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ST. CROIX, U. S. V. I.**

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ABSTRACT

Fourteen cores from deeper, shelf-edge reefs on St. Croix, USVI, record an impressive ability to build substantial thicknesses of carbonate material, both horizontally and laterally. At Salt River submarine canyon, over 24 m of Holocene reef material has been added laterally to a reef now in 30 m of water. Most of that thickness is caused by the accumulation of displaced rubble and larger talus blocks from shallower reefs above.

At Cane Bay, the amount of in-place framework decreases with depth, while the actual rate of reef accretion increases. Like at Salt River, much of this accretion was caused by the incorporation of debris derived from shallower water.

Both of these modern reefs are substantially or wholly collections of displaced reefal material derived from somewhere upslope. With the percentage of framework down near 30%, and much of that being out of place, it would clearly be difficult to distinguish these as true reefs in the ancient based on core data alone.

INTRODUCTION

Despite decades of interest in reefs, relatively little is known about the patterns of accretion along "deeper" margins of active carbonate shelves. Data from remote sampling (David and others, 1904; MacIntyre, 1972) have been recently supplemented by samples from explosive craters in the deep reef (Land, 1974; James and Ginsburg, 1979). Nevertheless, cores that document the patterns of reef accretion at the shelf edge are few (Adey and others, 1977; Beach and Ginsburg, 1980; MacIntyre and others, 1981; Shinn and others, 1982), and have dealt primarily with vertical reef accretion.

It has been tempting to assume that, because of the greatly decreased rates of coral growth at these depths, deeper reefs are limited to thin veneers over pre-existing topography. The cores described below show an impressive ability of these deeper reefs to add a substantial thickness of carbonate material, both vertically and laterally. The purpose of this paper is to summarize core information from the north shore of St. Croix, in the U. S. Virgin Islands (Fig. 1). This paper will concentrate on 14 cores taken in water depths greater than 10 m.

At the outset of the discussion the concept of "deep" as used in this paper should be understood. The authors are referring to that reef zone below the depth of rapid Acropora growth (i.e. greater than ten meters). These cores are included in this volume for two reasons, First, these carbonate shelf margins provide much of the source material for the truly "deep" deposits of the basins beyond. And secondly, within the ancient reef literature, anything below fair-weather wave base is often referred to as "deep".

Seven cores were drilled vertically into the shelf margin at Cane Bay (Fig. 1). Seven others were drilled horizontally into the steep reef flanks of Salt River submarine canyon (Fig. 1). All cores were taken with a diver-operated hydraulic drill similar to one described by

MacIntyre (1975). Radiocarbon ages are uncorrected for either compositional differences or recent atmospheric changes. Because all the samples are coral, these effects essentially cancel one another out (M. Tamers, Beta Analytic, pers. commun.).

For ease of discussion, framework is subdivided into four descriptive categories. These include: 1) fresh coral, 2) encrusted samples, 3) bioeroded samples, and 4) cemented sediments. While this is an admittedly simplistic classification, it does provide a convenient basis for organizing the discussion. Examples of each style of framework preservation are provided for each site, and some generalized about their distributions are made.

Also included are discussions of reef history in each area, and the factors most influential in that development. Of particular importance will be the styles of reef accretion seen at each site. The location of both areas adjacent to deeper water has imparted a unique style of accretion on the reefs, and the patterns are somewhat different from what would be expected from our knowledge of shallower reef systems.

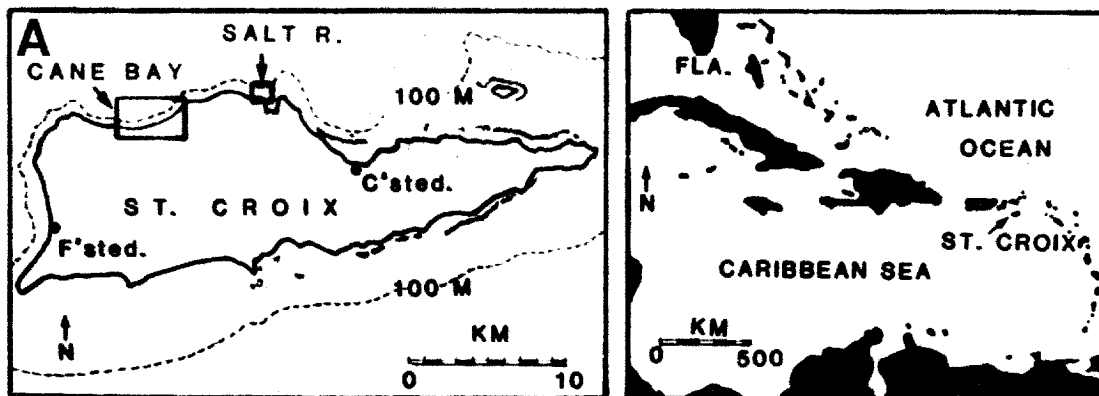
SALT RIVER

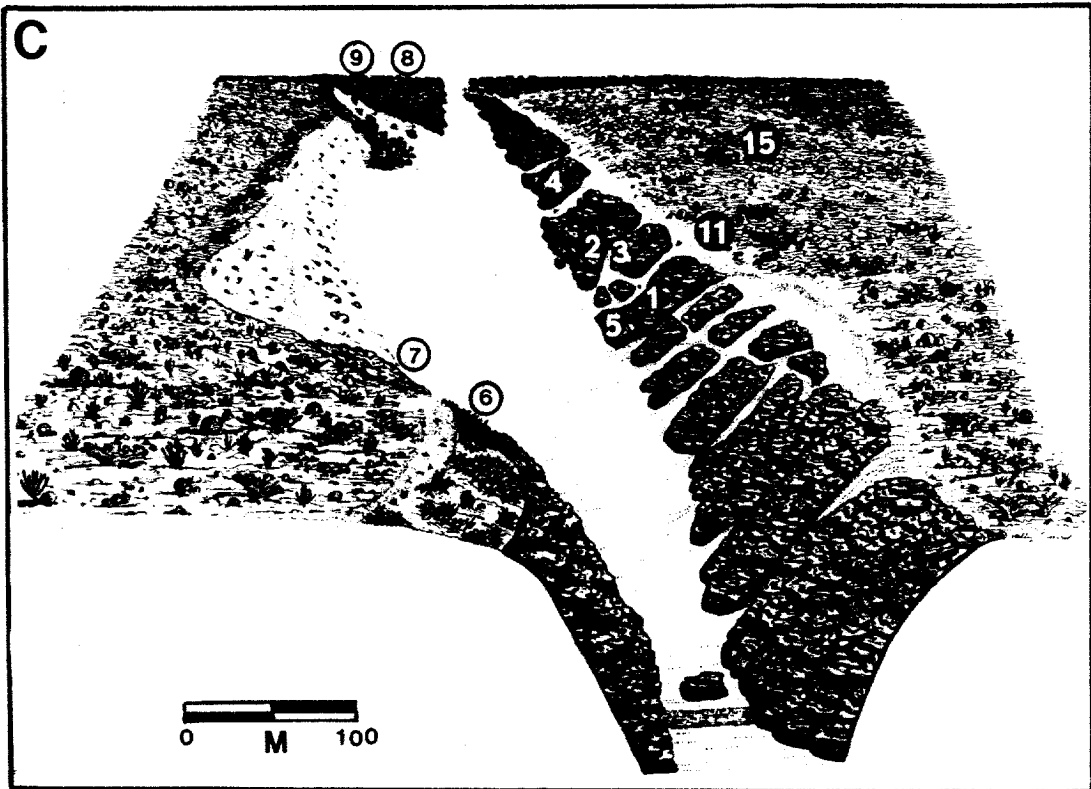
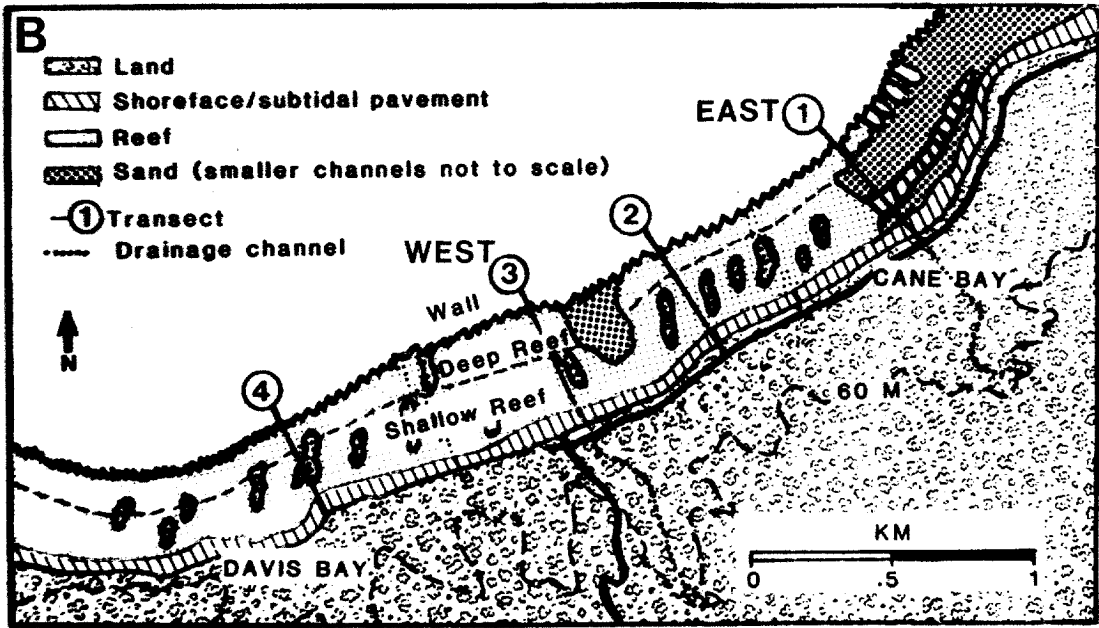
Salt River submarine canyon is located midway along the north shore of St. Croix (Fig. 1). The canyon head is separated from an estuary/bay complex by a narrow barrier reef that formed 5-6,000 years ago. The canyon extends northward to a depth of approximately 100 m, where it joins the steeper insular slope (Fig. 1C).

The canyon walls were formed by Holocene reef growth, and canyon morphology is closely tied to the westerly movement of sediments by the Trade Winds (Hubbard, in press). The eastern canyon margin is dominated by a sediment-veneered slope, nearly devoid of coral cover. In contrast, the west wall is covered by much heavier growth, a response to lower levels of bedload sedimentation.

FIGURE CAPTIONS

Figure 1. A. Map showing the location of Salt River and Cane Bay on St. Croix. The location of the island in the Caribbean Sea is also shown. B. Core locations at Cane Bay. Cores 1-3 are along Transect 3 (west). Cores 4-7 are along Transect 1 (east). C. Three-dimensional sketch of Salt River submarine canyon. The view is looking up the canyon toward the south. Note the steep face on the west (right) wall, and the more gently sloping pavement on the eastern side. Sediment moves in a westerly direction in response to the Trade Winds, and sedimentation rates are much higher on the eastern canyon margin. Core locations are shown by the circled numbers. After Hubbard and others (1981).





A total of fourteen cores were taken from the Salt River area. Six cores were drilled vertically into the reefs surrounding the canyon (Fig. 1). Seven cores were drilled horizontally into the steep reef faces of the canyon head (Cores SR-1 to 7; Fig. 1C). These horizontal cores record the lateral accretionary history of the canyon and will be the main topic of discussion.

Cores are located on Figure 1. Logs for the seven horizontal cores are given in Figures 2 and 3. The accretionary styles in the cores fall into two distinct categories, controlled primarily by the location of a core on either canyon wall. Cores from the west wall (typified by core SR-5, described below) show intervals of reef framework separated by large, open or sediment-filled voids. Cores from the east wall show alternations on a smaller scale, reflecting the higher rates of sedimentation as discussed later.

CORE SR-5

This core was drilled into the western canyon wall at a water depth of 30 m (Fig. 1). The hole was inclined slightly below horizontal, so that it reached an estimated depth of 35 m below sea level at its deepest penetration (24 m). This core shows a variety of fabrics ranging from fresh, unaltered coral to totally cemented sediment with no recognizable framework left from the original reef. A detailed log of Core 5 is given as Figure 3. Figure 4 is a photographic reproduction of the entire core.

A striking characteristic of Core SR-5 is the importance of open and sediment-filled voids. Average recovery was 32%, and only a portion of that was identifiable as coral. If this is extrapolated to the rock record, it raises interesting questions about our ability to discern in-situ reefs in the ancient. This area has been chosen as a long-term monitoring site for reef studies by the Federal government. Yet, what is preserved in the cores is a series of well-worked corals and coralline algae separated by substantial voids. Whether these voids are infilled

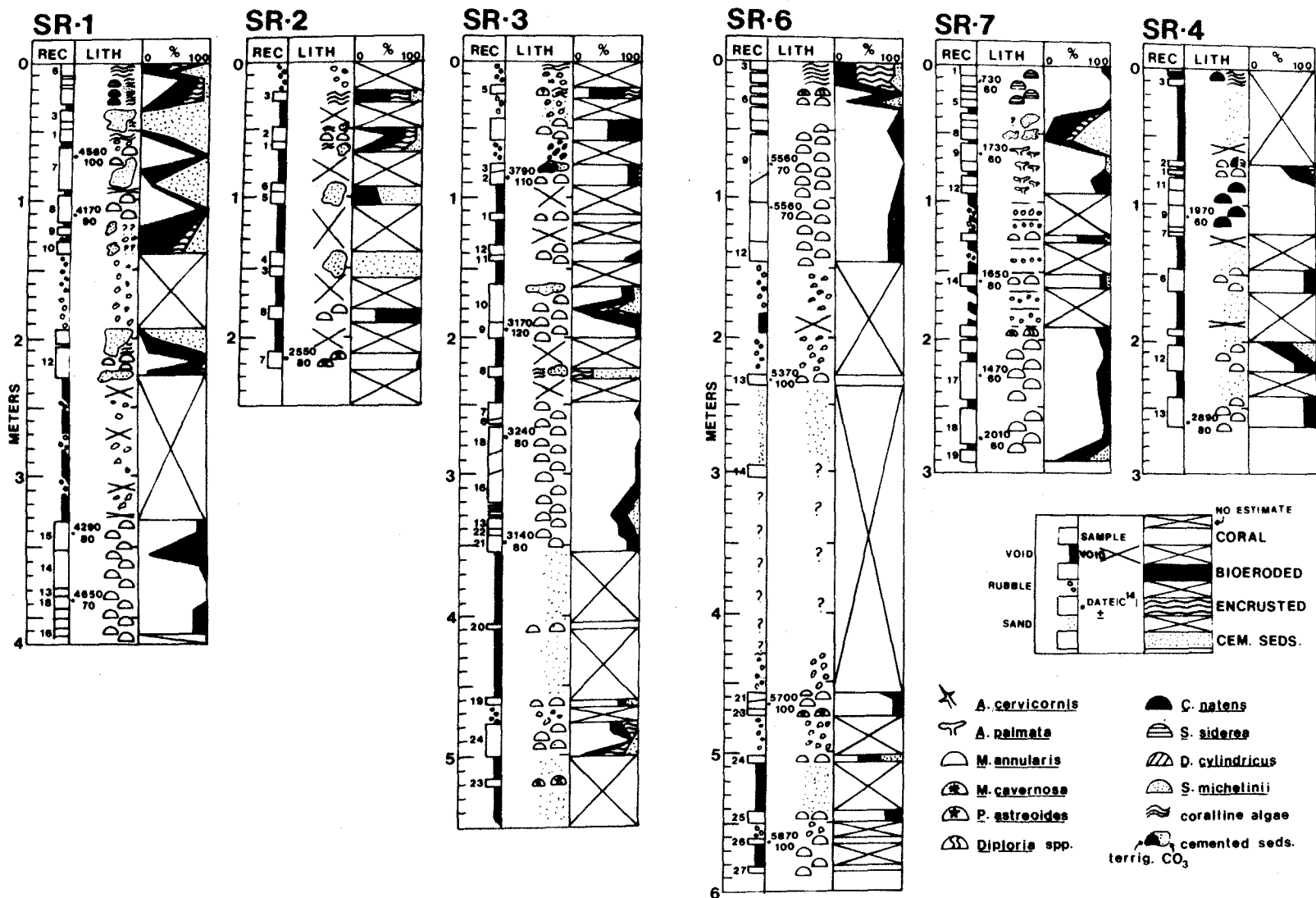


Figure 2. Logs for six horizontal cores from Salt River submarine canyon. Actual core recovery is shown in the left-hand column. Interpretations of core lithology, based on actual recovery and drilling notes, are shown in the center. The right-hand column summarizes estimates of original framework (coral), bioerosion, encrustation, and cemented sediments in the recovered core samples. Core penetration (horizontal) into the canyon walls, as well as radiocarbon ages of various samples are also shown.

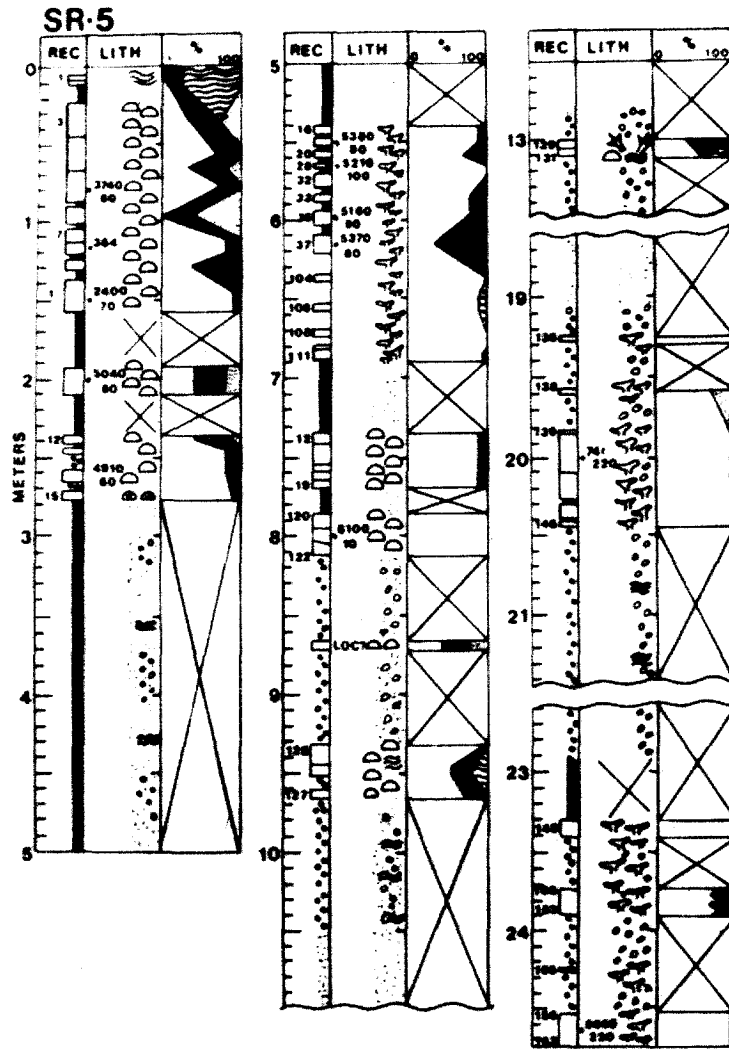


Figure 3. Log for Core SR-5 from the west wall of the canyon. This was the longest core taken in the study. It was also retrieved from the greatest water depth (30 m). Symbols are the same as in Figure 2. Note the importance of open and sediment-filled voids, as well as the high degree of reworking of the existing framework.

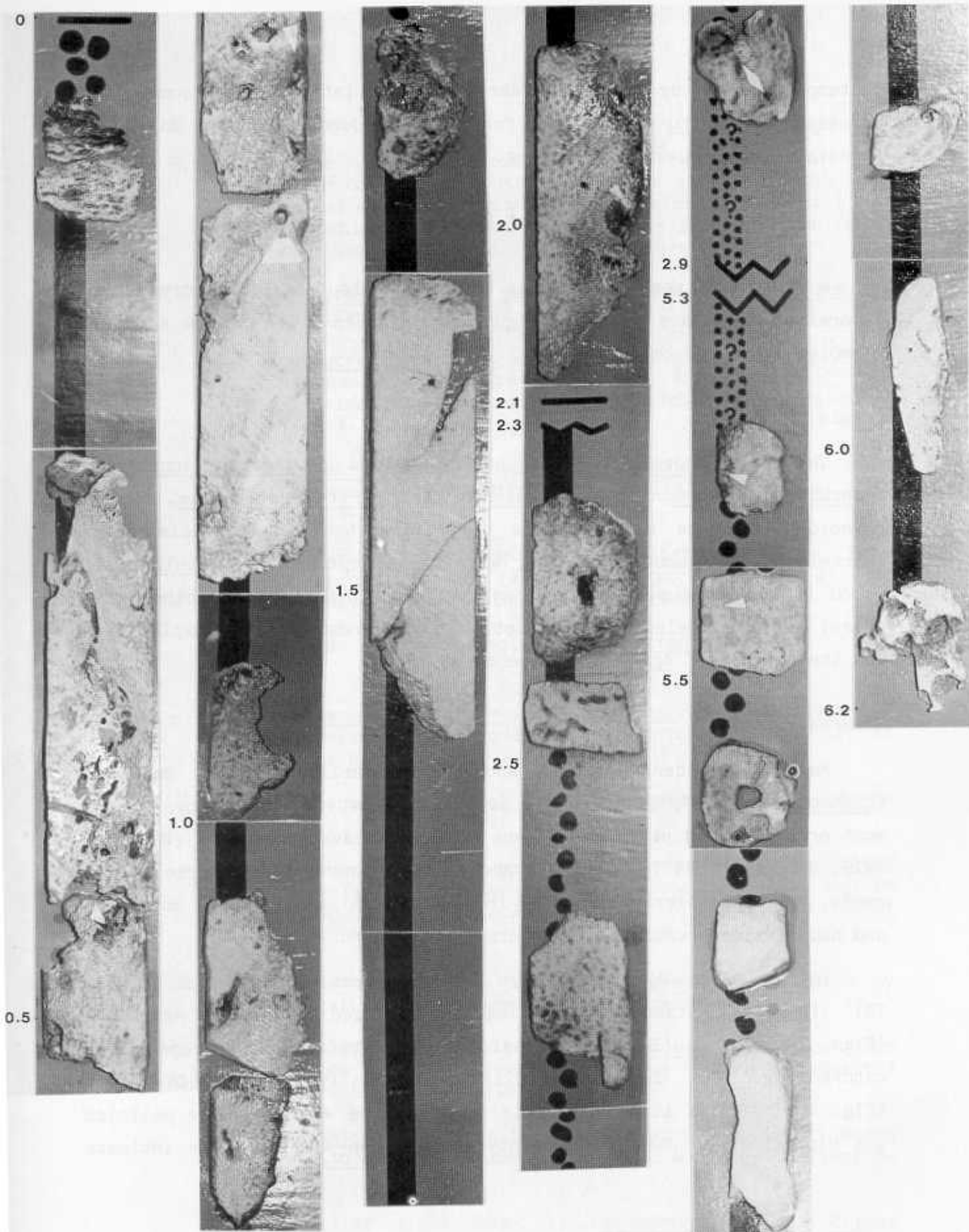


Figure 4. Photographic log of the outer 6.2 m of Core SR-5. Individual pieces have been placed in their actual positions within the core. Distances (in meters) are provided for reference to Figure 3.

contemporaneously by bioeroded debris or at a later time by some other process, an in-situ reef origin for such a sequence would be difficult to establish in an ancient setting.

Reef Fabrics

A variety of reef fabrics can be seen in the Salt River cores. Some general examples are given in Figure 5. Figures 6 and 7 show specific examples discussed below.

Corals

The major corals in the cores include Montastrea annularis, Siderastrea siderea, Acropora palmata, and Porites astreoides. These coincide with the major corals inhabiting the canyon walls today (Birkeland and Neudecker, 1979), with the exception of Agaricia spp., which is conspicuously absent from the cores. Hubbard and others (in press) proposed selective destruction by bioerosion as an explanation for the absence of Agaricia in the cores.

Bioerosion

Major bioeroders include sponges (primarily Cliona), molluscs (Lithophaga), and polychaete and serpulid worms. Cliona is by far the most prolific, and plays a dominant role in excavating modern (Rutzler, 1975; MacGeachy, 1977; Moore and Shedd, 1977) and ancient (Warne, 1977) reefs. Cliona galleries occurred in 41 of the 61 samples from core SR-5 and had similar abundance in the other cores.

In some cases, the borings are fresh and remain open (Figs. 5A, 6A, 7C). In other instances, the borings are infilled by cemented sediments (Figs. 5B and C, 6B, 7B), occasionally identifiable as geopetal in nature (Fig. 5C). Sediment infills are typically pelloidal in nature (Fig. 6C). While it is difficult to determine whether these pelloids are biological or chemical (MacIntyre, 1983) in origin, their intimate

Figure 5. Core slabs showing typical styles of reworking within the Salt River Cores. The outer end of the core is to the left in this and all subsequent figures. Refer to Figures 1 and 2 for locations (1-3 = core 1, piece 3). The scale is in centimeters and millimeters in all figures.

- A. Montastrea annularis moderately bored by Lithophaga (L) and Cliona (C). Piece 7-17.
- B. Montastrea annularis with more extensive boring. Note the cemented sediment (S) infilling many of the galleries. The gray color is staining by Mg-calcite. Piece 1-12.
- C. Montastrea annularis with heavy Cliona (C) erosion. Note that some of the sedimentary infills are geopetal (G). Piece 1-7.
- D. Heavily reworked sample of Montastrea annularis. Note the coralline algae (A), numerous worm burrows (W), and extensive cemented sediment (S). Piece 5-3.
- E. Heavily reworked sample of Montastrea annularis. Piece 3-10.

- Figure 6.
- A. Montastrea annularis with Lithophaga (L) and Cliona (C) galleries. Note the encrusting worm (W) in one of the larger Cliona galleries. Piece 7-17.
 - B. Sedimentary infill of Cliona galleries (arrows). Piece 1-12.
 - C. Photomicrograph of cemented sediments infilling Cliona galleries. At least two generations of infill can be distinguished by color. Most of the very light fragments are Cliona chips. Piece 5-31.

- Figure 7.
- A. Sample encrusted by coralline algae (A) and bored by several species of worms (W). Piece 1-2.
 - B. Cemented sediment (S) infilling Cliona galleries. The lighter and darker sediments were deposited separately. Piece 1-11.
 - C. Montastrea annularis (note calyx structure-arrow) bored by Cliona (C) and numerous Serpulid worms (W). Piece 5-9.
 - D. Coralline algae bored by Lithophaga (L) and Cliona (C). Note the remaining shell of the boring mollusc. Piece 6-4.

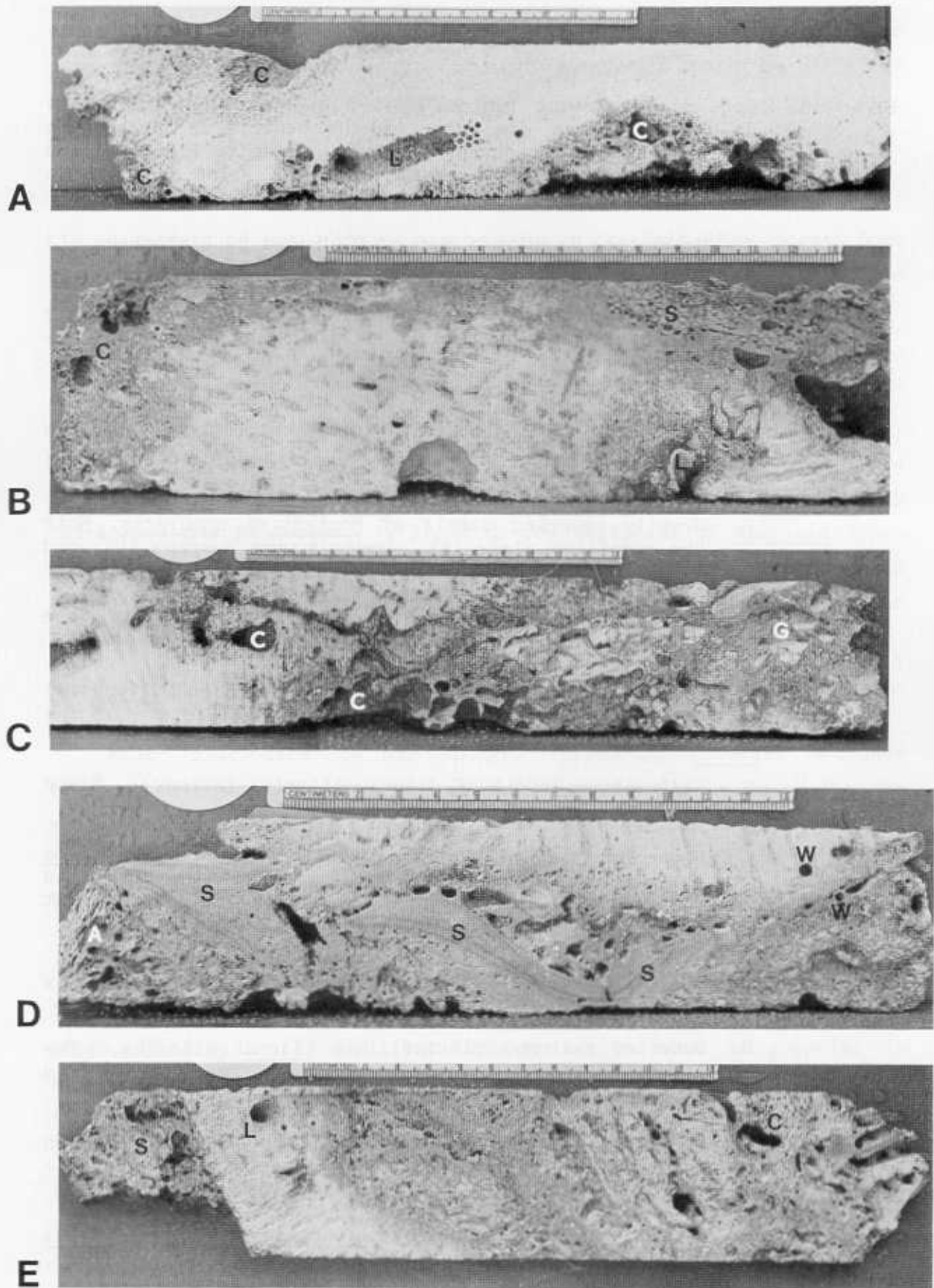
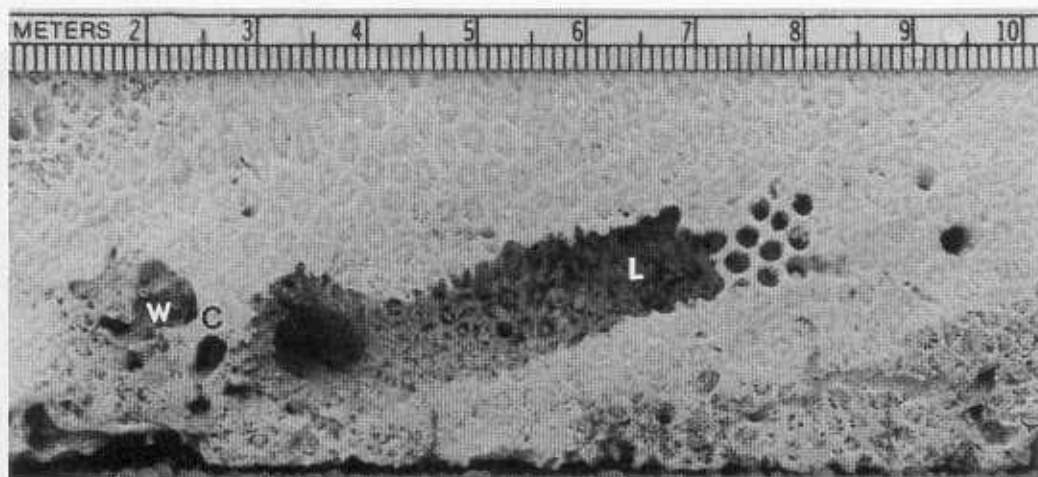


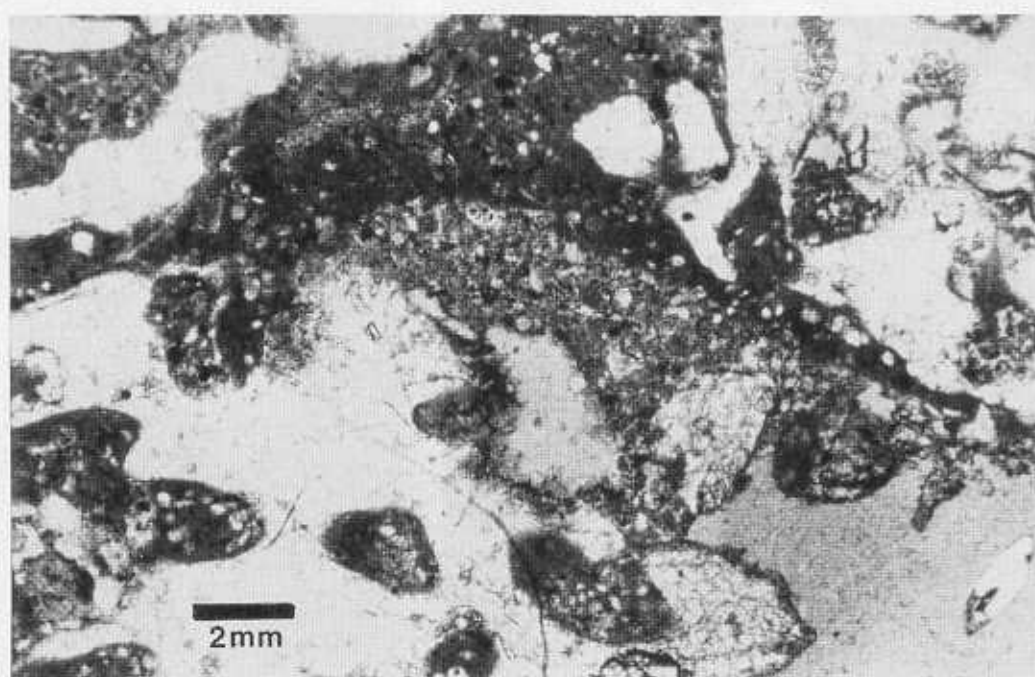
Figure 5



A



B



C

Figure 6

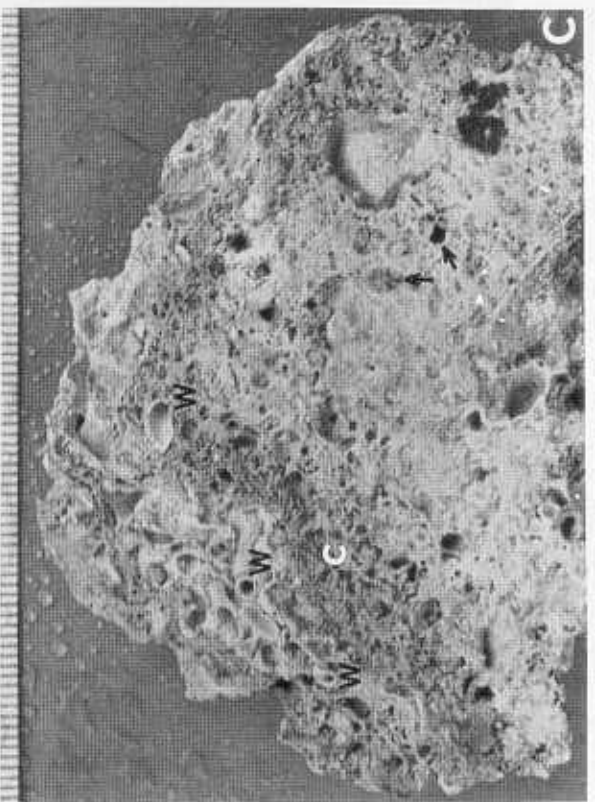
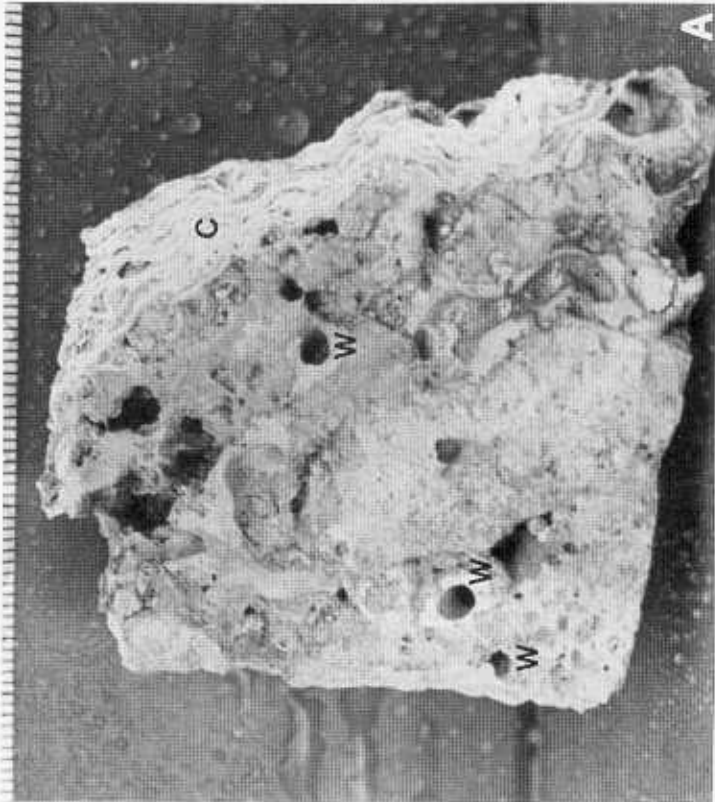
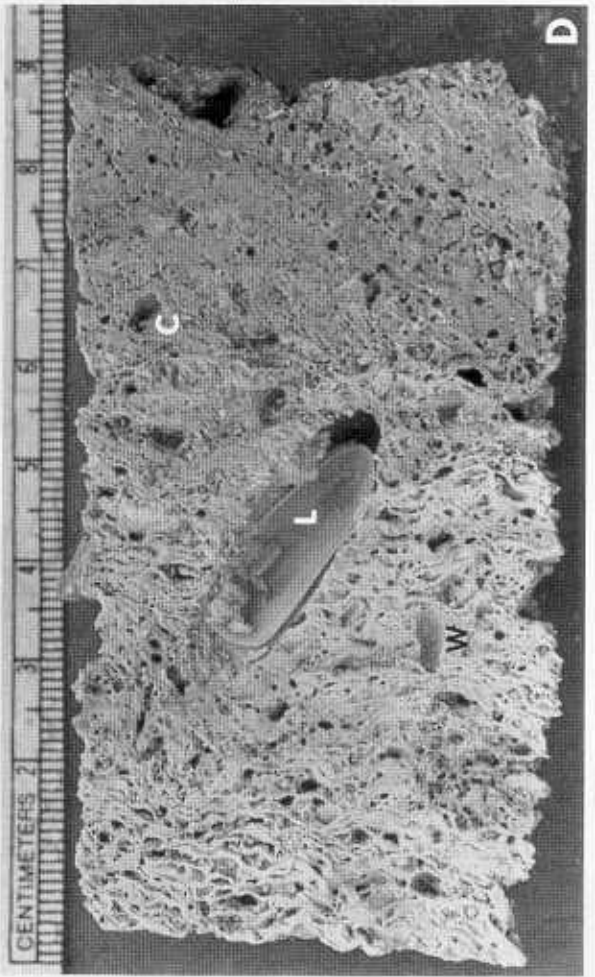
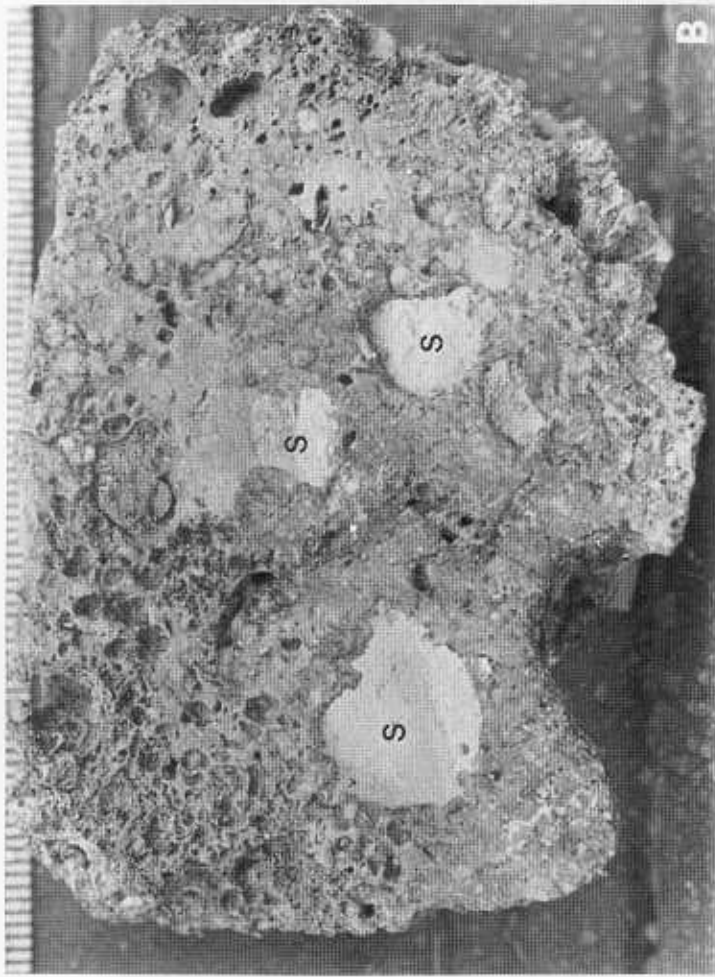


Figure 7

association with identifiable Cliona chips suggests that they are fecal by-products of the sponges.

Less abundant are borings by molluscs (Figs. 5A and B, 6A, 7D) and worms (Figs. 5D, 7A and C). Modification by these organisms represented less than 20% of the bioerosion seen in the cores.

An additional bioeroder that is not well represented in the cores is the urchin Diadema antillarum. Along with various grazing fish, these urchins remove more carbonate material than any other single organism (Ogden, 1977; Stearn and Scoffin; 1977). As they remove entire areas of substrate, and do not leave galleries to record their activity, their importance can only be inferred. Given their prolific nature on Caribbean reefs in general, however, it is safe to assume that they have played a profound role in developing the sequences recorded in the cores.

Encrusting organisms

The major encrusting organisms include coralline algae (Fig. 7A and D) foraminifera (especially Homotrema rubrum), and several species of vermetid worms and gastropods (Fig. 6A). The outer sections of most of the cores contain significant proportions of coralline algae (Fig. 7D), which marks a dramatic slowing of reef accretion between 3000 and 5000 YBP. This outer coralline layer may record a deterioration of reef conditions after that time. It is difficult to assess how active these corallines were, as their production is often nearly offset by grazing herbivores. The thin cap seen in all the cores probably represents considerably more calcification than is recorded in the remaining reef framework.

Cemented sediments

Cemented sediments occur in two forms. In one type, sedimentary detritus backfilling the open reef framework is bound by marine cements (Fig. 5D and E). Most of these sediments are probably secondary

deposits that occurred after the reef had accreted beyond the point of infilling. Cementation was undoubtedly facilitated by the high degree of interconnection that occurs within the reef framework (commonly, water pumped into the hole during drilling could be seen exiting the reef several tens of meters away in any direction).

Cemented sediment also occurs on a much smaller scale. Usually, finer-grained material fills small-scale cavities created by bioerosion (Figs. 5B and C, 6B, 7B). In some instances, numerous generations of sedimentation and cementation can be seen in a single sample (Fig. 7B). The dominant fabric is pelloidal sediment bound by micritic cements (Fig. 6C).

Cements

In general, the cores are surprisingly free of any secondary cements. This may be in part related to the turbid environment within the canyon head. The most common cement is Mg-calcite, which is reflected as a gray discoloration of the parent material in hand specimen. These cements form only very thin rims within voids unless they are associated with cemented sediments. Isolated examples of isopachous rims and syntaxial overgrowths by aragonite can be seen, but they are rare.

Styles of Reef Accretion

Core data indicate an extremely complex growth history for the walls of Salt River submarine canyon. Figure 8 summarizes the reef-accretion styles that dominate the margins of the canyon. Along the west wall, shelf-derived sediments are carried away from the canyon, and reef accretion has produced a complex and near-vertical slope. Hubbard and others (in press) showed that the dominant mechanism responsible for reversing date patterns seen in the cores (see Figs. 2 and 3) involves the breaking away of sections of the shallower reef as the underlying substrate becomes incapable of supporting the oversteepened reef face

(Fig. 8A). This mechanism is largely responsible for the surprisingly high lateral accretion rates (2.6 m/1000 yrs) measured in Core SR-5 at a water depth of 30 m.

Displaced reef material can range from coral-head size fragments to major blocks meters on a side. On the west wall, there are many large blocks, apparently moving down the steep reef face today. In the cores, at least two of the segments of displaced coral are part of meter-thick, continuous sequences.

Also important are pinnacle growth and processes that "weld" sections of reef together (Fig. 8A). Overgrowth by platy corals (Fig. 8B) can also cause localized caverns. These processes collectively result in a core pattern, on the west wall, of larger sections of framework separated by significant intervals of rubble or void (Cores SR-1 to 5).

On the east side of the canyon, shelf-derived sediments are moved into the canyon in high amounts, especially along the shallower inner margin (Hubbard, in press). The slope here is lower than on the west wall, and rapidly alternating episodes of coral growth and sedimentation dominate the accretionary style (Fig. 8C). The higher sedimentation rate is reflected in a more evenly-distributed occurrence of sand and rubble throughout the east wall cores, as opposed to the larger sediment-filled vugs and caverns to the west. Also, because of rapid burial of the inner east-wall reefs at about 1500 YBP, subsequent reworking was prevented, and some of the best coral preservation seen anywhere in the canyon occurs in Core SR-7 (Fig. 2).

Reef History

Accretion on the walls of Salt River submarine canyon began at least as early as 10,000 YBP. It appears that the Acropora reef that established itself on the western flank of the developing canyon was able to keep pace with the rapid rate of sea-level rise at that time (nearly 10 m/1000 yrs, Neumann, unpubl. data).

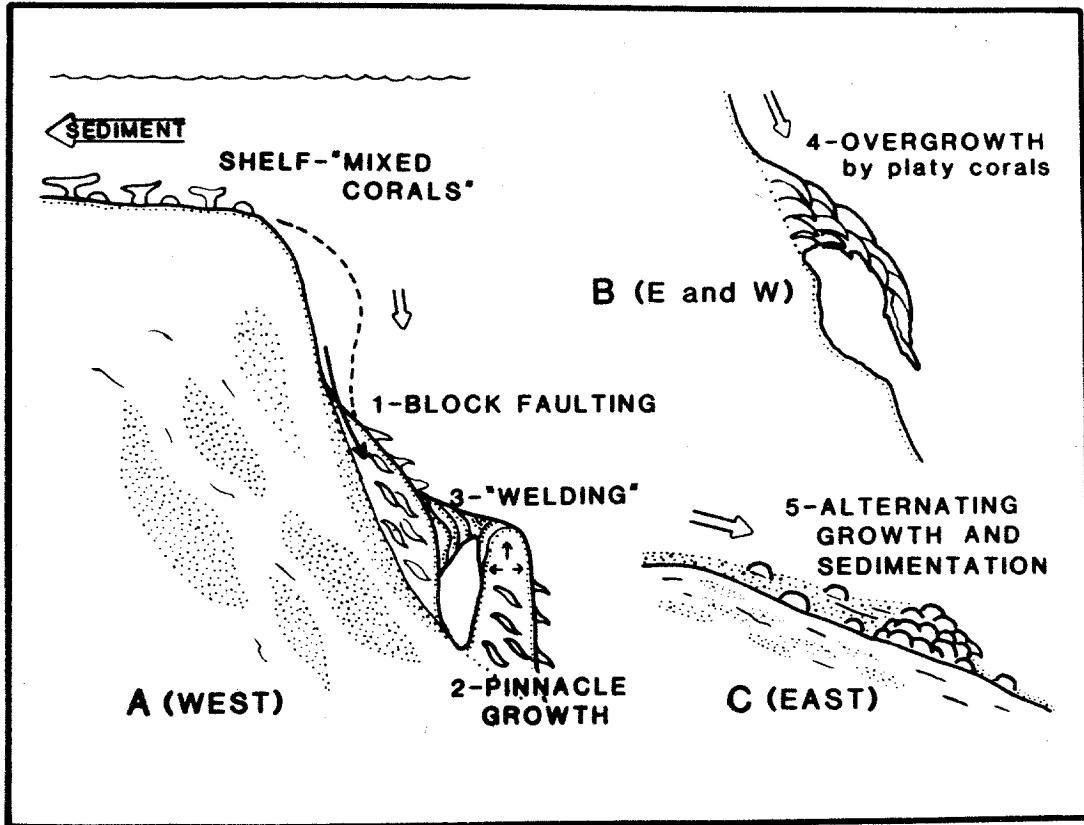


Figure 8. Styles of accretion in Salt River submarine canyon. Along the west wall, sedimentation is lower, and a steeper wall is dominated by downward-falling reef blocks (A-1), pinnacle growth (A-2), and cavern formation by overgrowth of platy corals (B). Along the eastern margin, high rates of bedload sedimentation inhibit coral growth, and bottom slope is limited by the angle of repose of the sediments. Coral growth alternates with periods of sediment burial (C). From Hubbard and others (in press).

It is assumed that the 9,600 year old reef cored at SR-5 is continuous with one encountered at the base of core SR-11 on the adjacent shelf (Figs. 1 and 9). Given the east-to-west sediment transport that probably occurred throughout the development of this reef, it is unlikely that the 20 m of vertical accretion separating the two cores could have been accomplished by any means other than active Acropora growth.

The period between 10,000 and 7500 YBP was marked by active reef accretion, both laterally and vertically (Fig. 9 A and B). By 7500 YBP, significant relief had developed along the west wall of the canyon. Debris generated from the active reef on the shelf (SR-11) inhibited reef development along its deeper flanks (SR-5).

This continued until about 6000 YBP, when the shelf-top reef reached sea level (Fig. 9C). In part, the inability of the reef to grow above sea level slowed reef development at SR-11. Probably more important, however, was the flooding of Salt River estuary at about this time. The quiet environment created by the newly formed barrier reef (recorded in cores SR-8 and 9, Fig. 1) would have allowed ponding of fine-grained sediments, and periodic sediment flushing onto the shelf-top reefs, as still occurs today.

With the sudden cessation of reef development (and debris generation) near SR-11, the reef at SR-5 was able to reestablish itself (Fig. 9C). The deeper location of this reef was apparently able to buffer the effects of increasing fine-grained sedimentation, and a reef dominated by deeper-water corals remained at site SR-5 until 3800 YBP (Fig. 9D).

Eventually, the effects of sedimentation from the developing estuary overcame the reefs throughout the canyon. Cores SR-8 and 9, in the barrier reef fronting the eastern half of the estuary, indicate initial enclosure of the bay at about 5-6,000 YBP. By 5800 YBP accumulation on the shelf-top reef at SR-11 had already slowed or stopped. Between 5500 and 3700 YBP, accretion rates on nearly all the

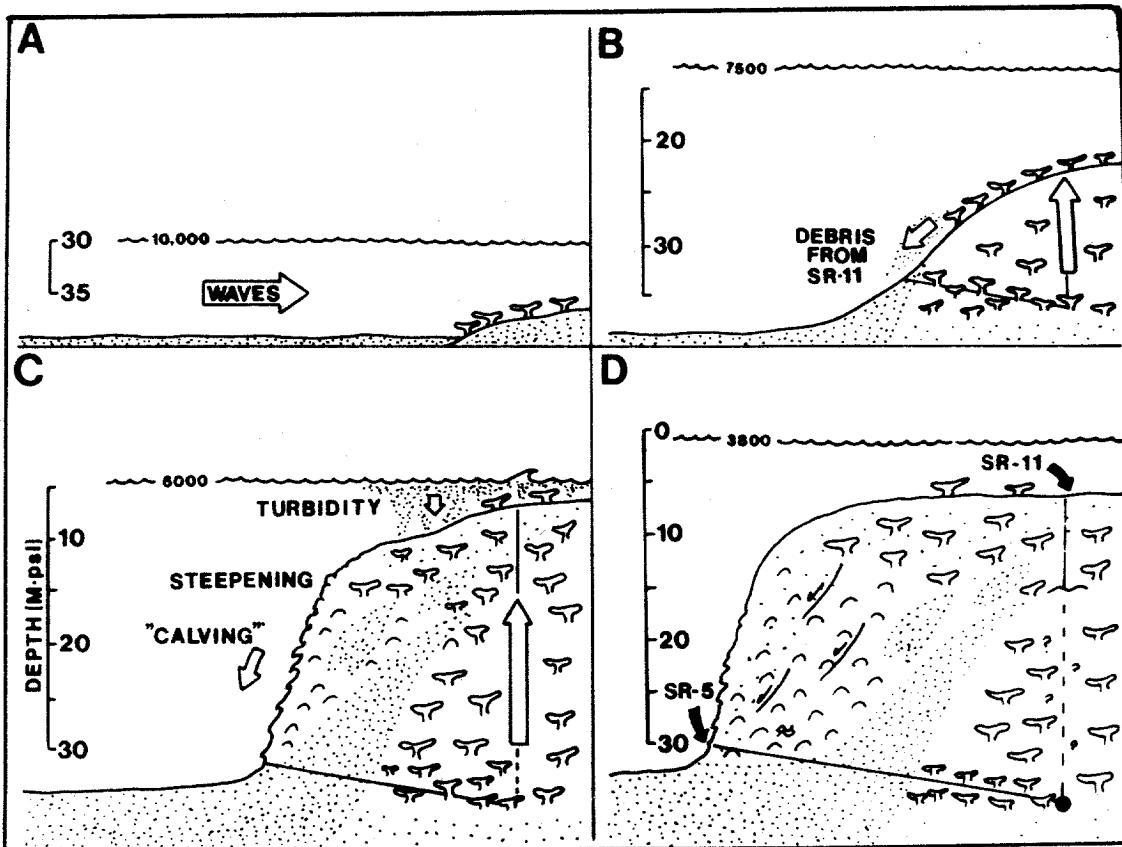


Figure 9. Inferred history along the west canyon near core sites SR-5 and SR-11 (Fig. 1C). Reef accretion started as early as 10,000 YBP (A). By 7500 YBP debris from an upward-growing reef at SR-11 buried the reef at SR-5 (B; also, see log in Figure 3). Around 6000-6500 YBP Salt River estuary was probably forming (based on preliminary core data from cores SR-8 and 9; Fig. 1C). Fine-grained sediments from the bay appeared to have overcome the reef at SR-11 at about this time. The decrease in debris from SR-11 allowed renewed accretion at site SR-5 (C). This lateral accretion dominated the west wall until ca. 3800 YBP (D), when outbuilding ceased, apparently a response to sedimentation as well.

reefs on either canyon wall had dramatically dropped, and less than one meter of accretion has occurred since that time (Fig. 10). Between 2500 and 1700 YBP, the reefs in the three remaining cores had all succumbed to the increased levels of turbidity.

Oddly, the last area to be seriously affected was the sediment-stressed eastern margin of the canyon (Core SR-7, Fig. 2). This area is less turbid than the west wall today, but it is subject to much higher levels of bedload sedimentation than anywhere else in the canyon. The more-recent demise of these reefs may indicate that the high levels of sedimentation experienced in this area today have developed in only the past 1500 - 1700 years.

CANE BAY

Along the northwestern corner of the island, the insular shelf narrows to a minimum of 200 m (Fig. 1). The shelf edge occurs at depths ranging between 25 and 90 m. On the core transects, water depth at the shelf edge is approximately 30 m. From that point, the bottom drops to oceanic depths (4-5000 m) at an average slope approaching 45°.

The dominant carbonate-producing organisms on the reef are the scleractinean corals Montastrea spp. and Agaricia spp., along with several species of coralline algae. Also present both on the reef and in the cores are Acropora palmata, Copophyllia natens, Dendrogyra cylindricus, Diploria spp., M. cavernosa, Porites astreoides, Siderastrea spp. and Stephanocoenia michelinii. Coral diversity is much higher both in the cores and on the reef at Cane Bay, compared to Salt River. Notably absent from the reefs at Cane Bay is the green alga Halimeda, usually found in high abundance elsewhere in the Caribbean.

Seven cores were drilled along two transects across the shelf (Fig. 1). These record a succession on reefs that developed in response to the latest Holocene sea-level rise. Generalized logs for all the cores are given in Figure 11. A photographic log of core CB-4 is

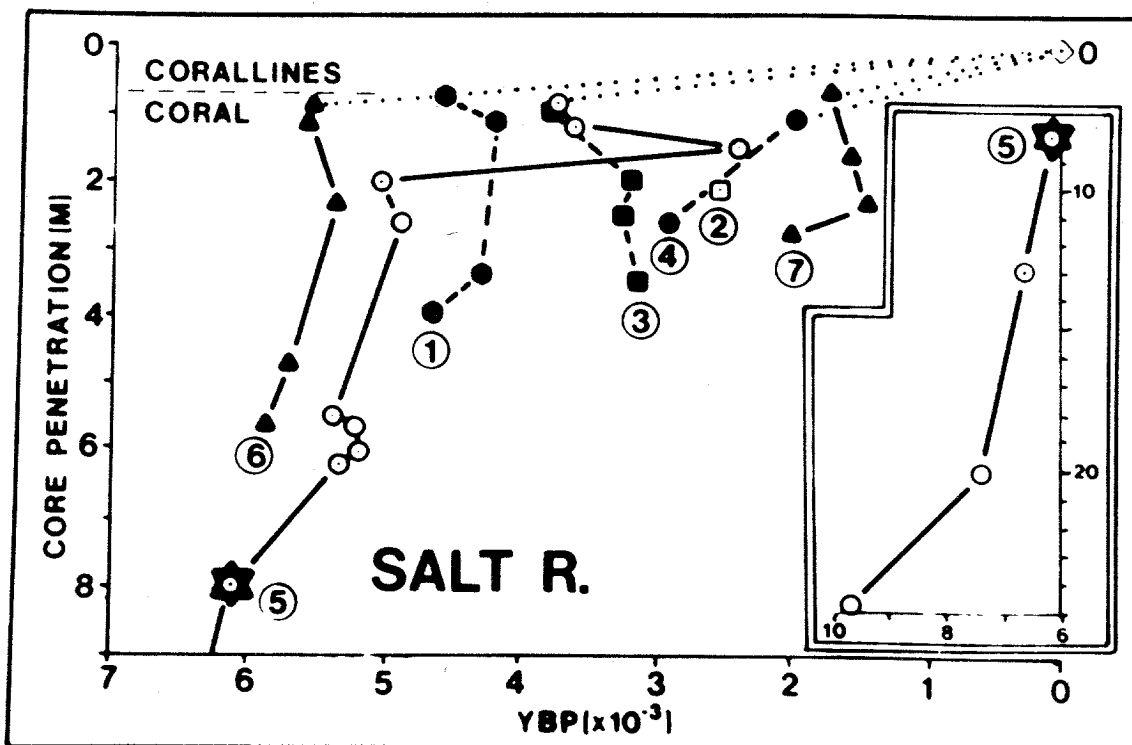


Figure 10. Graph of reef accretion in Salt River submarine canyon. Note the dramatic drop in accretion at about one meter into the cores (the dotted lines are inferred, assuming a surface date of 0). The timing of the transition from coral to coralline algal growth at each site is presumably a function of sedimentation levels in each area. The periodic reversals in accretion (e.g. SR-5 at ca. 5300 and 2-3000 YBP) reflect displaced reef blocks.

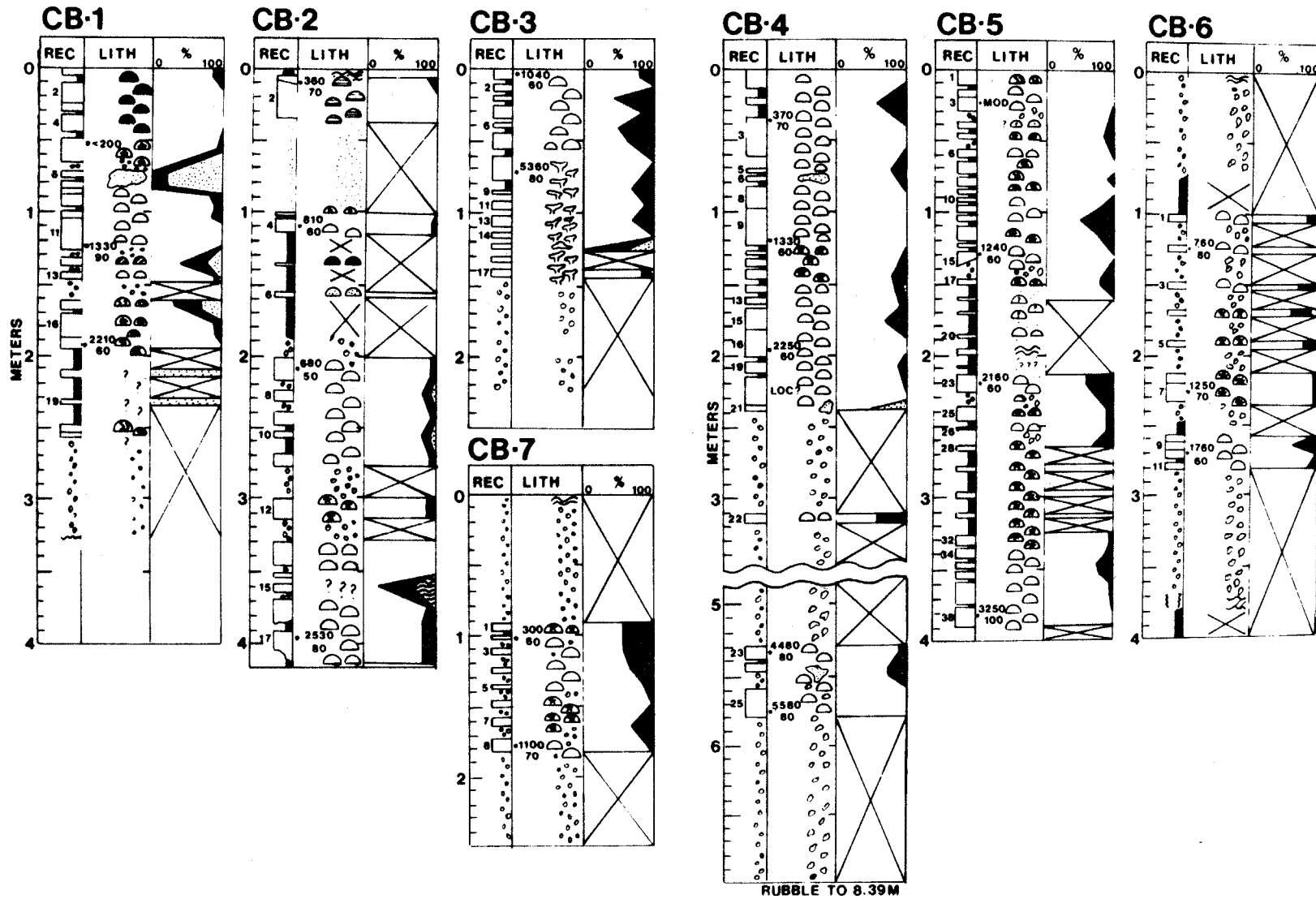


Figure 11. Logs for seven vertical cores from Cane Bay. Symbols and notations are the same as for Figure 2.

included as Figure 12. In general, the Cane Bay cores showed a dramatically lower amount of reworking than did the Salt River cores (Fig. 13). The major form of framework modification is bioerosion, primarily by Cliona (Fig. 14). Surprisingly little evidence of major encrustation was seen in the cores. Vermetids were occasionally seen on exposed surfaces, but were almost never encountered in the core slabs.

The reason for the difference in the degree of reworking is unclear, but it may be related to slower coral-growth rates at Salt River due to higher levels of turbidity. It may also be related to the higher wave energy at Cane Bay (the canyon head is much more sheltered due to both its location and orientation). This relationship is supported by the higher degree of bioerosion in the cores from the more-sheltered eastern portion of Cane Bay, which is subject to more frequent episodes of high turbidity than on the shelf to the west.

Accretionary Styles

The percent of recovered framework in the Cane Bay cores was similar to that for Salt River (31% vs 32%, respectively). Accretionary sequences at Cane Bay can be divided into three categories: 1) continuous accretion, 2) intermittent accretion, and 3) interrupted accretion.

Continuous accretion

The cores near a prominent slope break at 7-12 m show a history of reasonably continuous accretion since initial reef colonization 3-4000 years ago. At core sites 1, 5 and 7, reef accretion proceeded at a consistent rate throughout the entire length of the cores (Fig. 15). Figure 12 is a photographic reproduction of Core CB-5. The deepest part of the core recovered fresh Montastrea annularis, dated at 3250 ± 50 YBP. It is impossible to determine exactly when this reef initially colonized, but based on other cores along the transect, it is likely that the reef is less than 5500 years old (see History below). The core shows gradual and apparently continuous accretion which continues today.

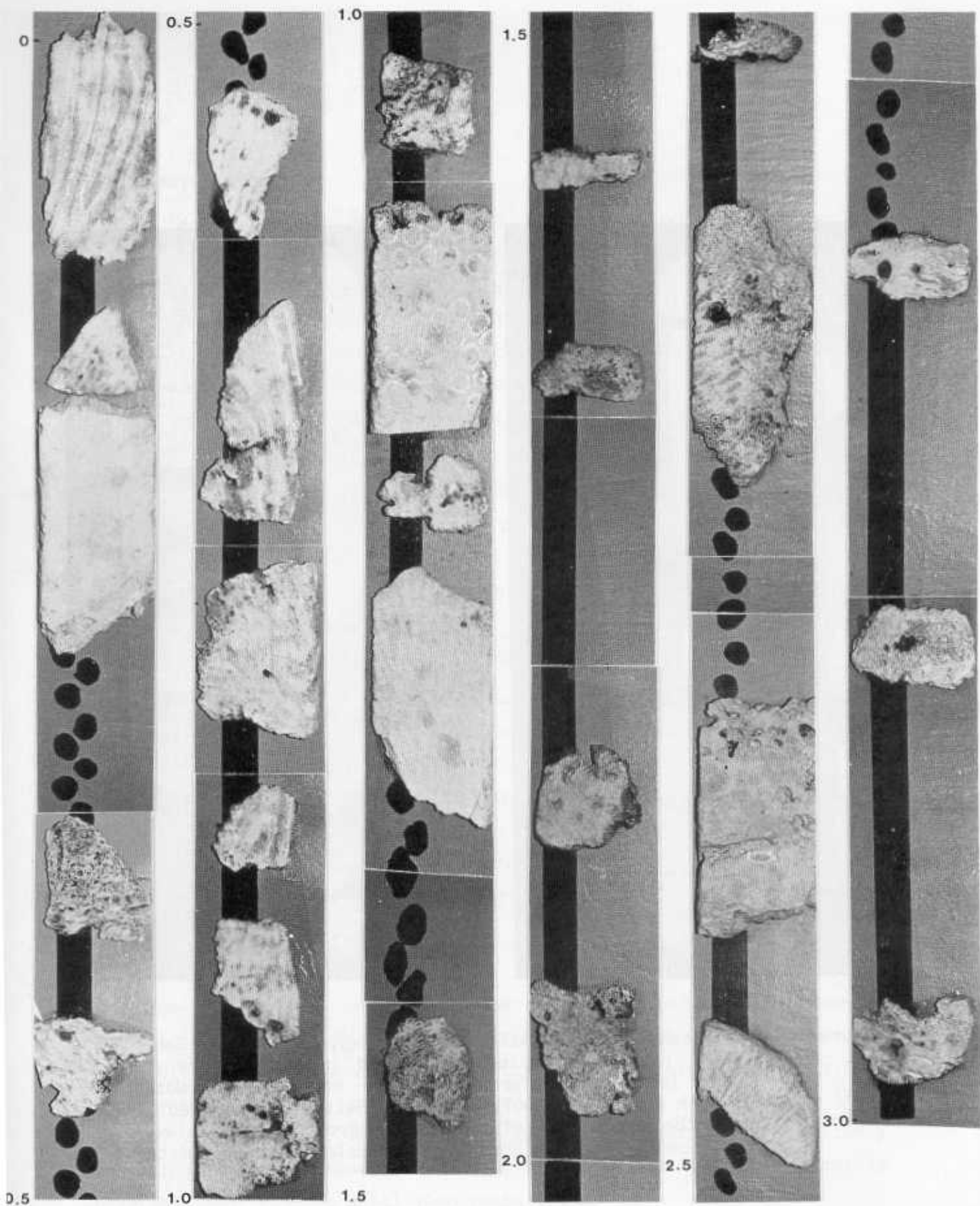


Figure 12. Photographic log of Core CB-5. Note the fresher appearance of the samples compared to Core SR-5 (Fig. 4). Also note the greater diversity of coral species. Refer to Figure 11 for details.

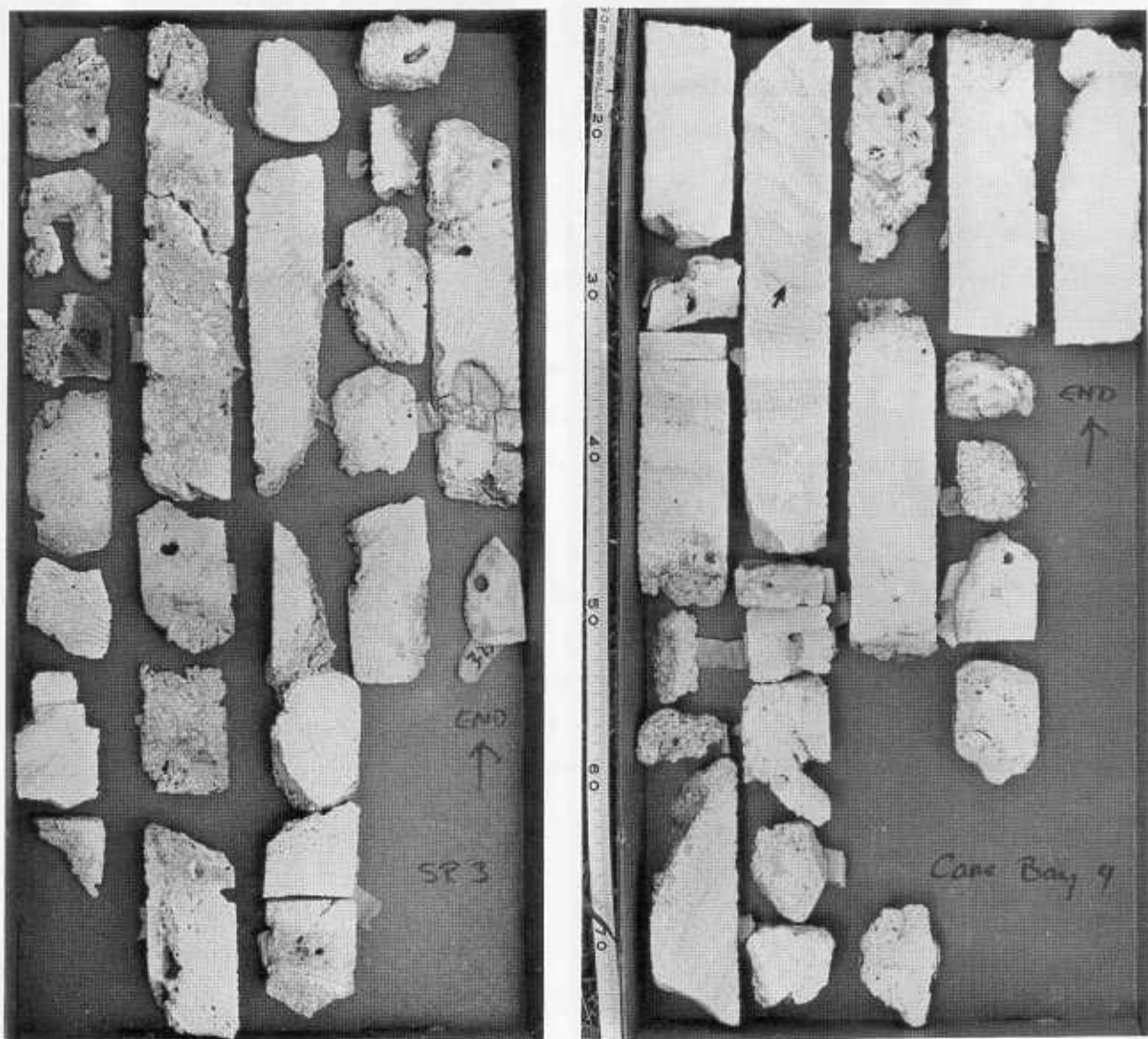


Figure 13. Core samples from Salt River (SR-3, left) and Cane Bay (CB-4, right). Samples are placed in order (core top to upper left) for reference to the core logs. Note the greater degree of reworking in the Salt River samples. Also note the expression of the annual growth bands in some of the Cane Bay corals (arrow). The scale is in centimeters.

Intermittent Accretion

In deeper water near the shelf edge, intervals of sedimentary debris become markedly more prominent (Cores CB-2 and 6, Figs. 11 and 16). The source of this material is presumably the accreting upslope reefs. While detrital material may be a secondary backfill of an already established reef, the pattern of alternating framework and rubble more likely reflects periods of intermittent reef accretion and burial, as well as the downward displacement of whole reef blocks from shallower water.

It is important to note that the entire reef was probably not undergoing periods of widespread accretion followed by wholesale burial. Rather, each core probably represents a specific set of conditions peculiar in their timing to that site alone. Each episode of rubble in a single core represents a time when sediment moved more actively through the specific area from which the core was taken.

These cores were in the deepest water on their respective profiles, yet they showed the highest rates of accretion for any cores (Fig. 15). As in the Salt River cores, the incorporation of detritus from the reefs above plays an important role in accretion along the deeper shelf margins. While the pattern is not as dramatic as that documented along the west wall of Salt River submarine canyon, the role of detrital influx from shallower reefs is nevertheless clear.

Interrupted Accretion

The landwardmost cores on either transect (CB-3 and 4) showed a dramatic hiatus in reef accretion between 5000 and 2500 YBP. Unlike the reefs with intermittent accretion, this pattern is interpreted as a bay-wide phenomenon that somehow affected an entire part of the reef community all at once. At site CB-3, an Acropora reef that was actively accreting suddenly stopped at 5300 YBP (Figs. 11 and 16). It ultimately reestablished, but not until 4000 years later.

Figure 14. Examples of reworking in the Cane Bay cores. Scale is in millimeters. A and D are at the same scale.

- A. Montastrea annularis bored by molluscs (M), worms (W) and Cliona (C). Piece 4-15.
- B. This piece is primarily various generations of cemented sediments (S). The lighter-colored sediments are younger. Piece 1-18.
- C. Acropora palmata bored by Cliona (C) and polychaete worms (W). Piece 4-24.
- D. Fresh (4-8, top) and bioeroded (6-10, bottom) M. annularis. Note the annual banding in the top sample. Most of the holes in the bottom piece are made by the boring sponge Cliona.

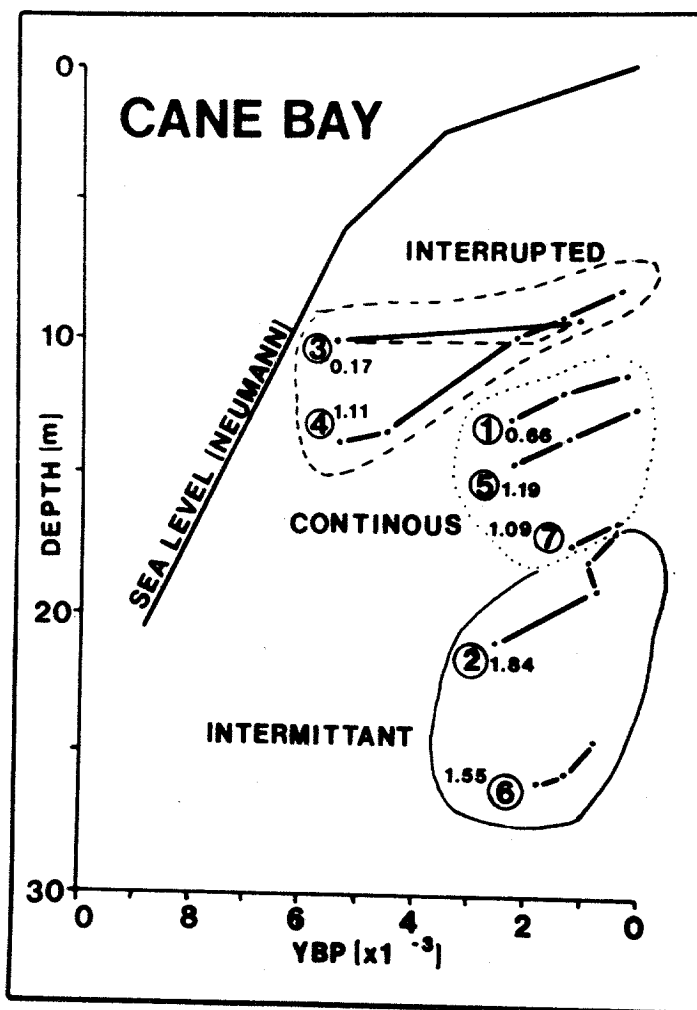


Figure 15. Reef accretion at Cane Bay. Rates in m/1000 years are shown. Also plotted is the Holocene sea-level curve of Neumann. Reef accretion is grouped as intermittent, continuous, or interrupted based on core data. Note that the highest accretion rates are associated with the deeper, intermittent reefs below the shelf edge (Cores CB-2 and 6). Much of this accretion is related to incorporation of rubble from reefs located upslope.

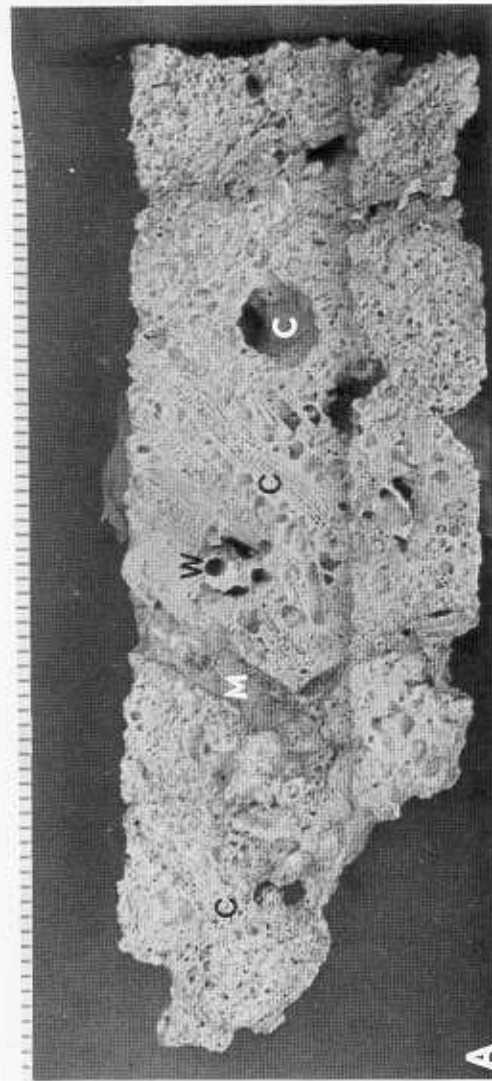
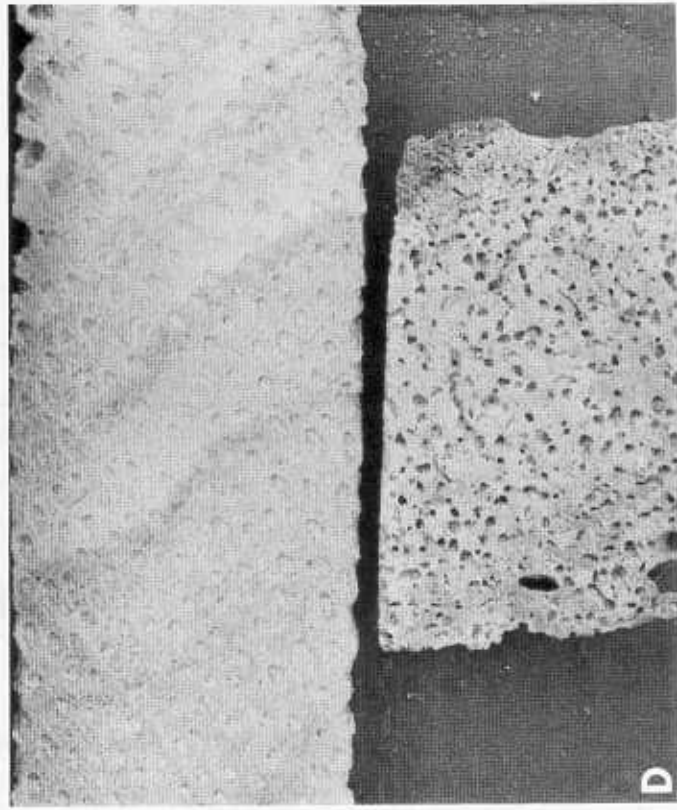
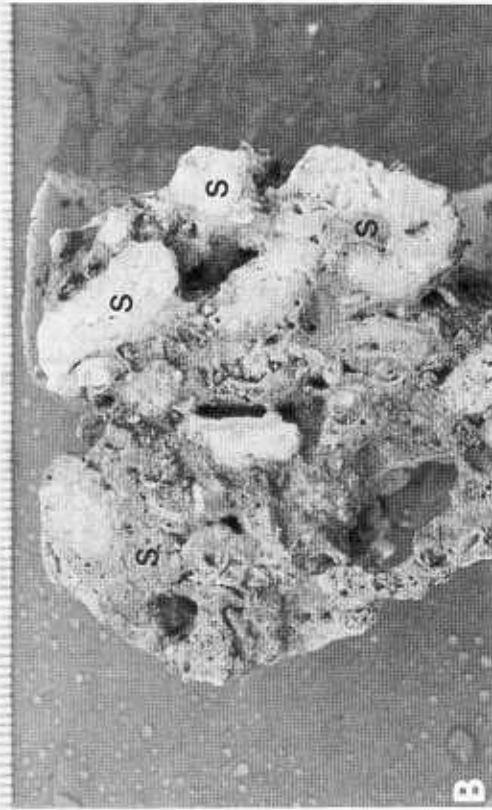


Figure 14

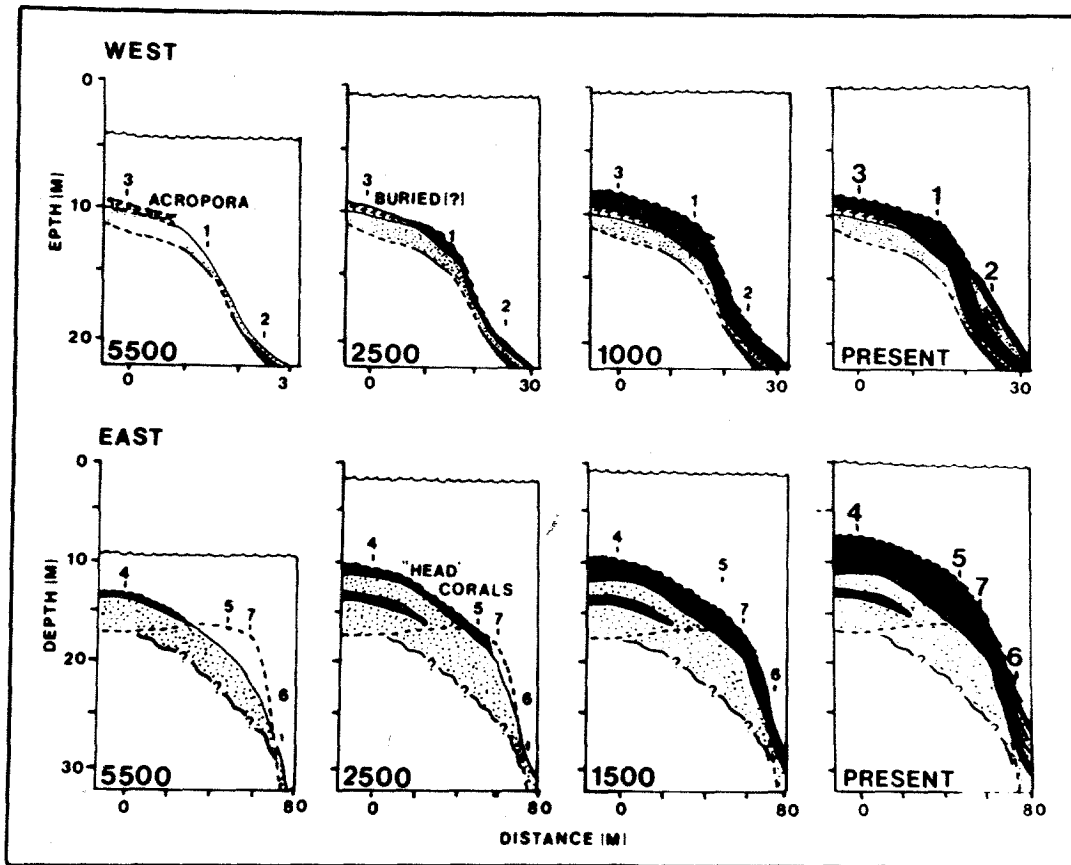


Figure 16. Inferred reef history at Cane Bay. At 5500 YBP reefs initially colonized on mobile rubble at the shallow end of both transects. Between 5500 and 2500 YBP active reef accretion apparently ceased. From 2500 YBP to the present, the reef showed reasonably continuous accretion. As the reef face steepened near Core 1, 5 and 7, increased calving of reef blocks and transport of smaller rubble from the shallower reefs are reflected in accelerated accretion in the deeper reefs (Cores 5 and 6, Fig. 15).

The reason for this hiatus can only be speculated. Adey and others (1977) noted a similar phenomenon along the south shore of St. Croix, and attributed it to increasing turbidity as rising sea level reworked the Pleistocene soil horizon. Alternately, it may represent an episode of intense grazing and bioerosion. A submerged nearshore pavement in eastern Cane Bay, which is underlain by fossil Acropora, yielded a date of ca. 5000 YBP. Sadd (1980) attributed this to bioerosion by Diadema which were present in high abundance during his study.

In core CB-4, a similar interruption occurred at about 4500 YBP (Fig. 16). In this case, however, the reef was dominated by M. annularis, and was clearly buried by rubble, probably from Acropora reefs accreting further up the profile (similar to the burial of the reef at SR-5 in Figure 9).

Reef History

Along both profiles, reef colonization occurred at about 5500 YBP on a mobile rubble substrate. Along the western transect (Fig. 16) this reef was dominated by Acropora palmata (core CB-3; Fig. 11). To the east, the reef was dominated by head corals, perhaps a response to a more turbid environment in that protected area of the bay. Shortly thereafter, accretion apparently ceased on both of these mid-shelf reefs, and was not reestablished until sometime between 1000 and 2200 YBP. As discussed above, the reason for this apparently widespread hiatus in these mid-shelf reefs is uncertain, but is probably related to some sort of localized decrease in the water quality along this portion of the shelf. Along the eastern transect, rubble in the interval above the initial reef in Core CB-4 indicates burial by debris from shallower reefs as a cause.

The recolonization of the shelf at about 2500 YBP was much more widespread than the initial one, and reefs extended to depths of at least 18-20 m. Once again, colonization occurred on a seemingly mobile substrate, contrary to the notion that corals require a more suitable

environment for settlement. Colonization of the deeper reefs in the eastern portion of the bay seemed to lag behind that to the west, again a possible response to more sheltered and turbid conditions toward the east. By 1500 YBP, widespread and continuous reefs covered the entire Cane Bay shelf (Fig. 16).

With the continued accretion of the shelf-edge reefs (cores CB-1, 5, and 7), the amount of biologically produced sediment gained importance. The periodic transport of this material into the deeper reefs (note higher percentage of rubble in cores CB-2 and 6, Fig. 11), coupled with the probable calving off of small blocks from the steepening reef front (note the anomalous 680 year old sample at a depth of 2 m into core CB-2, Fig. 11), resulted in a much lower percentage of original framework in the deeper cores.

Accompanying this decrease in preserved framework, however, was an increase in the rate of reef accretion in the deeper cores (Fig. 15). In a fashion similar to that occurring in the deep reefs at Salt River, detrital material from suprajacent reefs played a major role in the lateral and vertical accretion of these deeper-water reefs just below the shelf break.

DISCUSSION

The cores described above raise a number of interesting questions. Perhaps the most significant one centers around our criteria for recognizing reefs in the ancient. To a large extent, our expectations of significant in-place framework are fostered by early misconceptions that modern reefs are precisely that. While Newell recognized this problem as early as 1971, its significance has not yet been fully realized.

When swimming over a reef such as those at Salt River or Cane Bay, one sees a collection of living framework and intervening sediment. If these environments shift over time, then the result is a series of

sedimentary intervals separating episodes of active accretion. Such a sequence could be easily misidentified as being unrelated to the active reef core.

This is further confused by the constant minor shifts in the framework of these deeper shelf-edge reefs. Along the west wall of Salt River submarine canyon, downward displacement of shallower reef blocks all but negated the importance of in-place framework production as part of the accretionary process. Hubbard and others (in press) raised the question of whether the high rates of lateral accretion recorded at Salt River might be peculiar to that environment, where the canyon floor can catch the downward traveling reef blocks. Along the open shelf at Cane Bay, however, the highest accretion rates were likewise recorded in the deepest cores, and were related in large part to the incorporation of detritus from upslope reefs.

With respect to recognizing ancient reefs, this raises a clear problem. Both at Cane Bay and Salt River, the modern reefs are substantially or wholly the result of minor displacements of reefal framework from somewhere upslope. While the walls of Salt River canyon have been covered by true reefs for at least the last 10,000 years, little of those reefs are preserved in place. While it is possible to understand the minor nature of these adjustments in the modern, it is impossible in the ancient to tell whether material that is not in place has moved only a few centimeters or much more.

Despite major shifts in the position and orientation of framework blocks at both Salt River and Cane Bay, the collection of individual elements seen in the cores were all part of a reef that occurred at the place where those elements ultimately came to rest. It is unlikely that this sequence seen in an ancient setting could be interpreted as an in-place reef from core evidence alone.

We certainly have to be more careful in what we pass over as being "reef-associated" deposits, as opposed to what we call the reef itself. While in-place framework is certainly the best single criterion

we have in establishing the presence of a "reef" in the rock record, we must be very careful in dismissing what appears to be a less than perfect example as being "near to" but not part of the reef.

Equally noteworthy is the degree to which sequences of events in one part of the reef system can affect those occurring elsewhere. At Salt River, the protection of the estuary by the newly-formed barrier reef signaled the demise of once-flourishing reefs in the canyon. In another instance, the progressive development and steepening of the reef near SR-11 caused the burial of the one below at SR-5 (Fig. 9). Likewise, the hiatus in accretion in Cores CB-3 and 4 (Fig. 16) was probably affected by upslope reefs.

On the other hand, while burial by detritus can kill a reef, we must remember that the accelerated accretion rates (to be differentiated from reef growth or framework production) both at Salt River (Core SR-5) and Cane Bay (Cores CB-2 and 6) were largely the result of such processes. While it is probably impossible to construct a model which will predict whether such processes will enhance accretion or simply bury the reef, such complex interactions can have a profound effect on smaller-scale variability likely to be found in ancient reefs.

As a final point of lesser importance, one might ask "How deep is deep?" To an oceanographer, deep is measured in hundreds or thousands of meters. Some workers imply wave base (an equally ambiguous and ill-used term) as an arbitrary cut-off. We have arbitrarily made a break based in part on biological zonation, and in part on the depth below which the data base drops off significantly (a logistical limitation of SCUBA diving).

Certainly some effort to quantify this term is in order. In at least a few instances text books actually give a deeper depth for "shallow water" in one chapter than they do for "deep water" in another. While many would correctly argue that a precise depth cannot be attributed to a specific sequence, the author surely must have some absolute depth range (meters, tens of meters, etc.) in mind when using

descriptive terms such as shallow or deep. A trend toward quantifying this term certainly seems in order.

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REFERENCES

- ADEY, W., MACINTYRE, I. G., and STUCKENWRATH, R., 1977, Relict barrier reef system off St. Croix: its implications with respect to late Cenozoic coral reef development in the western Atlantic: Proc. Third Intl. Coral Reef Symp., v. 2, p. 15-23.
- BEACH, D. K., and GINSBURG, R., 1980, Facies succession, Plio-Pleistocene carbonates, Northwestern Great Bahama Bank: AAPG Bull., v. 64, p. 1634-1642.

- BIRKELAND, C., AND NEUDECKER, S., 1979, A study of the foraging behavior of two chaetodontids: Chaetodon capistratus and Prognathodes aculeatus: Final report to NOAA Undersea Research Program Office, Mission No. 78-1, West Indies Laboratory, St. Croix, U.S.V.I.
- CANT, R. V., 1977, Role of coral deposition in building the margins of the Bahama Banks, in: Proc. Third Intl. Coral Reef Symp., v. 2, p. 9-13.
- DAVID, T. W. E., HALLIGAN, G. H., and FINCH, A. E., 1904, Report on dredging at Funafuti, in: The Atoll of Funafuti, Sect. VII, Royal Society of London, p. 151-159.
- HUBBARD, D. K. (in press),: Sedimentation as a control of reef development, St. Croix, U.S.V.I.: Coral Reefs.
- HUBBARD, D. K., BURKE, R. P., and GILL, I. P. (in press), Styles of reef accretion along a steep, shelf-edge reef, Salt River submarine canyon, St. Croix, U.S.V.I.: J. Sed. Petrol.
- HUBBARD, D. K., SADD, J. L., MILLER, A. I., GILL, I. P., and DILL, R. F., 1981, The production, transportation and deposition of carbonate sediments on the insular shelf of St. Croix, U.S. Virgin Islands, Tech. Rpt. no. MG-1, West Indies Laboratory, Fairleigh Dickinson Univ., 145 p.
- JAMES, N. P., and GINSBURG, R. N., 1979, The seaward margin of Belize barrier and atoll reefs: IAS Special Publ., No. 3, Blackwell Scientific Pubs., Oxford, 191 p.
- LAND, L. S., 1974, Growth rate of a West Indian reef: Proc. Second Intl. Coral Reef Symp., p. 409-412.
- MACINTYRE, I. G., 1972, Submerged reefs of the eastern Caribbean: AAPG Bull., v. 56, p. 720-738.
- MACINTYRE, I. G., 1975, A diver operated hydraulic drill for coring submerged substrates: Atoll Res. Bull., v. 185, p. 21-25.
- MACINTYRE, I. G., 1983, Submarine cements-the peloidal question (abst.), in: Abs. and Prog. 1983 Ann. Mtg., AAPG, Dallas, TX, p. 120.
- MACINTYRE, I. G., BURKE, R., and STUCKENWRATH, R., 1981, Core holes in the outer fore reef off Carrie Bow Cay, Belize: a key to the Holocene history of the Belizean barrier reef complex: Proc. Fourth Intl. Coral Reef Symp, v. 2, p. 567-574.
- MCGEACHY, J. K., 1977, Factors controlling sponge boring in Barbados coral reefs: Proc. Third Intl. Coral Reef Symp., v. 2, p. 477-484.

- MOORE, C. H. AND SHEDD, W. W., 1977, Effective rates of sponge erosion as a function of carbonate production: Proc. Third Intl. Coral Reef Symp., v. 2, p. 499-506.
- NEWELL, N. D., 1971, An outline history of tropical organic reefs: American Museum Novitiates, No. 2465, 37 p.
- OGDEN, J. C., 1977, Carbonate sediment production by parrot fish and sea urchins on Caribbean reefs, in: Frost, S. H., Weiss, M. P., and Saunders, J. B. (eds), Reefs and related carbonates - ecology and sedimentology, AAPG Studies in Geology No. 4, p. 281-288.
- RUTZLER, K., 1975, The role of burrowing sponges in bioerosion: *Oecologia* (Berl.), v. 19, p. 203-216.
- SHINN, E. A., HUDSON, J. H., HALLEY, R. B., LIDZ, B., ROBBIN, D. M. and MACINTYRE, I. G., 1982, Geology and sediment accumulation rates at Carrie Bow Cay, Belize, in: Rutzler, K. and MacIntyre, I. G., (eds.), The Atlantic barrier reef ecosystem at Carrie Bow Cay, Belize, I. Structure and communities: Smithsonian Contribution to Marine Science No. 12, Smithsonian Institution Press, Washinton, D. C., p. 63-76.
- STEARNS, C. W. and SCOFFIN, T. P., 1977, Carbonate budget of a fringing reef, Barbados: Proc. Third Intl. Coral Reef Symp., v. 2, p. 474-477.
- WARME, J. E., 1977, Carbonate borers - their role in reef ecology and preservation, in: Frost, S. H., Weiss, M. P., and Saunders, J. B., (ed.), Reef and related carbonates - ecology and sedimentology, AAPG Studies in Geology No. 4, p. 261-280.