

ATOLL RESEARCH BULLETIN

NO. 545

THE DESTRUCTION OF A LARGE *ACROPORA PALMATA* BANK-BARRIER REEF AND SUBSEQUENT DEPLETION OF THIS REEF-BUILDING CORAL OFF BARBADOS, WI

BY

IAN G. MACINTYRE, PETER W. GLYNN, AND MARGUERITE A. TOSCANO

**ISSUED BY
NATIONAL MUSEUM OF NATURAL HISTORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C. U.S.A.
DECEMBER 2007**



Figure 1. Satellite map of Barbados showing the well developed bank-barrier reef called Cobbler's Reef off the southeast coast. As can be seen, this is the only major reef system off this island (reproduced with permission from Digital Globe ©).

THE DESTRUCTION OF A LARGE *ACROPORA PALMATA* BANK-BARRIER REEF AND SUBSEQUENT DEPLETION OF THIS REEF-BUILDING CORAL OFF BARBADOS, WI

BY

IAN G. MACINTYRE,¹ PETER W. GLYNN,² AND MARGUERITE A. TOSCANO¹

ABSTRACT

Nine study sites of the reef crest along the entire length of a 15 km-long bank-barrier reef off the southeast coast of Barbados indicated that the surface is composed of mostly reworked fragments of *Acropora palmata* covered with macroalgae, crustose coralline algae and turf algae. Known as Cobbler's Reef, this feature had no live colonies of *A. palmata* at our study sites and supported only small scattered colonies of corals, mainly *Diploria* spp., *Porites astreoides* and the hydrocoral *Millepora complanata*. Eleven of 29 surface-sample radiocarbon dates plot above the western Atlantic sea-level curve between approximately 3,300 to 4,500 cal yrs (calibrated, calendar ^{14}C years) ago. This suggests that the reef complex was extensively damaged by a series of severe storms during this period. A reduced number of *in situ* framework dates follow that period and plot at acceptable depths of growth below this sea-level curve. The most recent dates are 320 and 400 cal yrs old. The lack of coral framework recovery and final demise of this reef are probably related to a number of disturbances. Although white-band disease, bleaching, and recruitment limitations could have played a role, a lack of herbivory in this area of constant heavy wave action probably allowed heavy algal growth that prevented the re-establishment of a vigorous coral reef following the period of severe storm activity. Finally, the turbidity associated with the clearing of land for sugarcane agriculture in the mid-1600s likely killed the last of the sediment-sensitive *A. palmata* on Cobbler's Reef. The more recent almost complete loss of *A. palmata* from other reefs off Barbados is probably related to storm damage and nutrient runoff and construction associated with tourism development. This is an expanded report of an earlier publication of this study, with descriptions of sampling sites and documentation of the demise of *A. palmata* island wide.

¹ Department of Paleobiology, National Museum of Natural History, P.O. Box 37012, MRC 121
Smithsonian Institution, Washington, DC, 20013-7012.

² Division of Marine Biology and Fisheries, Rosenstiel School of Marine and Atmospheric Science,
University of Miami, 4600 Rickenbacker Causeway, Miami, Florida, 33149.

INTRODUCTION

Goreau (1959) was the first to identify the dominant role of *Acropora palmata* in Caribbean reef zonation with his description of Jamaican reefs. Several studies of the Pleistocene coral-reef terraces of Barbados have indicated how *A. palmata* was a major coral-reef framework builder (e.g. Mesolella, 1967; James et al., 1977). This was also shown in studies of the internal structure of Holocene reefs, which clearly illustrated the prominent role of *A. palmata* in the building of fringing reefs off Panama (Macintyre and Glynn, 1976) and Florida (Lighty et al., 1978).

Concern has been expressed over the widespread loss of *A. palmata* on Caribbean reefs that started in the 1980s (Diaz-Soltero, 1999; Buckner, 2002; Bruckner and Hourigan, 2002; Precht et al., 2002; Precht et al., 2004). The dominant cause for the loss of this coral species is white-band disease that only infects the genus *Acropora*. As a result, both *A. palmata* and *Acropora cervicornis* have been listed as threatened species by the National Marine Fisheries Service (Federal Register, 2006).

Despite its dominance of Pleistocene reefs forming the coral cap of Barbados, *A. palmata* has almost disappeared from the offshore waters of this island in the recent geologic and historic past. This trend started with the destruction of Cobbler's Reef (Macintyre et al., 2007) a few thousand years ago.

PREVIOUS WORK

Cobbler's reef has been largely unstudied by previous workers because it is exposed to the Atlantic trade wind swells and is subjected to heavy wave action throughout most of the year (Fig. 1)

The only published report on Cobbler's Reef was by Lewis and Oxenford (1996) who described the area off Sam Lord's Castle (Site A investigated in this study). They reported a coral-rock bottom covered with sand and algae (dominantly crustose coralline algae and *Dictyota* spp.). Other algae that occurred in abundance included *Stylopopodium* sp., *Caulerpa* sp., *Amphiroa* sp., *Galaxauras* sp., *Dictyopteris* sp., *Halimeda* sp., *Padina* sp., *Polysiphonia* sp., and *Valonia* sp. Small scattered coral colonies of *Siderastrea siderea*, *Porites porites*, *Diploria* sp., *Madracis* sp., and *Millepora* sp. were also noted. In addition, several species of sponges were found along with some gorgonid sea fans. Both the black sea urchin, *Diadema antillarum*, and the white sea urchin, *Tripneustes esculentus*, also were observed.

Lewis and Oxenford (1996) also described the reef-crest areas of three other sites investigated in this study. From South Point to Round Rock (Site G) the reef crest was found to be wide and flat. Leeward of the crest the rock surface was covered with crustose coralline algae and macroalgae that included *Dictyota* sp., *Dilophus* sp., *Sargassum* sp., and *Padina* sp. *Porites astreoides* colonies were common and the small sea urchin *Echinometra* sp. was abundant. Off Foul Bay (Site F) to the Crane (Site B) they noted that the back-reef zone was dominated by large fragments of *A. palmata*. The reef crest consisted of a relatively smooth rock surface covered by crustose coralline

algae. *Millepora* "thickets" were common along with some sea fans. Depressions in the rock surface sheltered the sea urchin *Echinometra* sp. and small colonies of *Diploria* spp.

Macintyre et al. (2007) presented an earlier report of this study but because of space limitations they were able to offer only a limited description of Cobbler's Reef and were unable to discuss the present status of *Acropora palmata* off the coasts of Barbados. In this report we show a detailed description of the storm-damaged reef crest of Cobbler's Reef and discuss the recent loss of *A. palmata* in shallow waters off Barbados.

MATERIALS AND METHODS

The best opportunity to work on Cobbler's Reef is in late September when tropical storms and hurricanes tend to disrupt the normal trade wind activity. September 2004 afforded a five-day window of low wave activity in which to establish nine study sites on the shallowest areas of the reef crests along the entire length of this reef system (Fig. 2). Three 10-meter-long chain-transect surveys and numerous digital camera photographs were completed at each study site to determine the composition of the epibenthic macrobiota. In addition, up to five substrate samples were collected at each site (Fig. 2). A total of only 40 rock samples were collected because of the difficulty of obtaining samples at some sites (Macintyre et al., 2007).

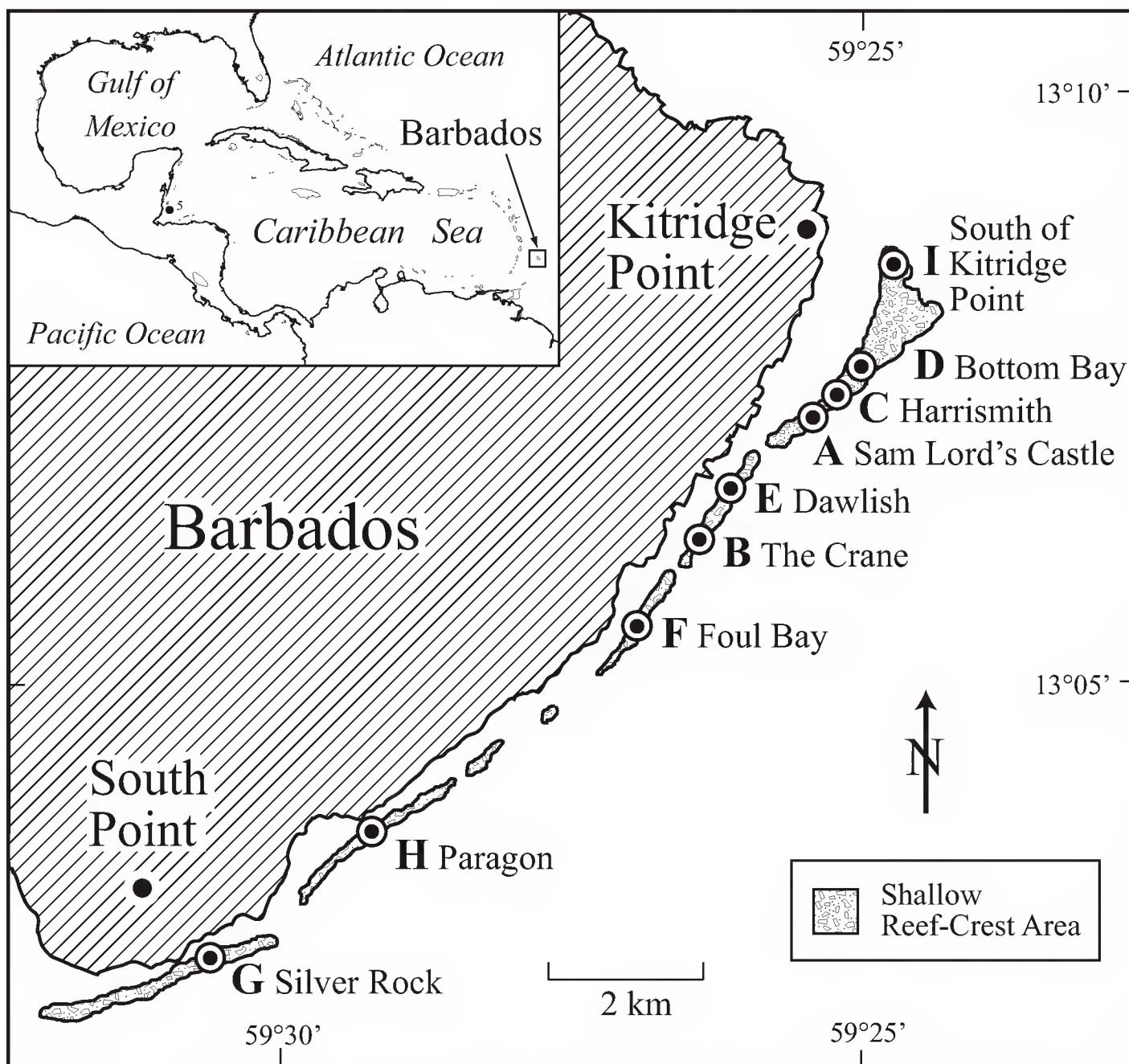


Figure 2. Index map showing the nine study sites (A-I) on Cobbler's Reef off the southeast coast of Barbados (Macintyre et al., 2007).

The first chain transect at each site was marked by a buoy and oriented perpendicular to the long axis of the reef. The remaining two transects were laid parallel to it, ~10 meters distant on either side. All macroscopic organisms and bottom types underlying each of 62 chain links per meter were recorded and assigned to six categories: zooxanthellate corals (ZC), macroalgae (MA), turf algae (TA), crustose coralline algae (CA), macroinvertebrates other than zooxanthellate corals (MI), and calcareous sediments and rock (SR). Corals included zooxanthellate scleractinians and hydrocorals (*Millepora*). Relatively large (macroscopic) algal species were assigned to the MA category. Turf algae included microfilamentous plants, generally no higher than 1-2 cm above the substrate. Crustose coralline algae generally formed thin crusts over the substrate, and macroinvertebrates included mainly a variety of sponges, alcyonarians and echinoids. No macroscopic organisms were observed on the sediment and rock category.

The enumerated transect data (3 transects per site, 9 sites) were subjected to a multidimensional scaling (MDS) ordination and an agglomerative hierarchical cluster analysis, both employing the Bray-Curtis similarity index as the distance measure (Primer-E, Clarke and Gorley, 2001). The relationships of the 27 transects were portrayed both as a two-dimensional ordination distance map and as a dendrogram to show groupings of the data (Macintyre et al., 2007)

A. palmata samples selected for radiocarbon dating were obtained from the fresh, unaltered inner cores of each specimen. A total of 29 samples (Macintyre et al., 2007) were dated by Beta Analytic Inc. using standard radiometric methods. Both Conventional ^{14}C ages and calibrated (calendar) ages (cal BP) are reported herein.

Calibration of shallow marine coral ^{14}C ages incorporates a time-dependent global ocean correction for the $^{14}\text{C}/^{12}\text{C}$ difference between atmospheric CO_2 and the ΣCO_2 of the surface ocean (~400 years; Bard, 1998; Stuiver and Reimer, 1993). A ΔR (difference in local/regional reservoir age) value of 5 ± 20 (Beta Analytic, Inc.; Stuiver and Braziunas, 1993) must also be applied to account for local effects. Calibration using standard marine calibration data (e.g. Marine04; Hughen et al., 2004) and measured sample $\delta^{13}\text{C}_{\text{PDB}}$ values were provided by Beta Analytic Inc. Conventional radiocarbon ages with their standard errors are reported in Table 1. Calibrated ages (Table 1) are reported as 1- and 2-sigma ranges intercepts to include the full (98% probability) age ranges of each sample; however, for time-depth plotting, the direct calibration curve intercept for each sample was used (indicated in Table 1). No multiple calibration curve intercepts occurred in this dataset.

RESULTS

Site Descriptions

There is considerable variation in the bottom relief and communities found at the nine study sites, which were all limited to the shallow crest of Cobbler's Reef. The topographic relief is controlled by the dead *A. palmata* substrate that either forms relatively flat interlocking plates or an exposed framework of robust plates and rods. Despite the fact that *A. palmata* forms the basic substrate of this reef complex, not

a single live colony of this coral was found at any of the study sites. Some of the community differences could be related to changes in hydrodynamics or nutrient concentrations.

Although crustose coralline algae cover a high proportion of the substrate, they did not form a crust more than 2 cm thick and are therefore not forming an algal ridge. The dominant species include *Porolithon pachydermum*, *Hydrolithon boergesenii*, the bright red *Peyssonnelia* cf. *crispata*, *Paragoniolithon solubile*, and *Neogoniolithon affine*.

Sam Lord's Castle – Site A (Depth 2 m) 13° 7' 12" N, 59° 25' 30" W. This area consisted of a relatively flat bottom with little relief (Fig. 3), but with rubble-filled depressions and some small exposures of the underlying *A. palmata* framework. Scattered colonies of the sea fan *Gorgonia ventalina* were present, along with a patchy cover of blue-green algal turf and some *Dictyota* sp. The bottom community also included scattered small colonies of *Millepora complanata*, *Diploria clivosa*, and *Porites astreoides*.

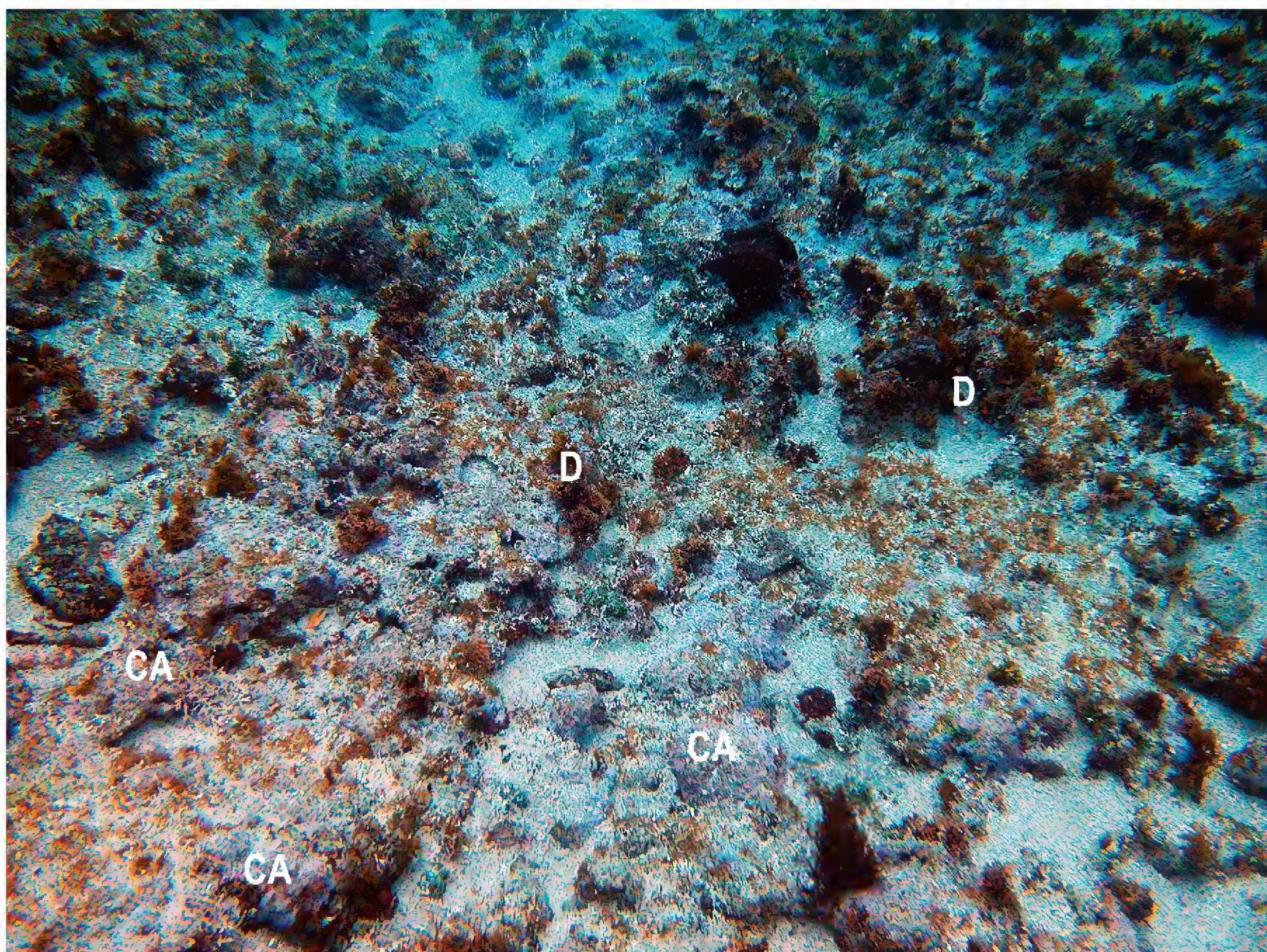


Figure 3 Site A (Sam Lord's Castle). Scattered *Dictyota* sp. (D), crustose coralline algae (CA), and blue-green algal turf on a relatively flat bottom formed by interlocking plates of *Acropora palmata*.

The Crane – Site B (Depth 2 m) $13^{\circ} 6' 12'' N$, $59^{\circ} 26' 30'' W$. Considerably more relief was found at this site, showing the framework of robust colonies of dead *A. palmata* (Fig. 4). The dominant bottom cover was crustose coralline algae along with algal turf and *Halimeda opuntia*. Octocorals included *Gorgonia ventalina*, a dead sea whip *Pterogorgia anceps*, and a species from the family Plexauridae. Only highly dispersed colonies of *Millepora complanata* were found.



Figure 4. Site B (The Crane). During this period of low wave energy, herbivorous fish range over algal-covered high relief formed by a jumble of fragments of reworked *Acropora palmata*. Note *Millepora complanata* (M).

Harrismith – Site C (Depth 2 m) $13^{\circ} 7' 27'' N$, $59^{\circ} 25' 12'' W$. Here the dead *A. palmata* framework was packed with coral rubble, forming a relatively flat bottom (Fig. 5). The dominant bottom cover was crustose coralline algae along with a rich cover of the hydrocoral *Millepora complanata*. Other algae included *Dictyota* sp., *Halimeda opuntia*, and blue-green turf. There were also scattered colonies of the sea fan *Gorgonia ventalina* and the round sponge *Ircinia strobilina*.

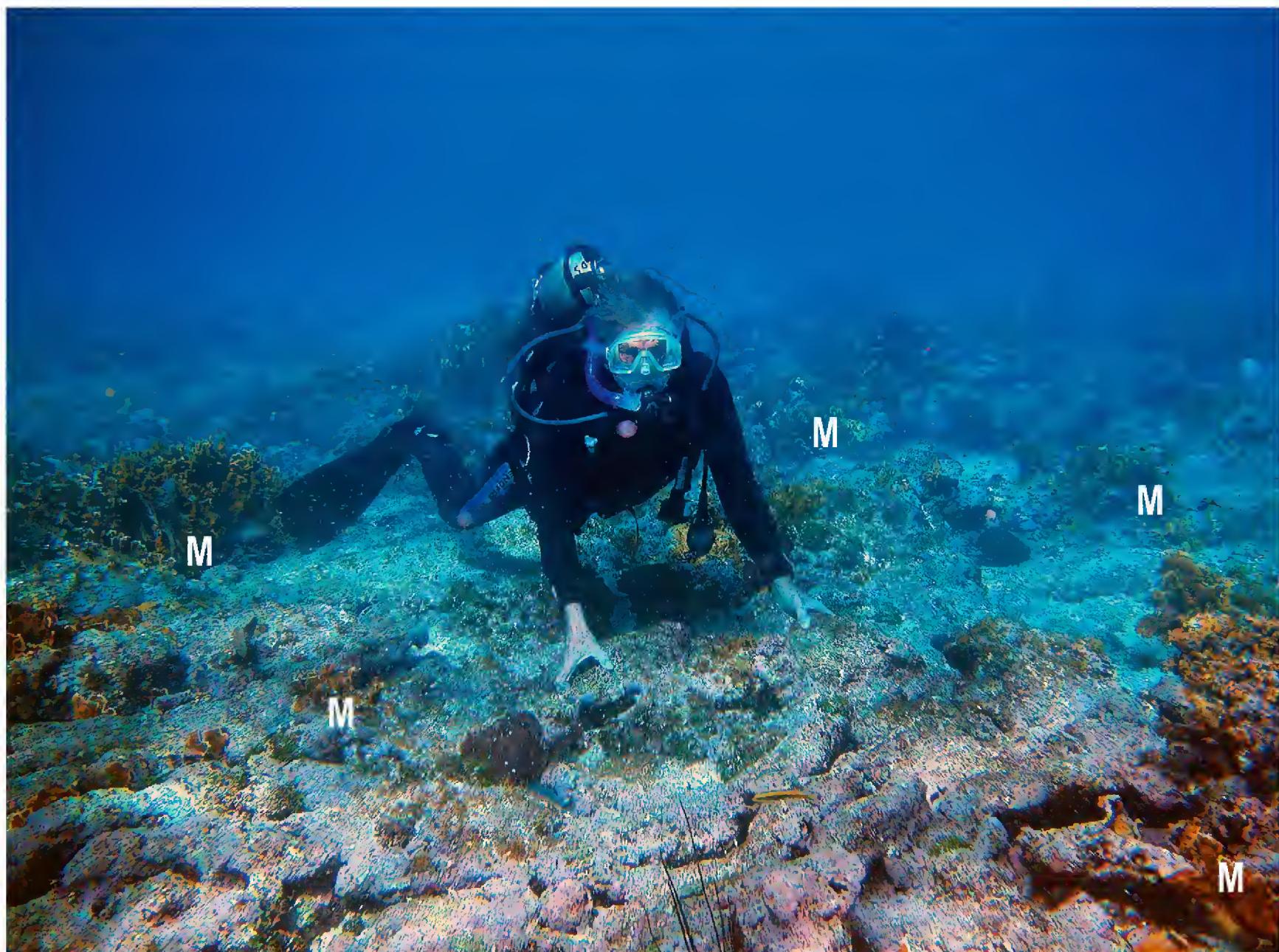


Figure 5. The generally flat area of Site C (Harrismith) with scattered fragments of *Acropora palmata*. Note the abundance of *Millepora complanata* (M).

Bottom Bay – Site D (Depth 3-3.5 m) 13° 7' 36" N, 59° 25' 3" W. Exposures in a relatively flat sea floor revealed a dead *A. palmata* framework (Fig. 6) with an extensive cover of crustose coralline algae over the dead coral surfaces and rubble. Other algae included *Dictyota* sp., *Halimeda opuntia*, and a blue-green algal turf. In addition, there were scattered colonies of the sea fan *Gorgonia ventalina* as well as a few sponges, including the branching *Pseudoceratina crassa* and the round *Ircinia strobilina*. Only one small colony of *Diploria strigosa* was found, but colonies of *Millepora complanata* were relatively common.

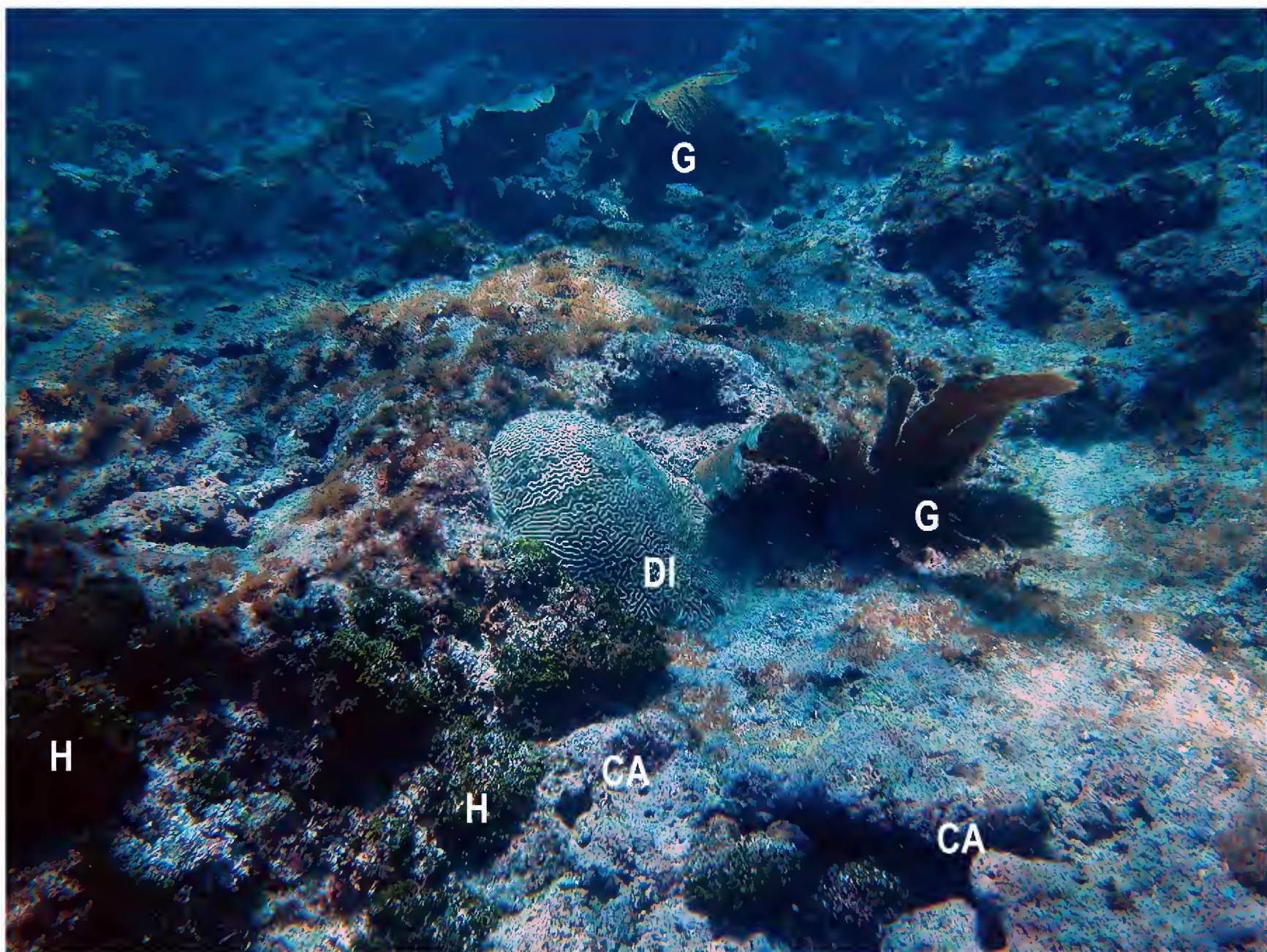


Figure 6. Site D (Bottom Bay) is another area with a relatively flat bottom. Note crustose coralline cover (CA), *Halimeda opuntia* (H), *Diploria strigosa* (DI) and the sea fan *Gorgonia ventalina* (G).

Dawlish – Site E (Depth 2.6 m) $13^{\circ} 6' 36'' N$, $59^{\circ} 26' 6'' W$. This was a smooth bottom formed dominantly by dead *A. palmata* interlocking plates that are sometimes exposed to form ledges (Fig. 7). This site had a very rich algal cover that included crustose coralline algae, large numbers of the common brown alga *Sargassum polyceratium*, two species of *Dictyota* (*D. caribaea* and *D. crispata*), *Styliopodium zonale*, *Padina* sp. and the bright green *Cladophoropsis macromeres*.

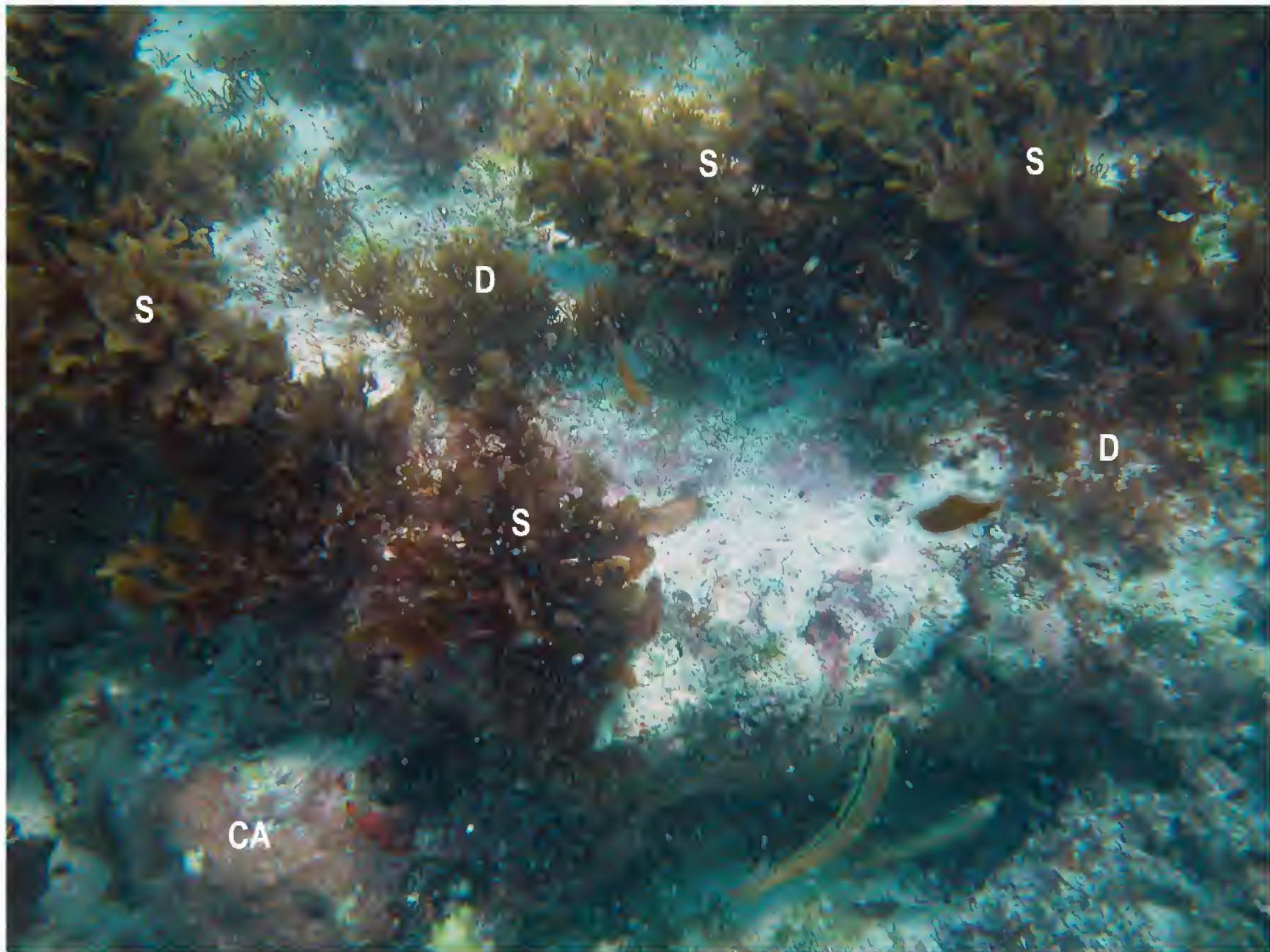


Figure 7. An exposed ledge of *Acropora palmata* on the relatively smooth sea floor at Site E (Dawlish). Note the heavy cover of *Sargassum polyceratium* (S), *Dictyota* sp. (D), and crustose coralline algae (CA).

Foul Bay – Site F (Depth 4.7 m) $13^{\circ} 5' 30'' N$, $59^{\circ} 26' 54'' W$. Dead robust colonies of *A. palmata* formed areas of 1-1.5m of relief over an otherwise smooth bottom (Fig. 8). Sea fans (*Gorgonia ventalina*) are relatively common, along with a few small colonies of the corals *Diploria strigosa*, *Porites astreoides*, *Siderastrea siderea* and the hydrocoral *Millepora complanata*. The rich algal cover included crustose coralline algae, *Dictyota* spp. (including *D. crispate*), *Sargassum polyceratum*, *Halimeda opuntia* and blue-green turf. Sponges were limited to round *Ircinia strobilina*, brown encrusting *Plakortis* sp. and boring *Cliona* sp.

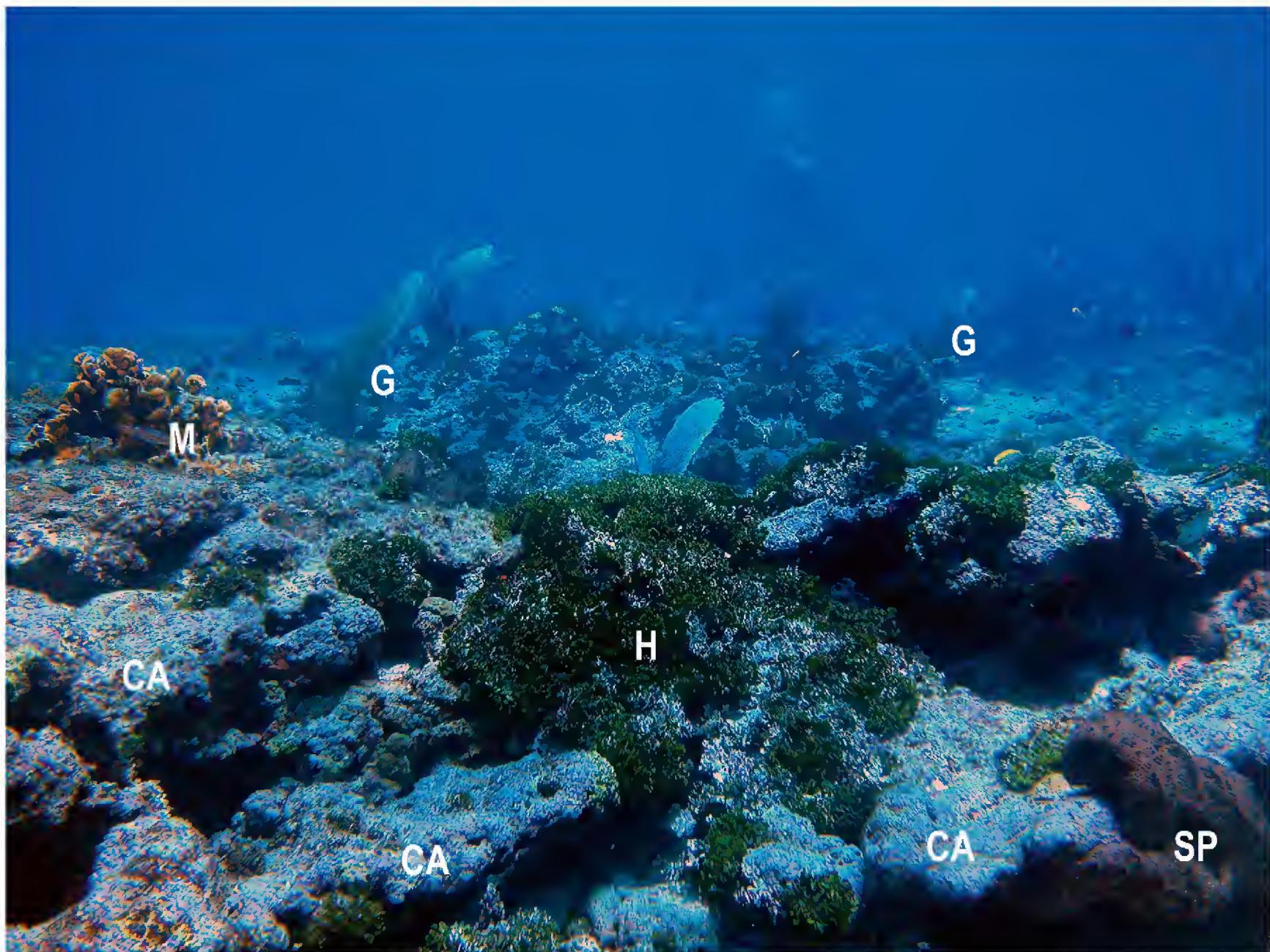


Figure 8. Site F (Foul Bay) with a jumble of broken *Acropora palmata* encrusted by crustose coralline algae (CA). Also, note brown encrusting *Plakortis* sp. sponge (SP), *Halimeda opuntia* (H), *Millepora complanata* (M), and *Gorgonia ventalina* sea fans (G).

Silver Rock – Site G (Depth 2 m) $13^{\circ} 2' 36'' N$, $59^{\circ} 30' 36'' W$. This site was characterized by a relatively flat undulating bottom formed by dead *A. palmata* plates and rubble. Ledges exposing the *A. palmata* framework were common (Fig. 9). A rich algal cover included crustose coralline algae, *Halimeda opuntia*, *Dictyota* spp., *Sargassum polyceratum*, and *Lobophora variegata*. Small colonies of the zooxanthellate corals *Porites astreoides* and *Diploria strigosa*, along with the hydrocoral *Millepora complanata*, were moderately common. One adult black sea urchin *Diadema antillarum* was observed in this area.

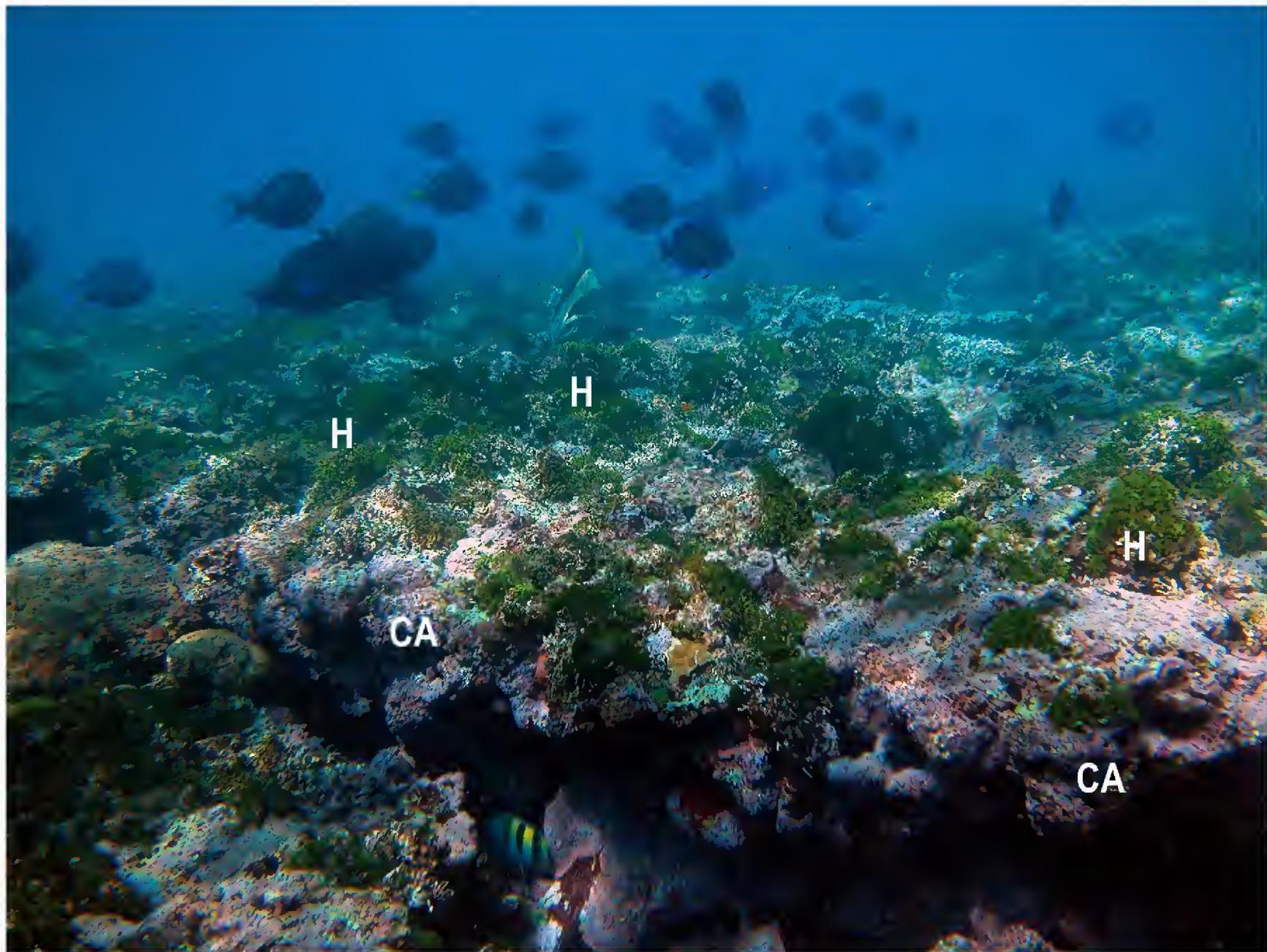


Figure 9. *Acropora palmata* ledge at Site G (Silver Rock). Note the heavy cover of crustose coralline algae (CA) and patches of *Halimeda opuntia* (H). School of acanthurid herbivorous fish.

Paragon – Site H (Depth 4 m) 13° 3' 42" N, 59° 29' 12" W. This relatively smooth algal-covered bottom provided occasional exposures revealing the dead *Acropora palmata* framework that forms this surface (Fig. 10). The rich algal cover consists of crustose coralline algae, *Dictyota* spp. (including *D. pfaffi*), *Halimeda opuntia*, *Sargassum polyceratum*, *Stylopodium zonale*, and *Padina* sp. A large aggregation of the white sea urchin, *Tripneustes ventricosus*, was found leeward of the crest at this site.

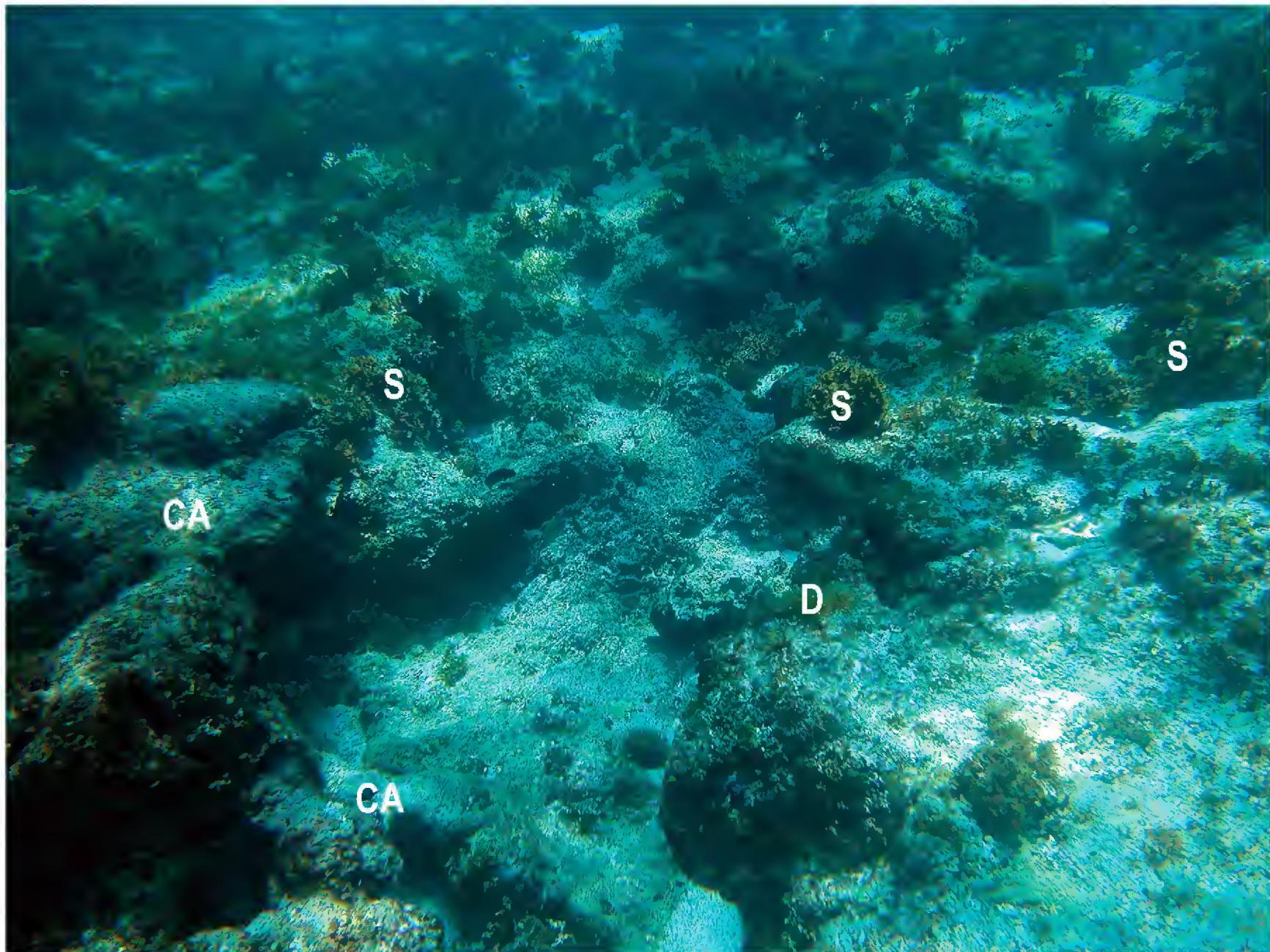


Figure 10. An opening in a relatively flat bottom at Site H (Paragon) exposing *Acropora palmata* ledges covered with crustose coralline algae (CA), *Sargassum polyceratum* (S), and *Dictyota* sp.(D).

South of Kitridge Point – Site I (Depth 5-7 m) 13° 8' 30" N, 59° 24' 42" W.
This northern limit of Cobbler's Reef has over two meters of relief in places (the most observed in this study) and clearly exhibits the dead robust *Acropora palmata* structure that forms this reef (Fig. 11). A higher diversity of coral species was noted at this site, including the zooxanthellate corals *Diploria strigosa*, *Diploria clivosa*, *Porites astreoides*, *Montastraea annularis*, *Montastraea cavernosa*, *Colpophyllia natans*, *Agaricia agaricites*, and the hydrocorals *Millepora complanata*, and *Millepora squarrosa*.

The bottom also had a rich cover of algae consisting of crustose coralline algae, *Dictyota* spp. (including *D. pfaffii*, *D. mertensii*, *D. crispata*), *Halimeda opuntia*, *Styliopodium zonale*, *Padina* sp., *Sargassum polyceratum*, and the encrusting brown *Haematocelis* sp. Sponges were also quite common and included the purple *Aiolochroia crassa*, the rope-like *Aplysina fistularis*, the red *Monanchora arbuscula*, the orange *Clathria* sp., and barrel-shaped *Verongula rigida*. The sea fan *Gorgonia ventalina* was also present at this site.

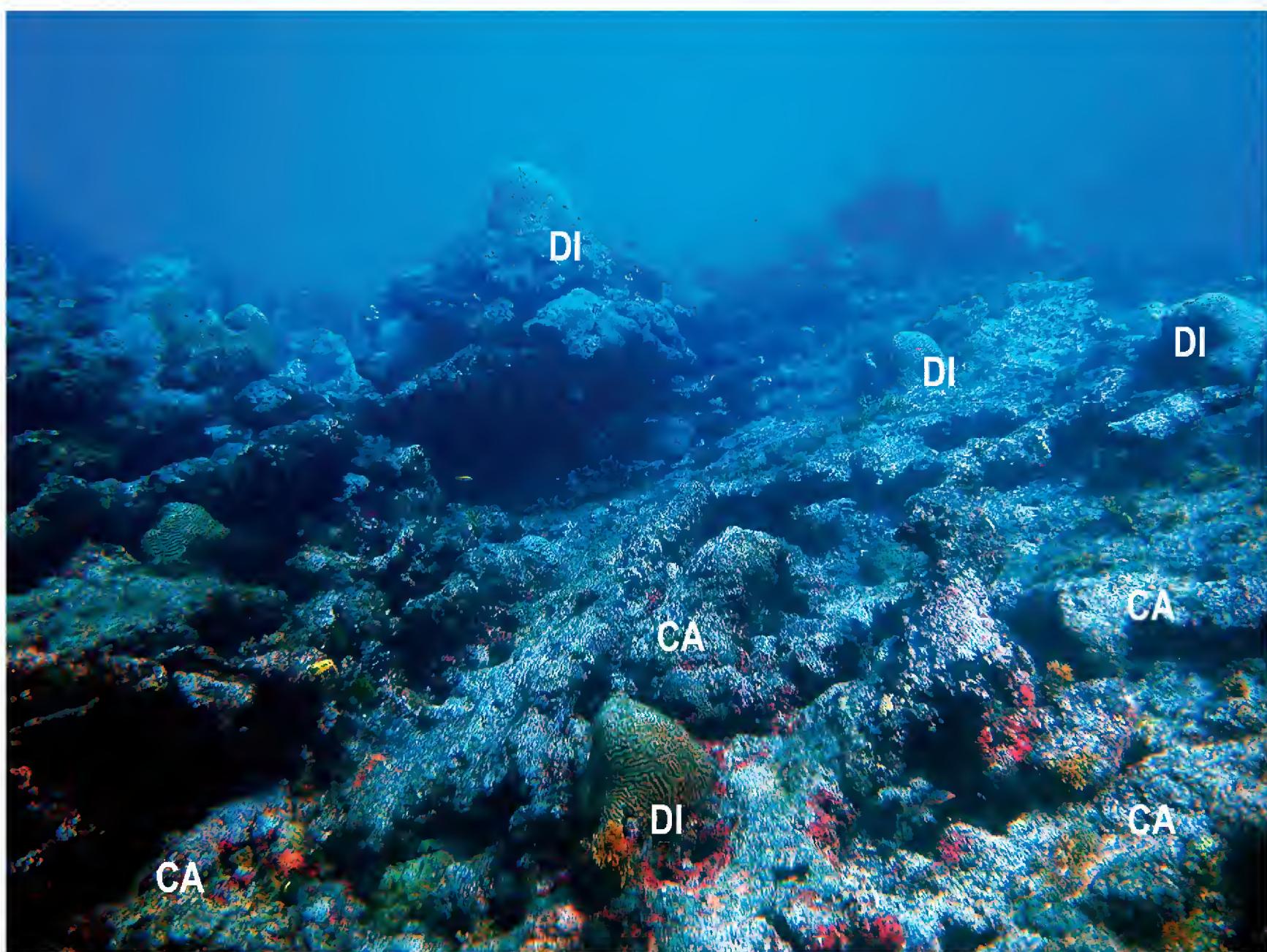


Figure 11. Site I (south of Kitridge Point) exhibits high relief formed by reworked *Acropora palmata* framework. Note extensive crustose coralline algal cover (CA) and scattered *Diploria strigosa* (DI).

Transect Surveys

Algae were the predominant biotic categories along our chain-transect surveys and included macroalgae, turf algae and crustose coralline algae (Fig. 12). Seventy eight percent of the sites had a macroalgal cover that ranged from ~25% to 80%, sixty seven percent of sites had a crustose coralline algal cover of about 40% to 50%, and fifty six percent of the sites had an algal turf cover of 5.0% to 33.8%. Zooxanthellate corals formed very little of the bottom cover, usually less than 5%. All other macroinvertebrate taxa, such as sponges, alcyonarians, and echinoderms, were uncommon to rare. Bare sand and rock were only prominent at three sites and ranged from ~30% to 50% of the cover (Macintyre et al., 2007). Two of these sites were located in the easternmost reef sector (Harrismith, Sam Lord's Castle) and one was near the mid-reef region at Foul Bay.

Macintyre et al. (2007) showed that multidimensional scaling and cluster analyses did not reveal any along-reef (NE-SW) trends in the benthic cover; however, five sites (A, D, E, F, G) scattered along the length of the reef showed high within-site (replicate) similarity.

Radiocarbon Dates

All radiocarbon-dated *A. palmata* samples (Table 1) were taken from surface sites along Cobblers Reef from -2 m MSL to -6 m MSL (present reef-top depths) throughout the study area. The 29 dated samples were plotted against Toscano and Macintyre's (2003) corrected western Atlantic sea-level curve (Fig. 13). At most sites the dated samples form distinct time-depth clusters, with the exception of those from site G at -2 m Mean Sea Level (MSL). Site G samples (all taken at -2 m MSL) plot across an age range from 4,270 cal BP (~1.5 m above the curve level for that time) to one sample at 2,680 cal BP (plotting on the curve for that time) to two samples of 320 and 400 cal BP (plotting 2 meters below the curve for that time). Samples from site A (-2 m MSL, average ~3,336 cal BP) all plot above the curve for that time, as do samples from site C (-2 m MSL, average ~3532 cal BP) and site E (-2.6 m MSL, average ~3855 cal BP). Including sample G1, a total of 11 ¹⁴C dates (Fig 14) plot above the sea-level curve within the interval ranging from about 3,300 to 4,500 cal BP.

Prior to and during the interval from 3,300 to 4,500 cal BP, a total of seven dates (Sites D and F) plot below the sea-level curve at realistic growth depths for *A. palmata*. Thus, while samples from site D (average age ~3,970 cal BP) and Site F (average age ~4,743 cal BP) plot presumably in place below the curve at -3.5 m MSL and -4.7 m MSL respectively, they are well below the series of high plots ranging from 3,300 to 4,500 cal BP from sites A, C, E and the oldest sample from Site G. Following this interval, eight samples plot on the curve or below at reasonable growth depths from 2,680-320 cal BP.

In addition, all samples from Site H cluster from 6,300-6,470 cal BP at about 2 meters above the sea-level curve.

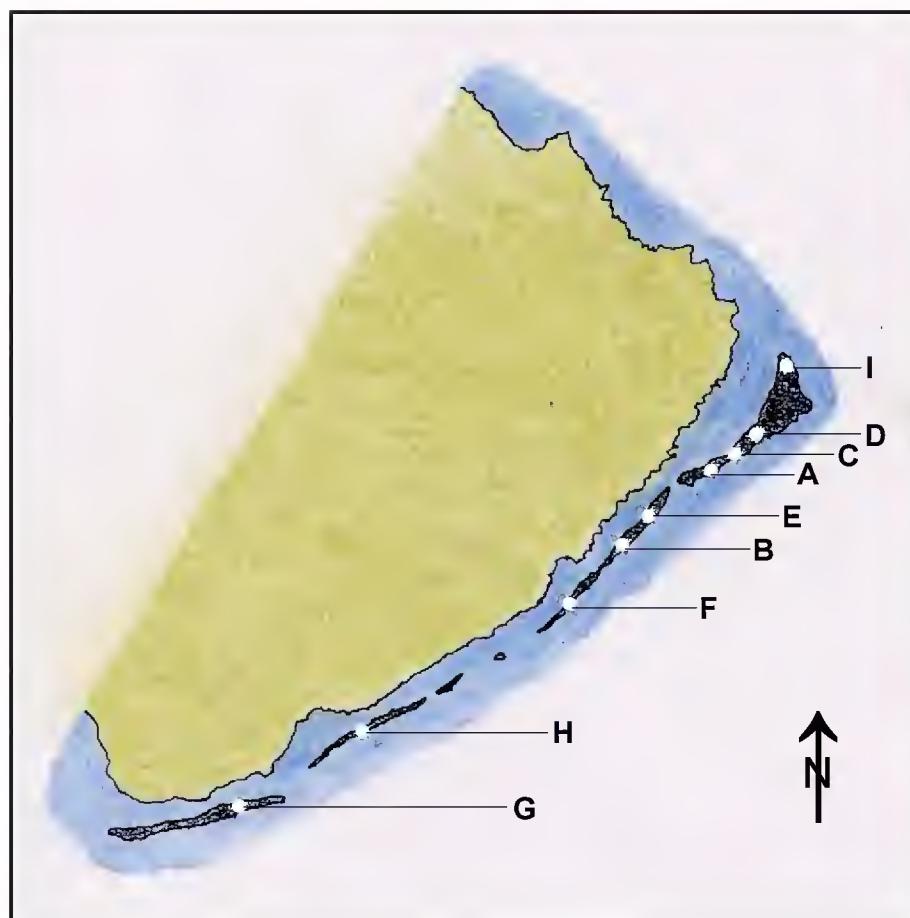
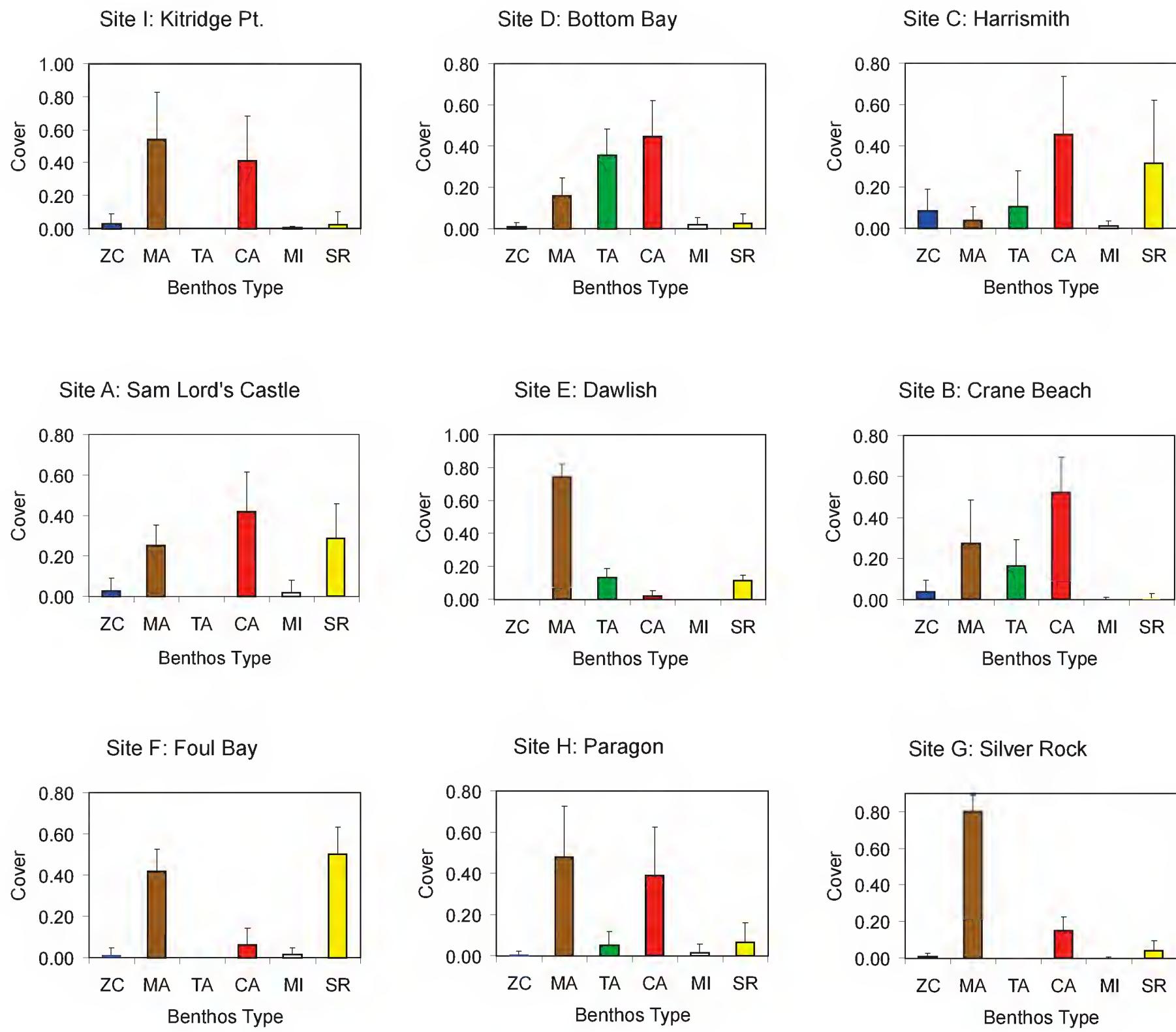


Figure 12. Histograms show the mean cover of epibenthos and sediment/rock surfaces at each of 9 sampling sites along Cobbler's Reef. Each panel denotes the overall mean (± 1 SEM) values of 3 transects per site (after Macintyre et al., 2007).

- LEGEND**
- █ ZC zoanthellate corals
 - █ MA macroalgae
 - █ TA turf algae
 - █ CA crustose coralline algae
 - █ MI macroinvertebrates other than zoanthellate corals
 - █ SR calcareous sediments and rocks

Table 1. Radiocarbon data for 29 *Acropora palmata* samples taken from the surface of Cobbler's Reef, southeast Barbados. Refer to Figure 2 for sample sites A-I. **Meas. Age BP** refers to the uncorrected radiocarbon date in years before present (1950) with error ranges. **Conv yrs BP** refers to the conventional radiocarbon date corrected for $\delta^{13}\text{C}$ and reservoir effect (age of local seawater), in years before present (1950) with error ranges. **Cal BP** refers to calibration of the conventional ^{14}C age to calendar ^{14}C years before present (Stuiver and Reimer 1993). Cal BP ages are direct calibration curve intercepts; **95.4% (2σ) cal age ranges** indicates statistically-significant 2-sigma age ranges.

Site/Sample	Depth (m) relative to Mean Sea Level	Meas. Age BP	Conv yrs BP	Cal BP	95.4% (2σ) cal age ranges
A1	-2	2940 \pm 70	3370 \pm 80	3240	cal BP 3330-3140
A2	-2	3120 \pm 60	3550 \pm 60	3440	cal BP 3570-3320
A3	-2	3050 \pm 80	3440 \pm 80	3330	cal BP 3470-3110
B1	-2	1590 \pm 60	1990 \pm 70	1540	cal BP 1620-1480
B2	-2	1650 \pm 70	2070 \pm 70	1630	cal BP 1810-1490
B3	-2	1850 \pm 80	2260 \pm 80	1860	cal BP 2050-1690
C1	-2	3300 \pm 70	3720 \pm 70	3630	cal BP 3710-3550
C2	-2	3150 \pm 70	3520 \pm 70	3390	cal BP 3560-3250
C3	-2	3320 \pm 50	3740 \pm 60	3650	cal BP 3820-3510
C4	-2	3180 \pm 60	3580 \pm 70	3460	cal BP 3630-3330
D1	-3.5	3660 \pm 70	4070 \pm 80	4090	cal BP 4220-3980
D2	-3.5	3480 \pm 70	3890 \pm 70	3850	cal BP 3950-3760
D3	-3.5	3690 \pm 80	4060 \pm 80	4080	cal BP 4330-3860
D4	-3.5	3520 \pm 70	3900 \pm 70	3860	cal BP 4070-3680
E1	-2.6	3470 \pm 70	3890 \pm 70	3850	cal BP 3950-3760
E2	-2.6	3510 \pm 70	3890 \pm 70	3850	cal BP 4060-3670
E3	-2.6	3520 \pm 50	3900 \pm 50	3860	cal BP 3980-3720
F1	-4.7	4370 \pm 50	4770 \pm 50	5020	cal BP 5060-4950
F2	-4.7	4160 \pm 70	4570 \pm 80	4810	cal BP 4840-4690
F3	-4.7	3820 \pm 50	4270 \pm 40	4300	cal BP 4420-4150
G1	-2	3780 \pm 60	4190 \pm 60	4270	cal BP 4370-4180
G2	-2	270 \pm 60	700 \pm 60	320	cal BP 420-280
G3	-2	310 \pm 50	740 \pm 60	400	cal BP 450-300
G4	-2	2430 \pm 60	2860 \pm 60	2680	cal BP 2710-2530
H1	-4	5470 \pm 70	5900 \pm 70	6300	cal BP 6390-6260
H2	-4	5610 \pm 80	6010 \pm 80	6410	cal BP 6500-6320
H3	-4	5630 \pm 50	6060 \pm 50	6470	cal BP 6610-6380
I1	-6	2140 \pm 70	2540 \pm 70	2200	cal BP 2300-2120
I2	-6	2000 \pm 60	2410 \pm 70	2040	cal BP 2120-1950

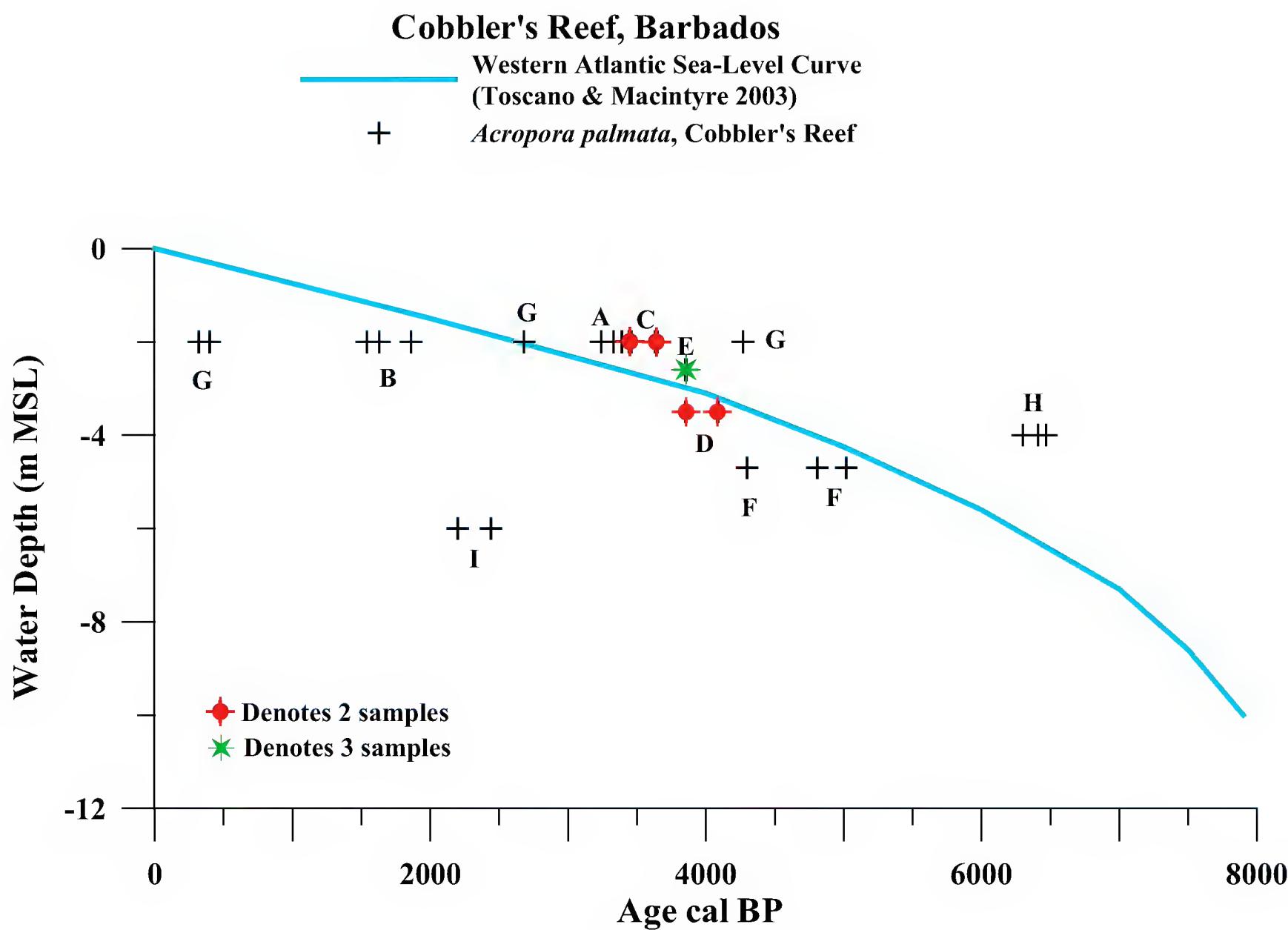


Figure 13. Plots of radiocarbon dates of *Acropora palmata* from the sampling sites along Cobbler's Reef in relation to the corrected Western Atlantic sea-level curve (Toscano and Macintyre, 2003). Samples that plot above the sea-level curve indicate storm transport (after Macintyre et al., 2007)

DISCUSSION

The predominant living epibenthic cover on the Cobbler's reef crest consisted of algae, which is in agreement with several other studies on Caribbean (Hughes, 1994; Chiappone et al., 1997; 2001) and Pacific (Jackson et al., 2001; Vroom et al., 2005; 2006) coral reefs. During the past three decades there has been a global scale phase shift on many reefs from high coral cover to high macroalgal cover due to a variety of circumstances (McClanahan, 2000; Wilkinson, 2002). Coral abundances have been reduced on many reefs in the Indo-Pacific from *Acanthaster* predatory outbreaks and bleaching events, and on Caribbean reefs by epizootics (Aronson and Precht, 2001; 2006), reduced herbivory (*Diadema*) and bleaching, and on reefs locally in all biogeographic regions from overfishing (Hughes, 1994; Jackson et al., 2001; Pandolfi et al., 2003), sedimentation stress and nutrient loading (Grigg and Dollar, 1990; Dubinsky and Stambler, 1996; Wilkinson, 1998). Cobbler's Reef may have undergone a phase shift from coral-to-algal predominance much earlier than the current perturbations noted at about 4,500 to 3,300 yrs BP, based on the age of frame-building *Acropora* colonies deposited above sea level (Macintyre et al., 2007).

The eleven *A. palmata* radiocarbon dates that plot above the western Atlantic sea-level curve (Toscano and Macintyre, 2003) indicate that storm damage has played a major role in the initial demise of Cobbler's Reef during an interval of 4,500 to 3,300 cal yrs ago (Macintyre et al., 2007). In addition, the three samples from Site H that yielded dates of 6,300 to 6,470 cal years ago and plotted ~2 m above the sea-level curve are probably storm debris from the seaward shelf-edge reef, locally known as the Fathom. This suggests that the *A. palmata* framework was probably heavily impacted by a millennial-scale cycle of very severe storm activity. Hurricane-forced destruction of massive *A. palmata* framework on Caribbean reefs has been documented (e.g. Woodley et al., 1981). The robust nature of the *A. palmata* rubble on Cobbler's Reef indicates that extreme bottom-water velocities would have been required to have converted such massive framework into rubble. Woodley et al. (1981) noted that transport of broken corals and other solid objects exacerbated the destruction of Jamaican north coast coral frameworks. They further reported that dense stands of 1-3 m high *A. palmata* (in depths from 0-5 m) were "leveled" and the reef crest was transformed into a "gently sloping rubble rampart" with scattered emergent rubble islands. Such exposed islands of coral rubble are well illustrated by Woodley (1993) in Discovery Bay, Jamaica following hurricane Allen.

Not all *A. palmata* was destroyed on Cobbler's Reef during the period of storm activity, as indicated by those samples which plot below the sea-level curve during that interval as well as all post-3,000 cal yr dates, some of which survived up to 300-to-400 cal yrs ago (Macintyre et al., 2007). In addition, the *A. palmata* framework within the fringing reefs off the west coast of Barbados (Lewis, 1984), which also shows some indication of storm reworking, yielded radiocarbon dates that range in age from about 1900 cal yrs ago right up to modern times.

There is an apparent gradual decline of *A. palmata* off the southeastern coast of Barbados. This started with the extensive damage of abundant robust communities of this species that formed the bank-barrier reef off this coast, probably by a series of storms mostly concentrated 4,500 to 3,300 cal yrs ago. Why did these corals not recover to continue thriving off this coast, an area with a long history of flourishing *A. palmata* reefs starting with the thick sections of *A. palmata* forming the Pleistocene cliffs at Foul Bay, shoreward of Site F (Fig. 14)? Offshore, an impressive series of back-stepping *A. palmata* reefs was established in response to the rising post-glacial seas. These relict reefs were initiated on the insular slope at depths of about 120 m and flourished from ~17,000 to ~12,000 yrs ago (Fairbanks, 1989; Fairbanks et al., 2005). This early reef system likely "gave up" because it could not keep pace with rapid rates of post-glacial sea-level rise. Another *A. palmata* reef was established shoreward at a depth of about 80 m and formed about 25 m of framework before it too was stranded by rapid sea-level rise caused by a major glacial meltwater pulse (Fairbanks, 1989; Fairbanks et al., 2005). At the shelf edge (at a depth of about -40 m), another *A. palmata* reef was established ~9,500 yrs ago and formed 15 m of framework before it "gave up" ~6,500 yrs ago (Fairbanks et al., 2005). The shelf edge reef was likely terminated due to sediment stress caused by the flooding of the shelf (Macintyre, 1988), possibly combined with storm activity and deepening water. Cobbler's Reef was the final phase of this impressive sequence of back-stepping of shallow-water *A. palmata* off this coast. As has been documented, this *A. palmata* community is now totally dead with a rich algal cover and a sparse cover of live non-acroporid coral species.



Figure 14. Pleistocene cliff at Foul Bay showing a reworked jumble of robust *Acropora palmata*. This indicates a long history of storm-destroyed *A. palmata* reefs on this coast.

Despite the fact that Cobbler's reef is named after the black-spined urchin *Diadema antillarum*, it appears that neither this urchin nor herbivorous fishes were capable of controlling algal growth in the reef-crest areas, particularly if the algal growth greatly expanded following major reef coral destruction from hurricanes. Algae can quickly colonize a devastated reef site before reef corals can reclaim the substrate, causing rapid phase shifts in the makeup of the reef (Aronson and Precht, 2006). In other words, such major shifts to algal dominance can be the result of reef devastation rather than the cause. On Cobbler's Reef, clearing the substrate for significant settlement of corals is probably related to the constant high-energy setting of this reef, which is exposed to the trade winds throughout most of the year (Macintyre et al., 2007). Adey et al. (1977) reported similar conditions on Vauclin Point Reef off the east coast of Martinique where the reef crest was an *A. palmata* pavement covered with macroalgae and crustose coralline algae. They found that the grazing activity of *D. antillarum* was limited to areas leeward of the crest. Therefore, the reef crests of reefs such as Vauclin Point Reef and Cobbler's Reef, which are exposed to constant maximum trade-wind energy, have minimum herbivory control of algal growth. Thus, if a robust *A. palmata* community in an area of year-round heavy wave conditions is destroyed by severe storms, it may not recover when limited herbivory allows algae to dominate the reef surface (Macintyre et al., 2007).

The relative lack of coral ages and limited indication of reef accumulation following 3,300 cal years indicate that *A. palmata* never recovered to actively form a reef framework following the period of storm activity. Along with the resulting algal dominance of the reef surface, other factors that could have played a role in the eventual loss of *A. palmata* on this reef include later severe storms of 1675, 1780, and 1831 (Schomburgk, 1848), white-band disease, coral bleaching, and recruitment limitation (Macintyre et al., 2007)

In addition, clearing of land for sugarcane agriculture during early colonization in the mid-1600s (Schomburgk, 1848; Watt, 1966) increased the amount of erosion and sediment-laden runoff, particularly off the east coast of Barbados where Tertiary clastic sediments are exposed (Senn, 1940). Because *A. palmata* is especially vulnerable to high turbidity (Rogers, 1983), land clearing and erosion was likely a decisive factor in limiting the proliferation of the surviving corals on Cobbler's Reef. Macintyre (personal observation) has noted extensive turbidity in nearshore water after heavy rains (Fig. 15). Longshore currents carry this sediment along Cobbler's Reef (Murray et al., 1977).



Figure 15. Extensive turbidity in offshore waters indicating rapid erosion of Tertiary clastic sediments in the Scotland District after heavy rains, east coast of Barbados, August, 1965.

The only historical records of flourishing *A. palmata* communities off Barbados are those of Nutting (1919). During his 1918 visit to the island he described “abundant” (p. 55) *A. palmata* close to shore off Pelican Island, which is now part of the Bridgetown deep-water harbor. He also saw “great rosettes” (p.102) of *A. palmata* off the south coast. Today the south-coast area is mostly a coral rubble bank and both of these sites are no longer areas of live *A. palmata*. The general decline of *A. palmata* off all coasts of Barbados has continued to the present. Lewis (1960) reported *A. palmata* as common in some of the reef-crest zones of the west coast fringing reefs, which were dominated by

Porites porites and *Porites astreoides* with *Montastraea annularis*, *Siderastrea siderea* and *Millepora alcicornis* present in less abundance. He also found “common disk-like colonies on a broad short stalk” (p. 1142) at about three meters depth off the windward east coast. Later, Macintyre (1968) mapped the reefs off the west coast and also noted some *A. palmata* in “appreciable numbers” (p. 96) in the reef-crest zones. In addition he described “scattered growths of large individual colonies” (p. 97) on bare rock surfaces north of Fryer’s Well at the northern section of the west coast. Today there appear to be only a very few living colonies of *A. palmata* off the west coast of this island (R. Roach, personal communication, Sept. 2004). It is apparent that increasing industrial effluent such as that from rum distilleries and sewage, enhanced by the growth of tourism, have severely depleted *A. palmata* colonies off the island of Barbados.

Tsunami or Storm Deposits?

Schellman et al. (2004) and Scheffers et al. (2006) studied windward depositional ridges, ridge complexes and ramparts on Bonaire and Curaçao consisting of coral clasts and sediments transported 5-6 m above sea level onto a late Pleistocene (substage 5e) terrace. At Bonaire subaerial deposits of coral clasts yielded electron spin resonance (ESR) ages ranging from 4,100-3,100 yrs ago (Scheffers et al. 2006) and scattered younger ¹⁴C ages. The occurrence of un-abraded coral surfaces suggested death of those corals due specifically to tsunamis and rapid deposition along with sediment matrix. In addition, the presence of very large limestone blocks (“megaclasts”), presumably broken from windward Pleistocene terrace overhangs and deposited upward and landward onto those same rock terraces, led Scheffers et al. (2006) to conclude that the deposits (and damage to Holocene reefs) had been caused by tsunamis approximately 3,100 and 4,100 yrs ago rather than by hurricanes (despite observation of hurricane transport of megaclasts on Bonaire by Scheffers and Scheffers 2006). In addition, Scheffers and Kelletat (2004) decided that windward rock ridges on Barbados (just south of Kitridge Point, the easternmost point along the south coast) and two megaclasts, weighing ~100 and ~170 t on the south coast landward of either end of Cobblers Reef, were likewise emplaced by Holocene tsunami events. SR Scheffers (pers. comm. 2007) therefore suggested that the seemingly concurrent demise of Cobblers’ Reef (compared to dates on presumed tsunami deposits on Bonaire) was due to these same tsunami events rather than by a series of severe storm activity as interpreted in this study.

Three issues must be resolved, including whether the timing of catastrophic events in both places was concurrent and whether the events themselves are datable or resolvable; whether tsunamis or storms were more likely to have affected both places concurrently; and whether the mega-reef clasts on Bonaire and Barbados require tsunami waves to be transported upward and landward.

1. Timing of Catastrophic Events? The timeframe comparison is heavily dependent on the comparability of the dating methods and the types of samples dated. In the case of Cobbler’s Reef, *A. palmata* clasts cemented to the dead reef surface yielded calibrated ¹⁴C dates ranging from 3300-4300 cal BP. These plotted above our well-constrained sea-level reference curve (Toscano and Macintyre 2003), and were grouped

into three clusters within that range. We have therefore been able to show that samples grouped into several age clusters were transported above sea level, and we have identified a period of intense storm activity, while not actually dating the storm events.

In contrast, Scheffers et al. (2006) and Radke et al. (2003) sampled least-abraded, random loose clasts of *A. palmata* or *Diploria* sp. from subaerial deposits, and reported ESR dates on the youngest portions of these samples. They assumed that the freshest-looking coral surfaces indicated a sample that was alive at the time of, and subsequently killed by, the proposed tsunami event, thus dating the event. They acknowledged the potential problems with this approach and also dated a variety of epibionts and *Strombus* sp., thinking to achieve a consensus of ages; however the pitfalls and time averaging likely to result from such varied sources suggest a highly equivocal geochronology. Indeed, their ESR dates, ranging from 2850 to 4250 years BP (with errors of up to ± 1000 years) do not separate into discrete clusters within this range and do not appear to resolve separate events interpreted as having occurred at 4100 and 3100 years ago by Scheffers et al. (2006). ESR dates may not be directly comparable to, or as precise as, ^{14}C ages. Radke et al. (2003) dated 51 samples by both ^{14}C and ESR and determined a mean difference of 73 ± 250 years between the two methods, with the ESR dates being generally older and with much higher (up to 4 orders of magnitude) error ranges than the ^{14}C dates (discussed in more detail in Radke et al. 2003; see their Table 1).

Thus in the case of Bonaire and Barbados, given the uncertainties in the sample selection and the ESR dating method, the authors have reported generally correct sample ages from a 1000 year timeframe, but not the timing of the inferred catastrophic events that deposited them.

2. Regional Effects of Storm waves vs. Tsunamis? The likelihood that tsunamis concurrently affected both southeastern Barbados and eastern Bonaire must take into consideration the distance between these islands and the history and characteristics of tsunamis in the region (Lander et al. 2002). Along the eastern Caribbean island arc, convergent, compressional and collisional tectonics produce earthquakes, volcanic activity, submarine landslides and flank failures, and pyroclastic flows that generate well-documented *local* tsunamis which affect one or a few islands, attenuate rapidly and thus do not have widespread impacts (Pararas-Carayannis 2004; Morton et al. 2006; Mattioli et al. 2007). Tsunamis ($\sim 2\text{m}$) generated by the subsea eruption of Kick'em Jenny in 1939 are described to have “probably reached the west coast of Barbados, but were not noticed as their heights had attenuated significantly.” (Pararas-Carayannis 2004). In fact, a “worst case scenario” postulated by Pararas-Carayannis (2004) involves a repeat of the 1939 eruption (from the present shallower summit of Kick'em Jenny), which would potentially generate waves with 3m maximum runup in the vicinity of the Grenadines and Grenada. These waves would attenuate to 1-2m along the *west* coast of Barbados, and to only 1m (at most) along the north coast of Venezuela and Bonaire. Thus any tsunami generated by tectonic or volcanic activity along the Caribbean island arc region would not be expected to have simultaneous significant impacts in both Barbados and Bonaire given the distances and nature of the waves. In addition, local tsunami impacts on the *west* coast of Barbados would be further attenuated by wave refraction around to the southeastern coast where they might finally reach Cobbler's Reef. The 20-30 m run-ups

indicated by Scheffers and Kelletat (2006) to explain megaclast movement on Barbados may thus be unrealistic for locally generated seismic sea waves. Historic tsunamis originating in Lisbon, Portugal (e.g. November 1, 1755; March 31, 1761; Lander et al. 2002) have reached the eastern-facing shorelines of Caribbean Islands including Barbados (yet not cited by Scheffers and Kelletat 2004) but have not been documented in Bonaire. Tsunamis have also been generated by earthquakes along the collision zone of the Caribbean and South American plates (Theilen-Willige 2006) offshore of Northern Venezuela. Thus local tsunamis are possible at Bonaire; however Theilen-Willige (2006) indicates Curaçao and Bonaire as the source earthquake generating area (close to the collision zone) for tsunamis impacting northeastern Venezuela. Again, no tsunamis have historically been reported as having hit Bonaire (Morton et al. 2006; Lander et al. 2002), but this does not preclude the occurrence of paleotsunami events.

3. Significance of Megaclast transport in Bonaire and Barbados? Making distinctions between destructive agents (severe storms vs. tsunamis) and their coastal deposits is complex. While hurricanes do not normally directly impact either Barbados or the ABC islands (Aruba, Curaçao and Bonaire), severe modern storms passing within 150km of these islands (in particular Hurricanes Allen – 1980, Lenny-1999 and Ivan-2004) have generated deep ocean swell and coastal waves of >12 m that have been observed depositing or reworking coral rubble ramparts, ridges and boulder fields as well as moving (pushing) megaclasts sitting on coastal terraces (Scheffers and Scheffers 2006; Morton et al. 2006). Thus even if hurricanes do not make direct landfalls, large hurricane-propagated ocean waves shoaling on island coasts over several hours or more have certainly been observed as destructive influences on reefs and coastal deposits in Bonaire, Barbados and the wider Caribbean. In addition, as observed by Scheffers and Scheffers (2006) and pointed out by Morton et al. (2006) the typically imbricated clasts of ridge and rampart deposits and boulder fields atop coastal terraces have been observed being deposited by storms, reworked, better packed and infilled with sediment by subsequent waves. Such deposits occur well within the elevation range of storm waves and surges and have been repeatedly reshaped by recent storms as well as by large non-storm waves. Megaclasts do not require tsunamis for emplacement above sea level – many instances of megaclast transport above sea level by storm waves have been documented worldwide (summarized by Morton et al. 2006).

Thus while catastrophic reef damage has occurred at both sites, and perhaps over the same timeframe, it is not likely related to the simultaneous impact of localized tsunamis, but to more regionally widespread severe storm events, waves of which have been observed on Bonaire to deposit boulders and move the large megaclasts attributed to tsunami transport (Scheffers and Scheffers 2006; Scheffers et al. 2006; Morton et al. 2006). Intense storm waves/surges act on elevated coastal areas for much longer intervals than proposed tsunamis, probably effecting more storm deposition and megaclast transport (Morton et al. 2006). We have also been impressed with the size of limestone blocks that have been thrown up on to the Rangiroa Atoll reef flat by hurricanes (Stoddart 1969). The western rim is “subject to hurricanes and resulting catastrophic modification” (p. 14) and the reef flat is covered with “reef blocks” for a distance of 1.6 km measuring up to 5.5m high and wide (Stoddart 1969).

The relatively minor effects of tsunamis on living reefs was documented via the major 2004 Indian Ocean tsunami (Stoddart (ed.) 2007), which caused significant coastal erosion and large overwash deposits but little actual reef damage (e.g. Campbell et al. 2007; Phongsuwan and Brown 2007) – most was highly localized and involved high volumes of sediment deposition in situ. This is in marked contrast to the almost complete stripping of the coral community on the windward side of Glover's Reef, Belize, down to a depth of about 10m, by Hurricane Mitch in 1998 (IGM pers. obs.). We therefore would suggest caution in proposing Holocene reef damage primarily by tsunamis at either Bonaire or Barbados. Widespread regional storm events are more likely to account for any overlap in dates for reef destruction in both places.

CONCLUSIONS

It appears that the *A. palmata* community of Cobbler's Reef never recovered fully from the 4,500 to 3,300 cal yrs ago period of storms that destroyed areas of the reef framework. Permanent decline of *A. palmata* was likely exacerbated by the continuous heavy wave action that limited herbivory and favored fleshy and filamentous algae over coral settlement. Other environmental factors including disease, bleaching and subsequent severe storms likely contributed to the demise of the reef. In historic times, the clearing of land for sugarcane plantations with the arrival of the British in 1627 probably resulted in extensive terrigenous runoff, particularly from the erosion of Tertiary sedimentary deposits exposed on the east coast. Turbidity stress resulted in the loss of much of the remaining sediment-sensitive *A. palmata*. Subsequently, increasing industrial effluent such as that from rum distilleries and sewage, enhanced by the growth of tourism, has dealt a final death knell to almost all of the last surviving *A. palmata* colonies off the island of Barbados.

ACKNOWLEDGEMENTS

We are indebted to Keith and Barbara Armstrong for advice on field work, Alison and Michael Pile for valuable support, Dean, Dereck, and Bruce Edgehill for field assistance, Allan G. Macintyre for field assistance, processing digital photographs and preparing rock samples. We are grateful to the Barbados Coastal Zone Management Unit for arranging a Research Permit to undertake this study and their observer Ramon Roach who assisted us. A special thanks to the following for identification of bottom communities at each site as recorded in numerous digital photographs: Diane S. Littler and Mark M. Littler - macroalgae; Frederick W. Bayer - octocorals; Klaus Ruetzler - sponges; and Stephen D. Cairns - scleractinian corals. In addition, Walter H. Adey and Susan Lutz identified crustose coralline algae in hand specimens. We also thank William T. Boykins for graphics layout and Mary E. Parrish for drafting assistance. Finally we thank Bernhard Riegl and Ian Enochs for help with statistical analysis and graphics.

REFERENCES

- Adey, W.H., P.J. Adey, R. Burke, and L. Kaufman
 1977. The Holocene Reef Systems of Eastern Martinique, French West Indies.
Atoll Research Bulletin 218:1-40.
- Aronson, R.B., and W.F. Precht
 2001. White band disease and the changing face of Caribbean coral reefs.
Hydrobiologia 460:25-38.
- Aronson, R.B., and W.F. Precht
 2006. Conservation, precaution, and Caribbean reefs. *Coral Reefs* 25:441-450
- Bard, E.
 1998. Geochemical and geophysical implications of the radiocarbon calibration.
Geochim Cosmochim Acta 62:2025-2038.
- Bruckner, A.W.
 2002. Proceedings of the Caribbean *Acropora* workshop: Potential applications of the US Endangered Species Act as a conservation strategy. *NOAA Tech Mem NMFS-OPR-24*.
- Bruckner, A.W., and T.F. Hourigan
 2002. Proactive management for conservation of *Acropora cervicornis* and *Acropora palmata* application of the US Endangered Species Act. *Proc. 9th International Coral Reef Symposium* 2:661-665.
- Campbell, S.J., M.S. Pratchett, A.W. Anggoro, R.L. Ardiwijaya, N. Fadli, Y. Herdiana, T. Kartawijaya, D. Mahyiddan, A. Mukminin, S.T. Pardede, E. Rudi, A.M. Siregar, and A.H. Baird
 2007. Disturbance to coral reefs in Aceh, northern Sumatra: Impacts of the Sumatra-Andaman tsunami and pre-tsunami degradation. *Atoll Res Bull* 544:55-78.
- Chiappone, M., K.M. Sullivan, and R. Sluka
 1997. Status of reefs in the central Bahamas based on a large scale survey. *Proc 8th International Coral Reef Symposium* 1:345-350.
- Chiappone, M., K. Sullivan-Sealey, G. Bustamante, and J. Tschirky
 2001. A rapid assessment of coral reef community structure and diversity patterns at naval station Guantanamo Bay, Cuba. *Bulletin of Marine Science* 69:373-394.
- Clarke, K.R., and R.N. Gorley
 2001. Primer v5: *User manual/tutorial*. Primer-E, Plymouth.
- Diaz-Soltero, H.
 1999. Endangered and threatened species: A revision of Candidate Species List under the Endangered Species Act. *Federal Register* 64:33466-33668.
- Dubinsky, Z., and N. Stambler
 1996. Marine pollution and coral reefs. *Global Change Biology* 2:511-526.
- Fairbanks, R.G.
 1989. A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 342:637-642.

- Fairbanks, R.G., R.A. Mortlock, T-C Chiu, L. Cao , A. Kaplan, T.P. Guilderson, T.W. Fairbanks, A.L. Bloom , P.M. Grootes, and M-J Nadeau
2005. Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired $^{230}\text{Th}/^{234}\text{U}/^{238}\text{U}$ and ^{14}C dates on pristine corals. *Quaternary Science Review* 24:1781-1796.
- Federal Register
2006. Endangered and threatened species: final listing determinations for Elkhorn Coral and Staghorn Coral 71:26852-26861.
- Goreau, T.F.
1959. The ecology of Jamaican coral reefs 1: Species composition and zonation. *Ecology* 40:67-90.
- Grigg, R.W., and S.J. Dollar
1990. Natural and anthropogenic disturbance on coral reefs. In: Dubinsky Z (ed) *Coral reefs, Ecosystems of the world* 25. Elsevier, Amsterdam, pp 439-452.
- Hughen, K.A., M.G.L. Baillie, E. Bard, A. Bayliss, J.W. Beck, C.J.H. Bertrand, P.G. Blackwell, C.E. Buck, G.S. Burr, K.B. Cutler, P.E. Damon, R.L. Edwards, R.G. Fairbanks, M. Friedrich, T.P. Guilderson, B. Kromer, F.G. McCormac, S.W. Manning, R. Bronk, P.J. Reimer, R.W. Reimer, S. Remmele, J.R. Southon, M. Stuiver, S. Talamo, F.W. Taylor, J. van der Plicht, and C.E. Weyhenmeyer.
2004. Marine04 Marine radiocarbon age calibration, 26 - 0 ka BP. *Radiocarbon* 46: 1059-1086.
- Hughes, T.P.
1994. Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. *Science* 265:1547-1551.
- Jackson, J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner, and R.R. Warner
2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293:629-638.
- James, N.P., C.S. Stearn, and R.S. Harrison
1977. Field guidebook to modern and Pleistocene reef carbonates, Barbados, West Indies. *3rd Intl Coral Reef Symp Miami*, The Atlantic Reef Committee, University of Miami, Miami Beach, Florida, 30pp.
- Lander, J.F., L.S. Whiteside, and P.A. Lockridge
2002. A brief history of tsunamis in the Caribbean Sea. *Science of Tsunami Hazards* 20:57-94.
- Lewis, J.B.
1960. The coral reefs and coral communities of Barbados, WI. *Can J Zool* 38:1133-1145.
- Lewis, J.B.
1984. The *Acropora* inheritance: A reinterpretation of the development of fringing reefs in Barbados, West Indies. *Coral Reefs* 3:117-122.
- Lewis, J.B., and H.A. Oxenford
1996. A field guide to the coral reefs of Barbados. *Biology Dept, McGill University*

- Lighty, R.G., I.G. Macintyre, and R. Stuckenrath
 1978. Submerged early Holocene barrier reef south-east Florida shelf. *Nature* 276:59-60.
- McClanahan, T.R.
 2000. Coral reef use and conservation. In: McClanahan TR, Sheppard CRC, Obura DO (eds) *Coral Reefs of the Indian Ocean: their ecology and conservation*. Oxford University Press, Oxford, pp 39-80.
- Macintyre, I.G.
 1968. Preliminary mapping of the insular shelf off the west coast of Barbados, WI. *Caribb J Sci* 8:95-100.
- Macintyre, I.G.
 1988. Modern Coral Reefs of Western Atlantic: New Geological Perspective. *American Association of Petroleum Geologists Bulletin* 73:1360-1369.
- Macintyre, I.G., and P.W. Glynn
 1976. Evolution of modern Caribbean fringing reef, Galeta Point, Panama. *American Association of Petroleum Geologists Bulletin* 60:1054-1072.
- Macintyre, I.G., P.W. Glynn, and M.A. Toscano
 2007. The demise of a major *Acropora palmata* bank-barrier reef off the southeast coast of Barbados, West Indies. *Coral Reefs* (in press).
- Mattioli G.S., B. Voight, A.T. Linde, I.S. Sacks, P. Watts, C. Widiwijayanti, S.R. Young, D. Hidayat, D. Elsworth, P.E. Malin, E. Shalev, E. Van Boskirk, W. Johnson, R.S.J. Sparks, J. Neuberg, V. Bass, P. Dunkley, R. Herd, T. Syers , P. Williams, and D. Williams
 2007. Unique and remarkable dilatometer measurements of pyroclastic flow-generated tsunamis. *Geology* 35:25-28.
- Mesolella, K.J.
 1967. Zonation of uplifted Pleistocene coral reefs on Barbados, West Indies. *Science* 156:638-640.
- Morton R.A., B.M. Richmond, B.E. Jaffe, and G. Gelfenbaum
 2006. Reconnaissance investigation of Caribbean extreme wave deposits – preliminary observations, interpretations, and research directions. *USGS Open File Report 2006—1293*, 41pp.
- Murray, S.P., H.H. Roberts, D.M. Conlon, and G.M. Rudder
 1977. Near shore current field around coral islands:control of sediment accumulation and reef growth. *3rd Intl. Coral Reef Symp. Miami*, 3:54-59
- Nutting, C.C.
 1919. Barbados-Antigua expedition. *University of Iowa Studies in Natural History* 8:1-274.
- Pandolfi, J.M., R.H. Bradbury, E. Sala, T.P. Hughes, K.A. Bjoerndal, R.G. Cooke, D. McArdle, L. McClenachan, M.J.H. Newman, G. Paredes, R.R. Warner, and J.B.C. Jackson
 2003. Global trajectories of long-term decline of coral reef ecosystems. *Science* 301:955-958.
- Pararas-Carayannis, G.
 2004. Volcanic tsunami generating source mechanisms in the eastern Caribbean region. *Science of Tsunami Hazards* 22:74-114.

- Phongsuwan, N., and B.E. Brown
 2007. The influence of the Indian Ocean tsunami on coral reefs of Western Thailand, Andaman Sea, Indian Ocean. *Atoll Res Bull* 544:79-92.
- Precht, W.F., M.L. Robbart, and R.B. Aronson
 2004. The potential listing of *Acropora* species under the US Endangered Species Act. *Marine Pollution Bulletin* 49:534-536.
- Precht, W.F., A.W. Bruckner, R.B. Aronson, and R.J. Bruchner
 2002. Endangered Acroporid corals of the Caribbean. *Coral Reefs* 21:41-42.
- Radke, U., G. Schellmann, A. Scheffers, D. Kelletat, B. Kromer, and H.U. Kasper
 2003. Electron spin resonance and radiocarbon dating of coral deposited by Holocene tsunami events on Curaçao, Bonaire and Aruba (Netherlands Antilles). *Quaternary Science Reviews* 22:1309-1315.
- Rogers, C.S.
 1983. Sublethal and lethal effects of sediment applied to common Caribbean reef corals in the field *Marine Pollution Bulletin* 14:378-382.
- Scheffers, A., and D. Kelletat
 2006. Recent Advances in Paleo-Tsunami Field Research in the Intra-Americas-Sea (Barbados, St. Martin and Anguilla). *Proceedings of the NSF Caribbean Tsunami Workshop*, Puerto Rico. World Scientific Publishing Co. Pte. Ltd.: 178-202.
- Scheffers, A., and S.R. Scheffers
 2006. Documentation of the impact of Hurricane Ivan on the coastline of Bonaire (Netherlands Antilles). *Journal of Coastal Research*, 22:1437-1450.
- Scheffers, S.R., A. Scheffers, U. Radke, D. Kelletat, K. Staben, and R.P.M. Bak
 2006. Tsunamis trigger long-lasting phase shifts in a coral reef ecosystem. *Annals of Geomorphology* 146:59-79.
- Schellman, G., U. Radke, A. Scheffers, F. Whelan, and D. Kelletat
 2004. ESR dating of coral reef terraces on Curaçao (Netherlands Antilles) with estimates of younger Pleistocene sea level elevations. *Journal of Coastal Research* 20:947-957.
- Schomburgk, R.H.
 1848. *The History of Barbados*. Longman, Brown, Green and Longmans, London.
- Senn, A.
 1940. Paleogene of Barbados and its bearing on history and structure of Antillean-Caribbean Region. *American Association of Petroleum Geologists Bulletin* 24:1548-1610.
- Stoddart, D.R.
 1969. Reconnaissance geomorphology of Rangiroa Atoll, Tuamotu Archipelago. *Atoll Research Bulletin* 125: 1-44.
- Stoddart (ed.)
 2007. Tsunamis and Coral Reefs. *Atoll Res Bull* special issue No. 544, 164p.
- Stuiver, M., and P.J. Reimer
 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. *Radiocarbon* 35:215-230.

- Toscano, M.A., and I.G. Macintyre
 2003. Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ¹⁴C dates from *Acropora palmata* framework and intertidal mangrove peat. *Coral Reefs* 22:257-270.
- Vroom, P.S., K.N. Page, K.A. Peyton, and J.K. Kukea-Shultz
 2005. Spatial heterogeneity of benthic community assemblages with an emphasis on reef algae at French Frigate Shoals, Northwestern Hawaiian Islands. *Coral Reefs* 24:574-581.
- Vroom, P.S., K.N. Page, J.C. Kenyon, and R.E. Brainard
 2006. Algae-dominated reefs. *American Scientist* 94:430-437.
- Watt, D.
 1966. Man's influence on the vegetation of Barbados 1627 to 1800. *Occasional Papers in Geography* 4:1-96.
- Wilkinson, C.R. (ed)
 1998. *Status of coral reefs of the world: 1998*. Australian Institute of Marine Science, Townsville.
- Wilkinson, C.R. (ed)
 2002. *Status of coral reefs of the world: 2002*. Australian Institute of Marine Science, Townsville.
- Woodley, J.D.
 1993. Hurricane and Damage in Jamaica. *Coral Reefs* 12:138.
- Woodley, J.D., P.A. Chornesky, P.A. Clifford, J.B.C. Jackson, L.S. Kaufman, N. Knowlton, J.C. Lang, M.P. Pearson, J.W. Porter, M.C. Rooney, K.W. Rylaarsdam, V.J. Tunnicliffe, C.M. Wahle, J.L. Wulff, A.S.G. Curtis, M.D. Dallmeyer, B.P. Jupp, M.A.R. Koehl, J. Neigel, and E.M. Sides
 1981. Hurricane Allen's impact on Jamaican coral reefs. *Science* 214:749-755.