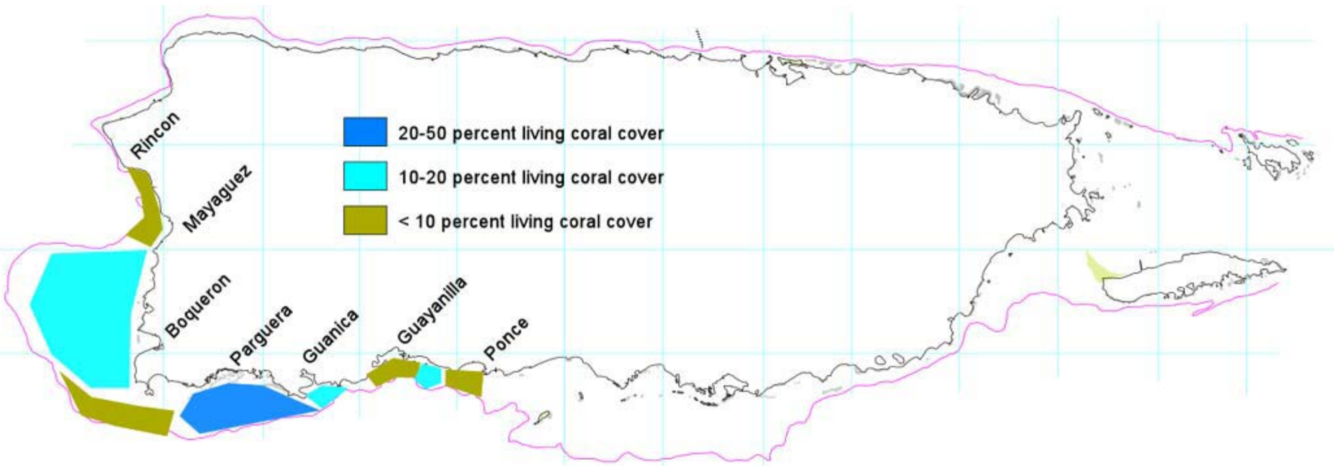


Figure 83. General coral cover in areas of southwest Puerto Rico

Rico has turned from coral reef to "hard ground" condition with a loss of more than 35 percent of the original Modern coral cover. This is especially evident if we compare the total cover by species at the 20 m level for sites (see figure 55) discussed in this paper. The La Parguera and Peñuelas platforms are the only areas of "normal" coral cover at 20 m. The western platform insular slope has low coral cover due to some natural process. The Añasco-Mayagüez and Guayanilla-west Ponce reefs have very low total coral cover at 20 m compared to the La Parguera and Penuelas reefs at this depth (Figure 84). The shelf edge reef at Guánica still has a moderate cover of living coral at 20 m.

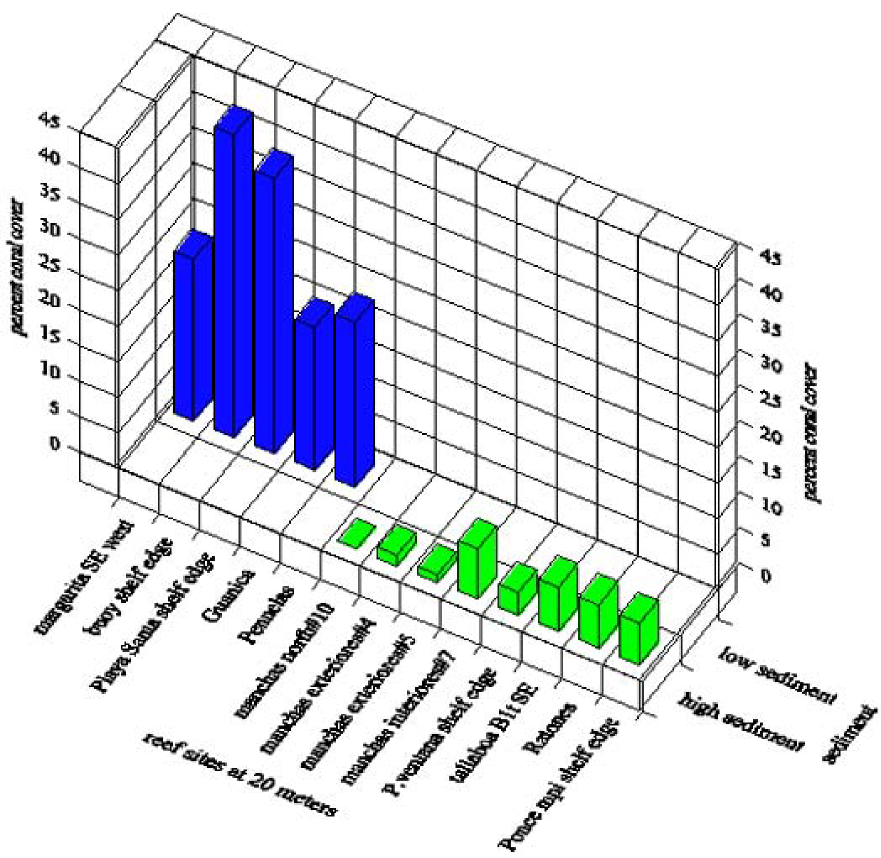


Figure 84. Total coral cover at 20 m for low and high sediment influx sites

Individual reefs on the carbonate platforms show loss of coral cover by areas of dead coral rock. Continued rapid urbanization and development has contributed to sheet runoff and influx of terrigenous sediments even into areas without river discharge. The development of the coastal area has also increased discharge from the sewer outfalls at Ponce, La Parguera, Boquerón and Añasco. This untreated sewage has raised nutrient levels and promoted the growth of algae on the reef.

And finally, overfishing and drastic reduction of the biodiversity around the reefs is leading to rapid loss of coral to a shift in competition balance favoring algae and destroyers of coral such as corallavores, fire worms, echinodermatra and damsel fish. Along with this we are finding increased coral disease and invasion by sponge.

Specific members of the reef-building coral community have suffered higher loss under present conditions. The two major reef building species - *Acropora palmata* and *Montastraea annularis* have been drastically reduced in percent of cover on the stressed reefs. At depths greater than 12 to 15 m, dead coral is all that remains of reefs that must have once had a cover comparable to the shelf edge reefs at La Parguera.

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