# Depositional Environments of Salt River Estuary and Submarine Canyon, St. Croix, U.S.V.I.

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## INTRODUCTION

West of Christiansted Harbor, the northern insular shelf of St. Croix narrows dramatically (See Figure 3 in the Modern Carbonates article, this volume). A reentrant in the shelf near Salt River forms a well-developed submarine canyon and estuary, separated by a narrow barrier reef (Fig. 1). In addition to its geological significance, Salt River represents an important historical and archaeological landmark. Several prehistoric societies have occupied the banks of the estuary, recorded in the pre-Columbian artifacts uncovered there. In 1493, on his second voyage to the New World, Christopher Columbus made his first landfall at Salt River. There he encountered a group of not-so-friendly Caribe indians who, according to his log, attacked from the nearby "Cape of Arrows" with great ferocity. The remains of an earthen fortress record later occupation under at least two flags. Today, Salt River canyon is a focal point for long-term reef research utilizing first the undersea-research habitat "Hydrolab", and now its replacement "Aquarius".

Salt River submarine canyon diverts both terrestrial and carbonate sediments into the 5000-m deep basin north of St. Croix. Because of its proximity to the shore, the canyon provides an ideal opportunity for the study of oceanographic processes, sedimentation and submarine-canyon morphology in a carbonate setting. Over a distance of less than 2 km, one can examine a transition from the terrestrial environments of the upper estuary to open-marine conditions within the canyon.

## THE ESTUARY

### *Flora and Fauna*

The estuarine system occupies a low stream valley that drains the second largest watershed on St. Croix. The estuary is divided into three smaller embayments, Triton, Sugar and Salt River Bays (Fig. 1). Areas of Triton and Salt River Bays are gradually becoming developed as economic pressures overcome environmental concerns in the area. Undeveloped portions of the estuary are rimmed by lush stands of the red *(Rhizophora mangle), black (Avicenna nitida)* and white *(Laguncularia racemosa)* mangrove as well as buttonwood *(Conocarpus erecta).* The red mangroves trap fine sediment during periods of heavy runoff, as evidenced by the gradual encroachment of the mangrove complexes into open water over time. The retention of fine-grained sediments by the mangroves buffers seaward environments from elevated levels of sedimentation. In addition, the root systems of the red mangroves harbor many juvenile species that move out of the estuary and populate open-marine environments during adulthood. The dominant biota of the estuary floor are the seagrasses *Thalassia testudinum* and *Syringodium filiforme,* the green algae *Halimeda* sp. and *Penecillus sp.,* and various species of infaunal molluscs and crustaceans (Fig. 2).

### *Oceanography*

In the strictest sense the area is not truely estuarine. During most of the year, salinities range from 33 to 36 parts per thousand (ppt) and would be considered restricted marine. During periods of heavy rain (usually between October and January), salinities can be greatly reduced, however, especially in the upper reaches of Triton and Sugar Bays. Schaefer and Tatnum (1976) measured salinities of 29 ppt near the head of Sugar Bay during a rainy period in January of 1976 (Fig. 3). Although Salt River is presently an ephemeral stream and does not reduce salinities within the bay to below brackish levels, there is historical evidence of a greater and more permanent discharge during earlier times.

Currents within the outer bay are driven by winds, waves and tides. Current patterns break down into two distinct flow cells within Salt River Bay (Fig. 4). Just behind the reef, an east-to-west current is driven by waves breaking on the eastern end of the reef. An inner flow cell reverses direction with the tides and facilitates the exchange of water between the open Caribbean and the upper reaches of Triton and Sugar Bays.

During storms, water is trapped in the estuary by large waves breaking on the reef. Water levels can be elevated within Triton and Sugar Bays by more that 30 cm during even small to moderate-intensity storms. Late in the storms, or as they pass, water trapped within the estuary is flushed through the reef cut, moving large quantities of sediment and organic debris into the canyon. Such processes continually discourage coral growth along the inner reaches of the western canyon wall, as discussed below.

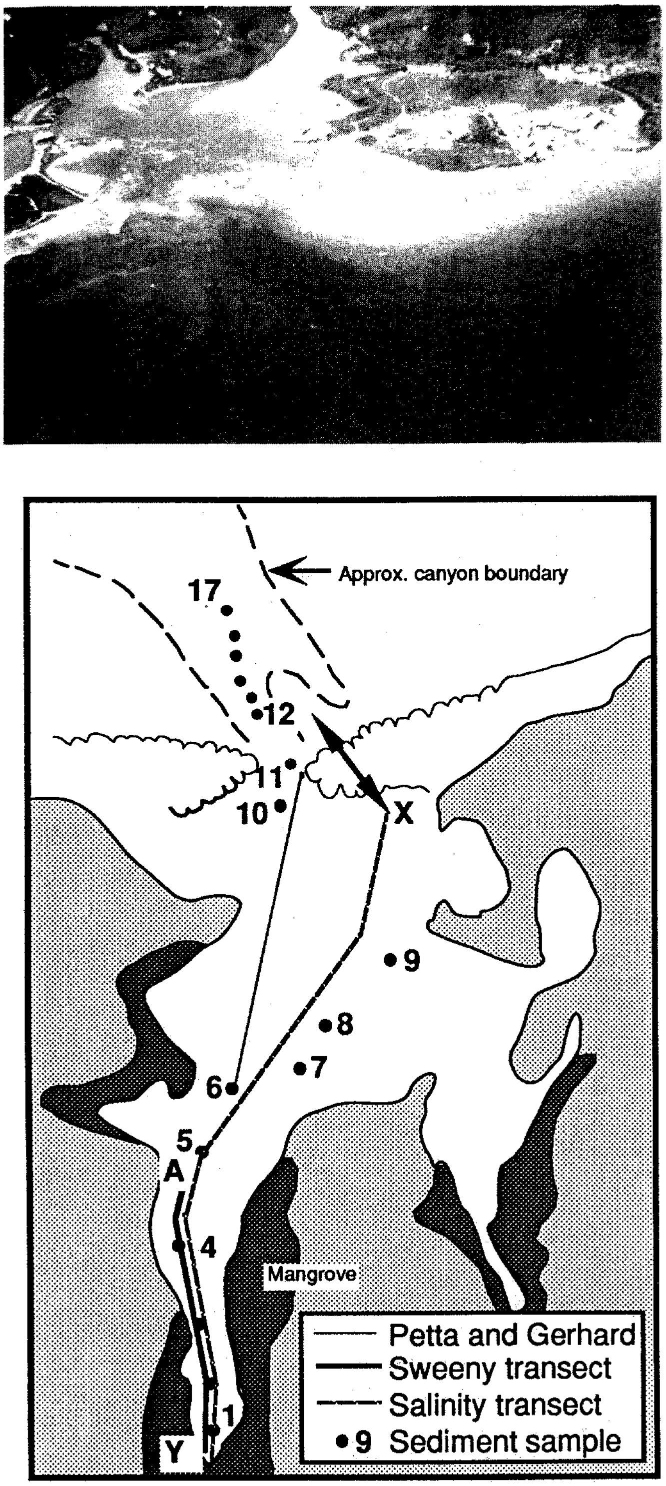

***Figure 1**. A. Aerial photograph of the Salt River canyon-estuary system. The dark area (arrow) is the deep water of the canyon. **B.** Map showing Salt River submarine canyon and estuary. The locations of sediment samples (Fig. 5), sediment cores (Fig. 6) the salinity transect of Figure 3, and. the approximate location of the transect in Figure 7 are indicated.*

### *Sediments*

Surface sediments within the upper estuary are dominantly fine-grained and are comprised mostly of terrigenous material and fragments of molluscs and *Halimeda* (Fig. 5). Behind the reef, the outer-bay sediments coarsen dramatically, and reefal constituents become more important. Sediments from cores taken in the axis of Sugar Bay (Fig. 1b) generally grade from sandy muds at their bases to darker muds toward the present sediment surface (Fig. 6), probably reflecting the gradual enclosure of the estuary and a decrease in open-marine conditions. Exceptions include a horizon of *Halimeda* (Fig. 6) and a layer of shell and pebbles that occurs near the surface in the more seaward cores. The *Halimeda* lens is the result of dense stands of this marine alga throughout much of the estuary (Fig. 2), and comprises a significant portion of the sediment. The shell/pebble layer may represent the incursion of open-marine sediments during a major storm.

Depositional patterns seen in the estuary provide direct analogues to similar systems in ancient settings. Numerous canyon systems and associated basin fills are exposed in the Alps (Bosellini and Rossi, 1977; Stanley *et al.,* 1979) and may have been very similar in character to Salt River canyon and the basin north of St. Croix. Petta and Gerhard (1977) proposed that slightly coarser sediments trapped in "grass banks" similar to those found in the estuary may be responsible for carbonate lenses found in the Cretaceous Pierre Shale of Colorado (Fig. 7). The abundance in the ancient examples of infaunal pelecypods *(Nymphalucina occidentalis)* capable of feeding on macrodetritus from seagrass beds further supports this comparison (Bretsky, 1978).

## THE CANYON

### *General Description*

Salt River submarine canyon cuts into the open shelf in a direct line with the present estuary. Although the origin of the canyon is unknown, it is likely related to a remnant river course cut during a previous lowstand of sea level. Since the most recent flooding of the shelf, syndepositional processes that continue into the present have significantly modified the original topography of this presumed paleo-drainage system. These have resulted in a submarine landscape that is controlled as much by patterns of local sediment transport and reef accretion as by antecedent topography.

Originally it was thought that the canyon extended to a depth of approximately 3000 m where it joined Christiansted canyon. Recent seismic data and DSRV ALVIN dives indicate that this is not the case, and that Salt River submarine canyon is largely confined to the upper slope on the northern side of St. Croix (Hubbard *et al.,* 1982). The deeper canyon channel reported by Shepard and Dill (1977) and Shepard (1979) is likely one of several discontinuous gullies that extend below the end

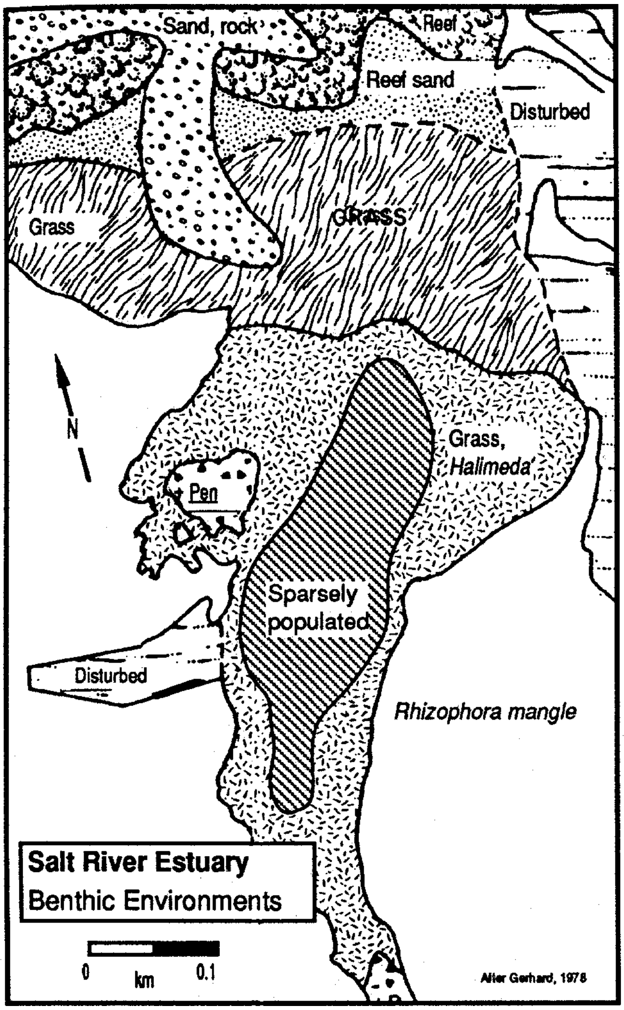

***Figure 2**. Benthic communities within Salt River estuary. Redrawn from Gerhard (1978).*

of the main canyon. Shepard (1979) describes the canyon as continuous down to a depth of 300 m, becoming discontinuous below that. Direct observations using SCUBA, however, have verified the end of the canyon head at a depth of 80-100 m.

The present channel that connects the canyon and estuary occupies a position roughly midway along the reef extending between two headlands. Core data infer that prior to reef development the channel occupied a more easterly position. That channel corresponded to the now-blind eastern arm of the upper canyon and may have been an extension of Triton Bay (Fig. 1).

Suspended-sediment levels are generally high within the canyon, owing to the regular tidal flushing of the estuary. Suspended load is increased dramatically during and after periods of even moderate wave action. After a large tropical storm in the Fall of 1977, visibility was reduced to less than one meter for several months. Severe coral mortality resulted from this extended period of poor water quality.

Currents within the canyon axis are generally weak. Under normal wind and wave conditions, currents reverse on a regular basis, but rarely exceed 10-15 cm/sec (Fig. 8). During stormy weather, however, downcanyon currents exceeding 50 cm/sec have been measured, and stronger currents have been observed. During the Fall of 1979, a storm with 5-m waves moved the 65-ton "Hydrolab" underwater habitat a distance of approximately 5 m (note: the size of "Hydrolab" is -1125 phi).

The insular shelf on either side of the canyon slopes gradually to depths of 10-20 m at the shelf edge. Most of the bottom is covered by widely scattered colonies of *Acropora palmata*, *A. cervicornis*, encrusting *Millepora* sp., various head corals and gorgonians. The shelf to the east serves as a major source for canyon sediments which are moved to the west by waves and currents associated with the dominant trade winds.

The character of the east and west canyon margins differs markedly (Fig. 9). The west wall is steep, and often vertical. In several instances, overhangs and caves are found (Fig. 10a). A variety of anthozoans inhabit the west wall, with antipatharians, scleractinean corals and plexaurids dominating (Table 1). The most abundant corals include *Montastrea annularis*, *Siderastrea* sp. and *Agaricia sp.* (Table 2), with live cover averaging 10-20%. Vertical grooves and side tributaries (Fig. 10c) cut into the canyon wall and serve as avenues of transport for sediment produced locally by bioerosion. Similar features oriented horizontally reflect fracturing along the reef face and subsequent slumping of large sections of the upper reef wall (Fig. 10d).

In contrast, the eastern margin is characterized along most of its inner section by a cobble-covered slope (Figs.

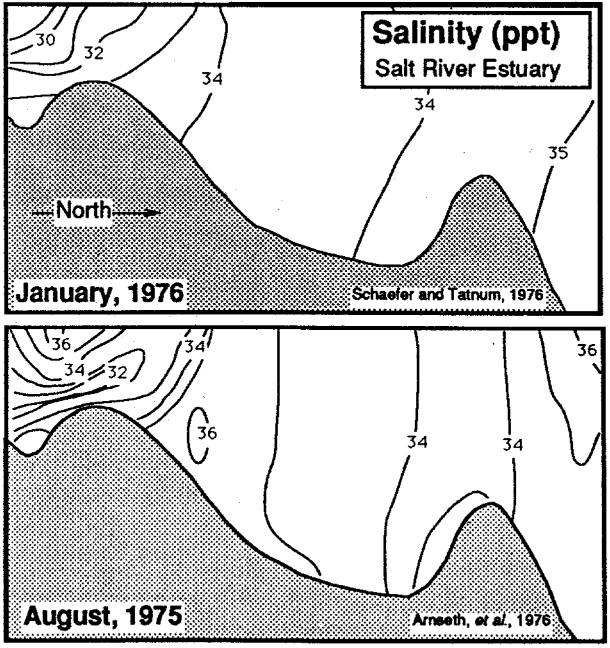

***Figure 3**. Salinity measurements from Salt River estuary during August (upper) and January (lower). From Arnseth, et al. (1975) and Schaefer and Tatnum (1976), respectively.*

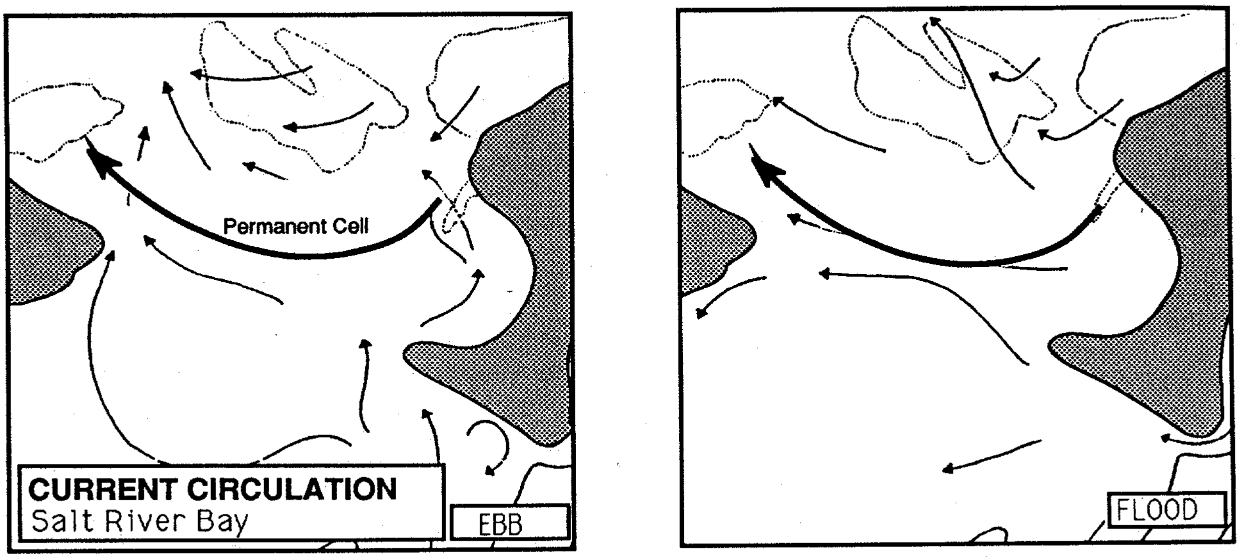

***Figure 4.*** *Current circulation in Salt River Bay.*

9 and 10b), typically at angles of 15-20 degrees or less. The dominant organisms are sponges and gorgonians, along with widely scattered colonies of sediment-tolerant corals (Table 2). The small size of the corals reflects their frequent burial by sediment moving into the canyon over this margin.

The cobbles that litter the east slope are typically algal-covered, coral clasts derived from the upwind shelf to the east. The nuclei of the rhodoliths are generally fragments of corals that inhabit the shelf, although terrigenous clasts derived from adjacent upland areas occur as well. The coatings are typically comprised of *Porolithon sp.,* with secondary contributions by the encrusting forams *Gypsina* and *Homotrema* (McGovern, 1985). Other red algae (Rhodophyta) are common on the surface of the rhodoliths, but they do not appear to be preserved due to herbivory. In general, both abundance and size of the rhodoliths increases toward the base of the east slope (Fig. 11a). The increase in abundance away from the source likely reflects a final site of deposition near the base of the slope. The increased size results from the successive addition of algae as the rhodoliths are intermittently rolled down the slope by storm waves. This is supported by the increase in crust thickness toward the canyon (Fig. 11c) as well as the dramatic increase in the importance of the coating relative to the size of the nucleus downslope (Fig. 11b).

*Table 1. Relative proportions of anthozoans in terms of surface area at depths of 15 and 30 m on the margins of Salt River submarine canyon. From Birkeland and Neudecker (1978). Note that these values reflect the percetage of total live cover, and not total surface area.*

| Area (margin)<br>Depth (m) | West<br>15 | East<br>15 | West<br>30 | East<br>30 |
|---|---|---|---|---|
| scleractineans | 21 | 15 | 35 | 1 |
| scleraxoarts | 10 | 1 | 0 | 0 |
| Plexaurids | 36 | 83 | 4 | 80 |
| Gorgoniids | 3 | 1 | 0 | 4 |
| Antipatharians | 30 | 0 | 58 | 15 |
| Anemones | ++ | ++ | ++ | ++ |
| Zoanthids in sponges | 1 | 1 | 2 | 1 |
| Free zoanthids | 1 | 0 | 0 | ++ |

The canyon floor is dominated by medium to coarse sand (range = 0.27-0.99 mm) that is moderately to poorly sorted (Fig. 12). In general, sediments become progressively finer with increasing water depth along the canyon axis (Figs. 5a and 12). The dominant sedimentary constituents are corals, coralline algae, forams, molluscs and *Halimeda* fragments (Fig. 5b). The abundance of terrigenous material drops abruptly seaward of the reef reflecting the importance of that feature as a depositional barrier that separates estuarine from open-marine sedimentation.

Normally the sediment surface is a featureless slope with only occasional mounds of the burrowing shrimp *Callianassa* sp. During storms, however, large oscillatory ripples can be seen on the canyon floor (Fig. 10f). After the passage of many storms, these are masked by downcanyon-oriented bedforms that are generated as water trapped by storm waves flushes from the estuary. After such events, the bottom is littered with debris from the estuary and shallower canyon environs.

In the deeper portions of the canyon head (water depth = 20-90 m), large reef blocks which are broken off the west wall become incorporated in the canyon fill. Once introduced into the canyon, these blocks move slowly down the canyon axis. One such block, shown diagramatically in Figure 9, has reached the end of the upper canyon and will likely be moved over the shelf edge during a future storm or by the gradual creep of surface sediments.

### *Sediment Transport in the Canyon*

In general, sediment moves from east-to-west along the adjacent shelf. This overall pattern has a dramatic effect on the differing morphology of the two canyon margins described above. Along the east slope, high levels of bedload influx discourage all but the most sediment-tolerant organisms, and coral cover is sparse. Along the western side of the canyon, sediment from the shelf is moved away and stress from bedload is greatly reduced. Were it not for the regular influx of fine-grained sediment from the estuary, coral cover along the west wall would likely be very high. However, the daily introduction of terrigenous muds during the ebb tide and the periodic flushing of fine detritus during storms inhibit coral recruitment and growth. Under normal conditions light attenuation is sufficient to reduce the growth rate of corals along the west wall below those measured at similar depths in a more open-shelf setting (Fig. 13). The

***Table 2**. Percent cover of the more-important scleractinean corals from 9, 18, 27 and 37 m along the eastern and western margins of Salt River submarine canyon. Note that this is the percent of total live corals, and not total surface area. Total coral cover averages between 10 and 2090 on the west wall and much lower on the east slope. From Rogers, et* al. *(1984). For a more complete list, see that paper.*

| | EAST WALL | | | | WEST WALL | | | |
|---|---|---|---|---|---|---|---|---|
| | | 18m | 27m | 37m | 9m | 18m | 27m | 37m |
| *Stephanocoenia Michelinii* | | 1.6 | 3.4 | 1.5 | 13.3 | 4.0 | 7.0 | 3.9 |
| *MadracisDecactis* | | 12.0 | 10.4 | 14.4 | 3.3 | 30.9 | 6.0 | 15.4 |
| *Acropora cervicornis* | 4.6 | | | | | | | |
| *Agaricia agaricites* | 3.0 | 14.2 | 19.5 | 3.8 | 17.8 | 18.5 | 6.4 | |
| *Agaricia lamarcki* | | 11.9 | 43.3 | 48.4 | | 12.7 | 53.4 | 79.9 |
| *Agaricia fragilis* | | | | 15.7 | | 1.0 | 0.4 | |
| *Siderastrea siderea* | 9.0 | 5.6 | 5.4 | 9.2 | 10.4 | 6.0 | 8.5 | 1.0 |
| *Porites astreoides* | 6.6 | 7.6 | 2.9 | | 7.2 | 5.6 | 1.8 | |
| *Diploria sp.* | 9.2 | 7.2 | | | 1.5 | | | |
| *Colpophyllia sp.* | | | 2.9 | | | 9.8 | 5.8 | 0.7 |
| *Montastrea annularis* | 6.9 | 10.7 | 5.9 | | 10.6 | 4.3 | *6.0* | |
| *Montastrea cevernosa* | 47.6 | 12.7 | 4.0 | 1.5 | 12.1 | 4.5 | 8.9 | |

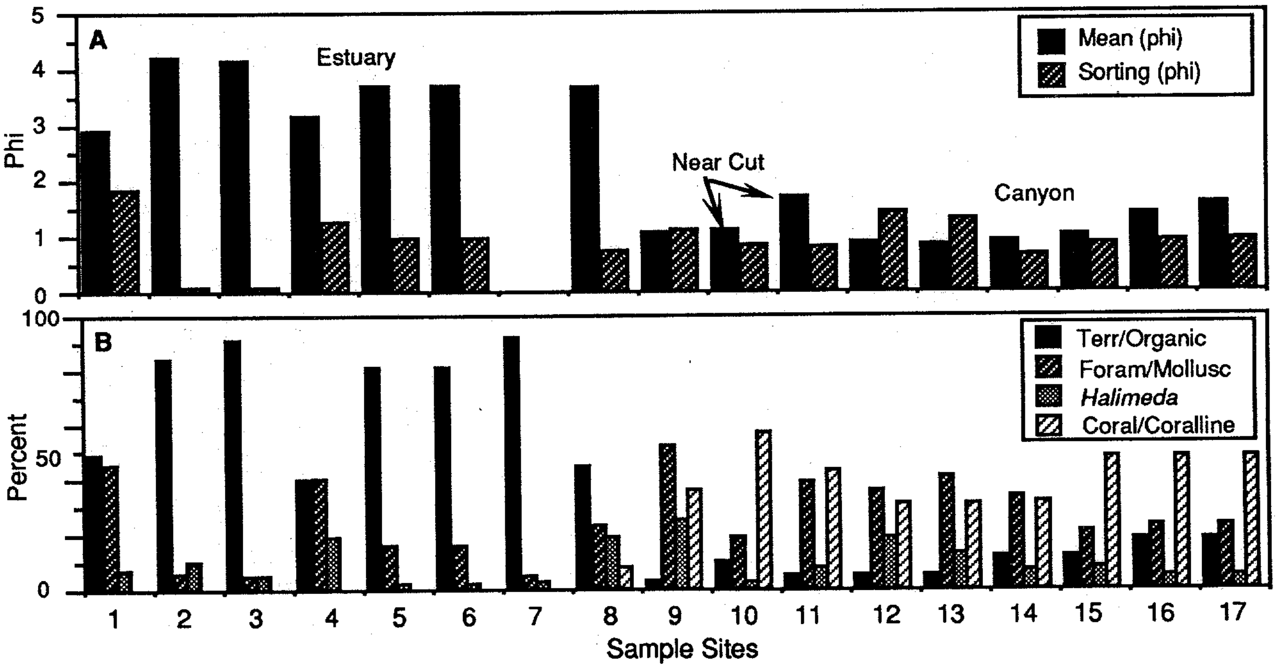

***Figure 5**. **A**. Mean grain size and sorting of surface sediments in Salt River estuary and canyon. Note the coarsening of the sediments within the outer estuary and canyon. **B**. Sedimentary constituents of Salt River estuary and canyon. Note the abrupt change in sedimentary constituents between stations 8 and 9. Samples are located in Figure 1. Data from Chmil (1978).*

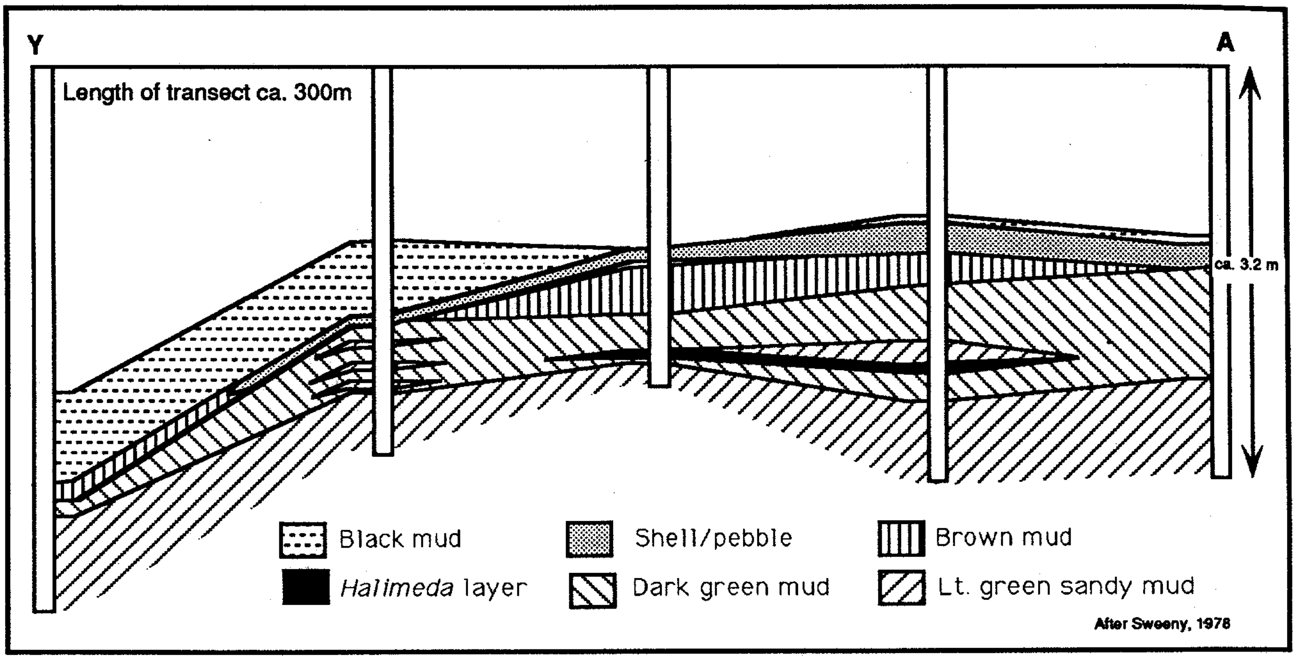

***Figure 6.*** *Subsurface sedimentology of upper Sugar Bay. The section is dominated by terrestrial muds. Coarse sediments are derived locally by* Halimeda *growing in the estuary and shell and pebble layers brought in during storms. The core transect is located in Figure 1. Redrawn from Sweeny (1978).*

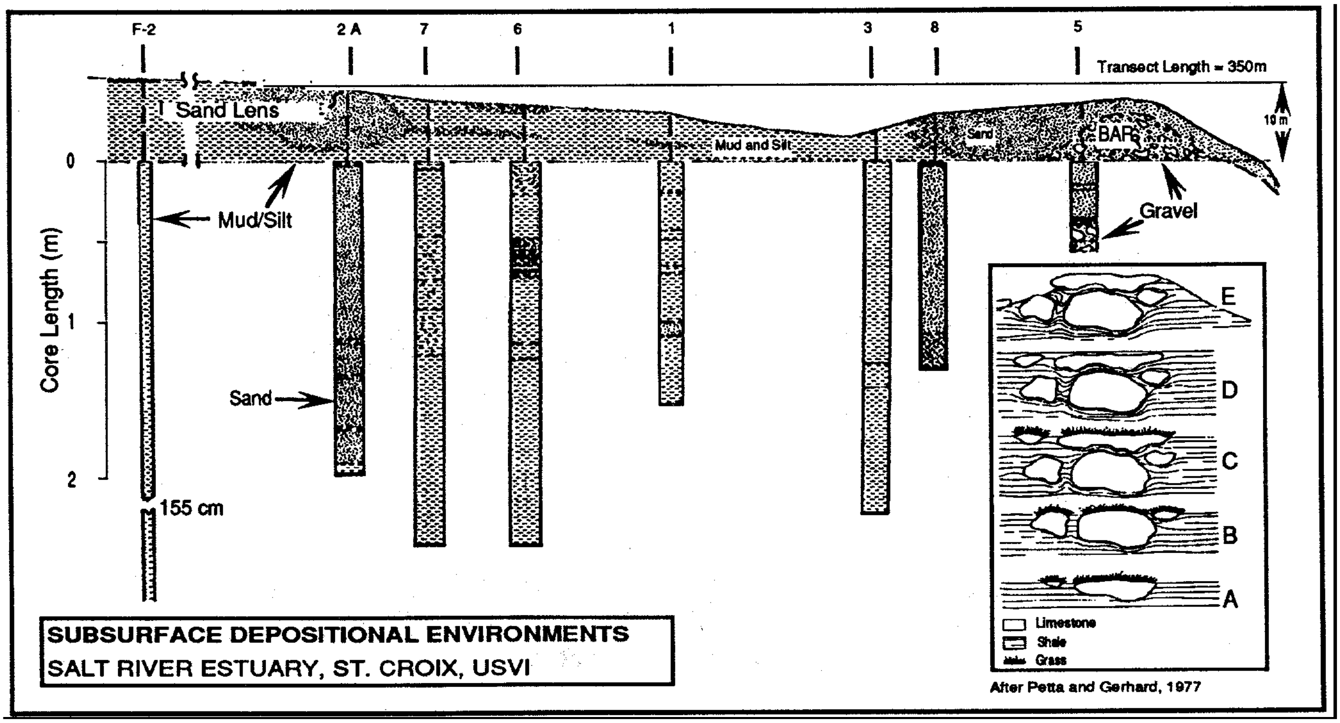

***Figure 7.*** *Salt River grass beds as an analogue to carbonate lenses in the Pierre Shale of Colorado. The transect (located approximately in Figure 1) shows lagoonl muds containing lenses of coarser silt and sand associated with modern grass beds. The inset shows the progessive upbuilding and burial of a sandy lense as envisioned by Petta and Gerhard (1977). In the final stage, erosion around the grass bank produces a "tepee"-like structure. The lens-shaped bodies that result would be further enhanced by differential compaction after burial. Redrawn from Petta and Gerhard (1977).*

steep nature of the west wall is largely a result of accretionary processes related to active coral growth under previous conditions of better water quality.

*Sediment input* - Sediment entering the canyon is derived primarily from bioerosion and, to some extent, physical breakdown of the reef and associated hard substrates. On the western side of the canyon, these are generated locally on the steep reef wall and move through the vertical channels that empty onto the canyon floor. Along the east slope, a major contribution is made from the broad, updrift shelf (Fig. 14). Sediment input to the canyon was measured over several years using sediment traps placed along both walls of the canyon (Hubbard, 1986). On an annual basis, a total of 66,000 kg of sediment enter the canyon; 19,000 kg are derived from bioerosion along the west wall, and 47,000 kg are introduced along the eastern margin (i.e. *in situ* production on the east slope plus sediment derived from the updrift shelf). Nearly one third is introduced during approximately two weeks of stormy weather spread over the year. It is estimated that during major storms, sediment input increases by at least an order of magnitude.

*Sediment export* - Three sediment-tracer experiments deployed across the canyon at a depth of approximately 30 m measured a total export of 18,000 kg of sediment annually as bedload. Again, roughly one third occurred during small to moderate-sized storms. Under normal conditions, annual sediment export is 48,000 kg less than the amount introduced along the canyon margins. The resulting storage over the past 6,000 years amounts to roughly three times the sediment presently found in the canyon (Hubbard, 1986; Fig. 14). Therefore, either sediment input has been lower in the past, or some other mechanism of sediment export must be operating.

Based on Neumann's sea level curve for Bermuda, as well as several others developed around the Caribbean, it is likely that the shelf to the east of the canyon was flooded by at least 6,000 ybp. Therefore, that large sediment source was probably available throughout much of the depositional history of the canyon. While it could be argued that sediment supply was probably lower in the past, the magnitude of this decrease would not be sufficient to make up the difference. Another source of error is the fact that the sediment-export experiments measured only bedload, ignoring the material being exported through the water column. Again, however, this is not thought to be a major source of error in that most of the material trapped along the canyon margins was sand-sized. Therefore, while suspended load is underestimated by the budget calculations of Hubbard (1986), this cannot be invoked to "balance the sediment budget" for the canyon.

It is most likely that the difference is made up during the passage of large tropical storms and hurricanes. During such events, both sediment input from the adjacent shelf and export from the canyon would increase. Because of the thin sediment cover to the east, however, that source could quickly become diminished. As input decreased, the budget within the canyon would gradually shift toward net export.

Evidence supporting this idea has been observed in Salt River as well as elsewhere in the Caribbean. In Jamaica, the shelf-edge sand channels off Discovery Bay were flushed clean of sediment during the passage of Hurricane Allen in 1981 (Woodley *et al.*, 1981). In 1979, a storm that generated long-period waves 3-5 m in height flushed a volume of sediment from Salt River canyon equalling 5-10 years of storage (Hubbard, 1986). Given the likelihood that high wave action can play such a major role in the sediment-transport picture at Salt River (and at other Caribbean sites as well), storms emerge as major controls of sedimentation in carbonate settings.

### *Reef Accretion*

Coring studies indicate that the present-day controls exerted on canyon morphology by sediment transport persisted throughout most of the accretionary history of the area. The following summary is derived from ten cores taken from the canyon walls and the surrounding shelf (Figs. 9 and 15). These are described in more detail in Hubbard *et al* (1985; 1986), and the reader is referred to those references for further information.

*Character of the "reef"* - Along both canyon margins the material recovered in cores was largely detrital in nature. This ranged from well-preserved coral blocks that have slumped down from their original growth positions to in-place or displaced corals that have been so bored and reworked that their origin as scleractineans is difficult to discern. In most of the core samples some evidence of bioerosion can be seen (Fig. 16a). The dominant bioeroders include the excavating sponge *Cliona* (Fig. 16g,h), the mollusc *Lithophaga (*Fig. 16a,e) and various

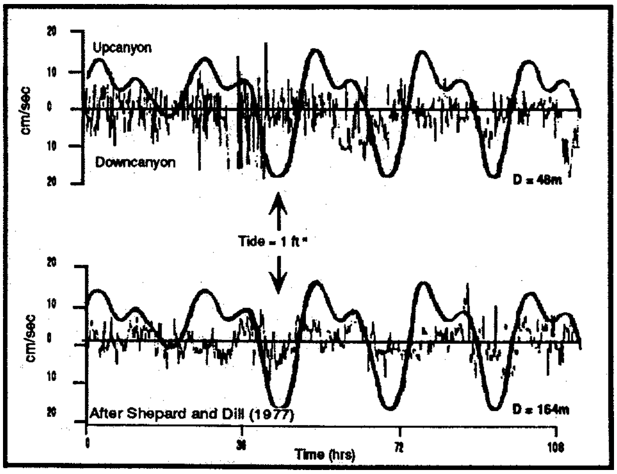

***Figure 8.*** *A. Reversing currents measured by Shepard and Dill (1977) in Salt River submarine canyon at depths of 48 (upper) and 164 m (lower). Tidal patterns (bold line) during the period of record are also shown. The lower station was probably located in a discontinuous gully below the main canyon head above. Redrawn from Shepard and Dill (1977).*

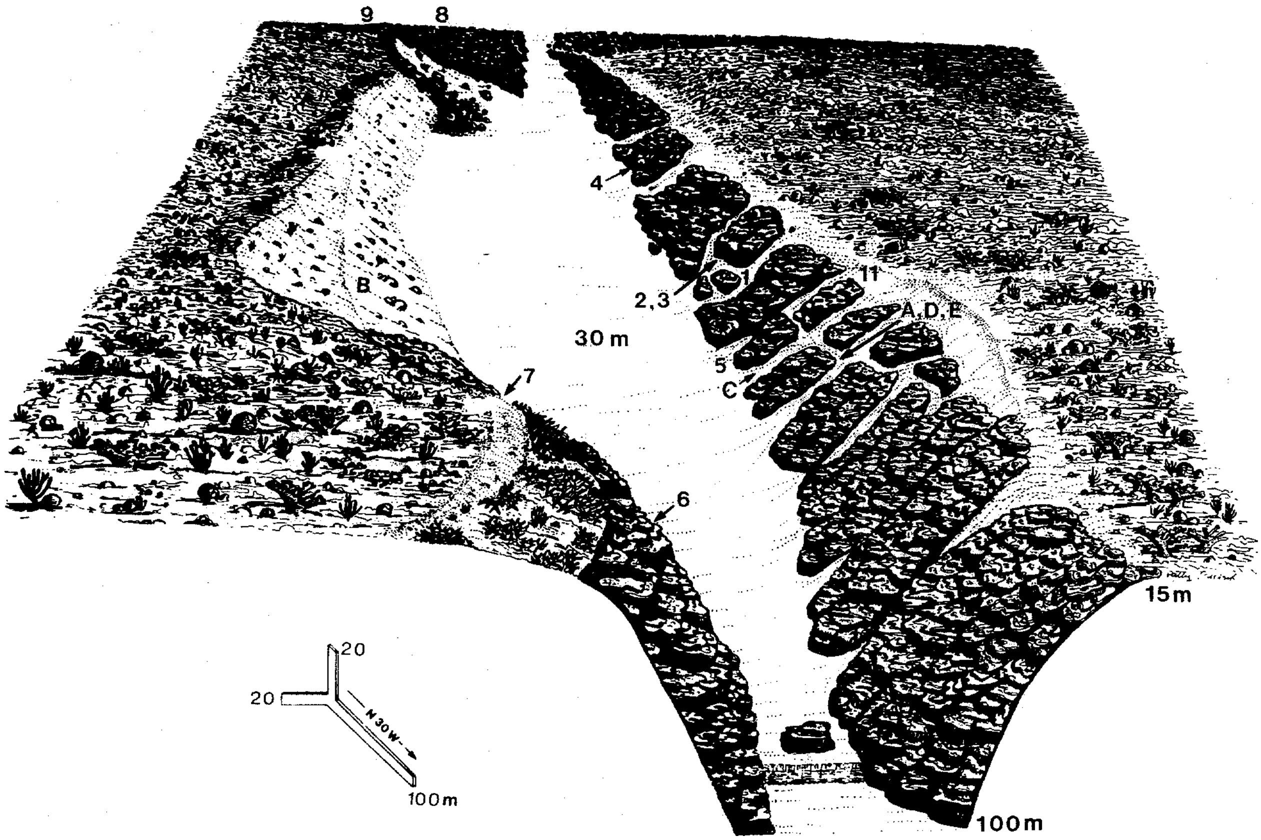

*Figure 9.* *Three-dimensional diagram showing the gross morphology of Salt River submarine canyon. Note the more-gradual, cobble-covered slope to the east (left), compared to the steep, reef-covered wall to the west. Sediment transport in this area is dominantly from east to west (left to right). Core and photo locations are approximately located on the diagram. The gross morphology is from a computer-plotted orthographic projection based on a detailed bathymetric survey conducted by the author in 1977 and 1978. Bottom type is based on SCUBA observations. From Hubbard et al. (1981).*

species of worms. Most of the evacuated galleries have been infilled by detrital sediment (Fig. 16,c,f,h) that has become cemented by aragonite and Mg-calcite. In some instances, the processes of bioerosion, sedimentation and cementation have been repeated multiple times rendering the original coral barely recognizable (Fig. 16c). In thin section, the dominant fabric consists of cemented detrital infills from bioerosion (Fig. 16b,h). In some (but not most) corals, secondary cements of fibrous aragonite (?) line the interiors of the calices (Fig. 16d). Preservation is often better along the east slope of the canyon, owing to an environment that favors more rapid burial and the resulting protection of recently dead substrate from the ravages of bioerosion and physical degradation.

*The importance of slumping* - Along the west wall, there are numerous sediment-filled fractures formed as large blocks of the reef have broken away from the main reef structure. On a smaller scale, meter-sized blocks (Fig. 10e) and smaller displaced corals also contribute to the detrital fabric of the reef. Blocks that make it into the canyon axis and ultimately out into the basin north of St. Croix are probably analogous to the ancient "cipit" blocks seen in Triassic basins of northern Italy (Bosellini, 1984; 1987) and the allochthonous blocks seaward of the Permian reefs of west Texas (Pray and Crawford, 1984). Within the reef interior cores reveal a complex pattern of coral growth and slumping. Dates from horizontal cores in both margins show not a regular pattern of progressively younger material toward the reef surface, but rather a confusing succession of younger, then older, then younger-again dates (Fig. 15, Table 3).

Possible mechanisms that could cause this pattern are summarized in Figure 17. They include slumping, in-place pinnacle growth and the formation of small caverns by the overgrowth of platy corals. A comparison of the growth rates of the corals in the cores to the growth rates of present-day corals at the same depth (allowing for changes in sea level) shows that the fossil corals apparently lived at much shallower depths and subsequently slumped to their present positions (Hubbard *et al.,* 1986; Fig. 13).

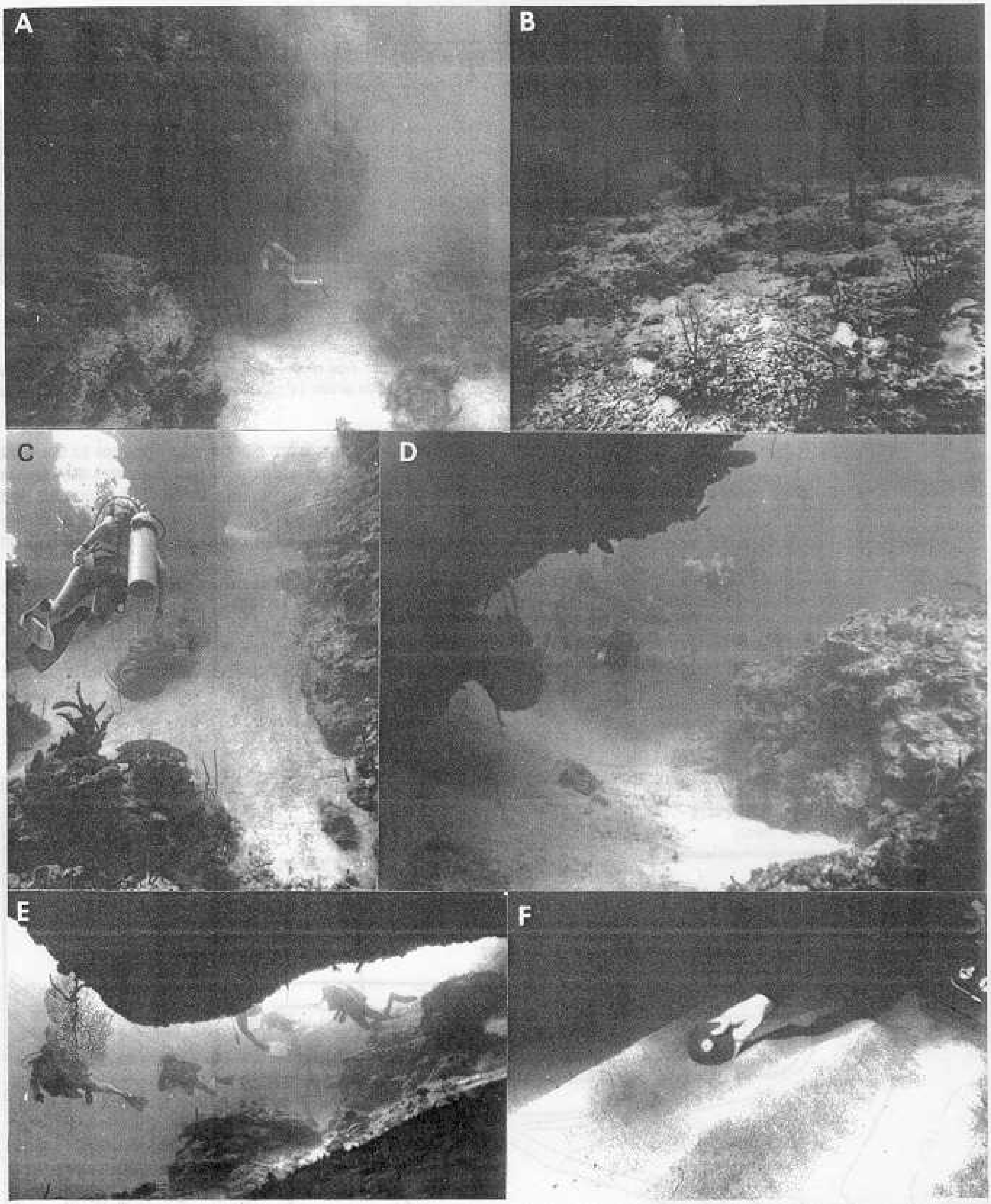

***Figure 10.*** *Photographs from Salt River submarine canyon.* ***A.*** *General view of the west wall. Note the steep nature of the wall and the numerous channels culling vertically.* ***B.*** *General view of the east slope. Note the lower slope angle and the general lack of coral cover. The cobbles that litter the surface are generally rhodoliths derived from the shelf to the east.* ***C.*** *Close-up of a sand channel along the west wall.* ***D****. Horizontal sand channel caused by fracturing of the upper reef margin on the west wall.* ***E.*** *Meter-sized reef blocks moving down the steep sedimentary apron along the west wall.* ***F.*** *Oscillatory ripples formed during heavy seas in the Fall of 1977. Depth is approximately 25 m.*

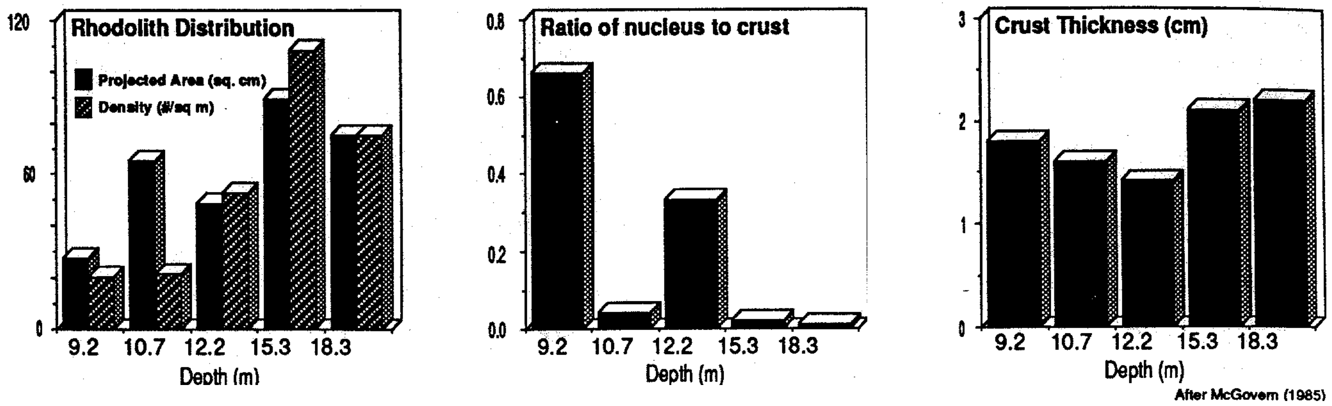

*Figure 11. Graphs summarizing rhodolith distribution and character along the east slope of Salt River canyon.* ***A****. Projected size and abundance of rhodoliths at various depths.* ***B****. Ratio of nucleus vs. crust areas in slabbed cross-sections.* ***C****. Thickness of the algal/foram crusts vs. depth. Data from McGovern (1985).*

The importance of such slumping and the abundance of detrital sediment in the reef interior (nearly 70% of the reef matrix is occupied by open or sediment-filled voids) reveal a picture not of in-place framework with corals "growing on the backs of other corals", but one of a "garbage pile" bound together by syndepositional cementation and biological overgrowth. Core studies elsewhere around St. Croix are starting to indicate that this type of fabric is much more important in reefs in open-shelf settings than one would assume from the available literature. A re-examination of what constitutes reef "framework" is likely in order.

*Reef history* - Seven horizontal cores were recovered from the east and west sides of the canyon. In addition, three vertical cores were drilled, one adjacent to the west wall and two in the shallow reef that separates the canyon from the estuary (Fig. 9). Cores SR-5 (horizontal) and SR-11 (vertical) from the west wall allow a three-dimensional interpretation of the canyon morphology in this area.

Accretion within the inner 30 m of the canyon probably began about 10,000 years ago (Fig. 18). While no core data are available, it is likely that earlier reefs formed further down the canyon. Both sides of the canyon were probably occupied by gradual slopes similar to that on the present eastern margin. The reef on the western slope faced into the prevailing seas, and active physical processes likely resulted in efficient flushing of detrital

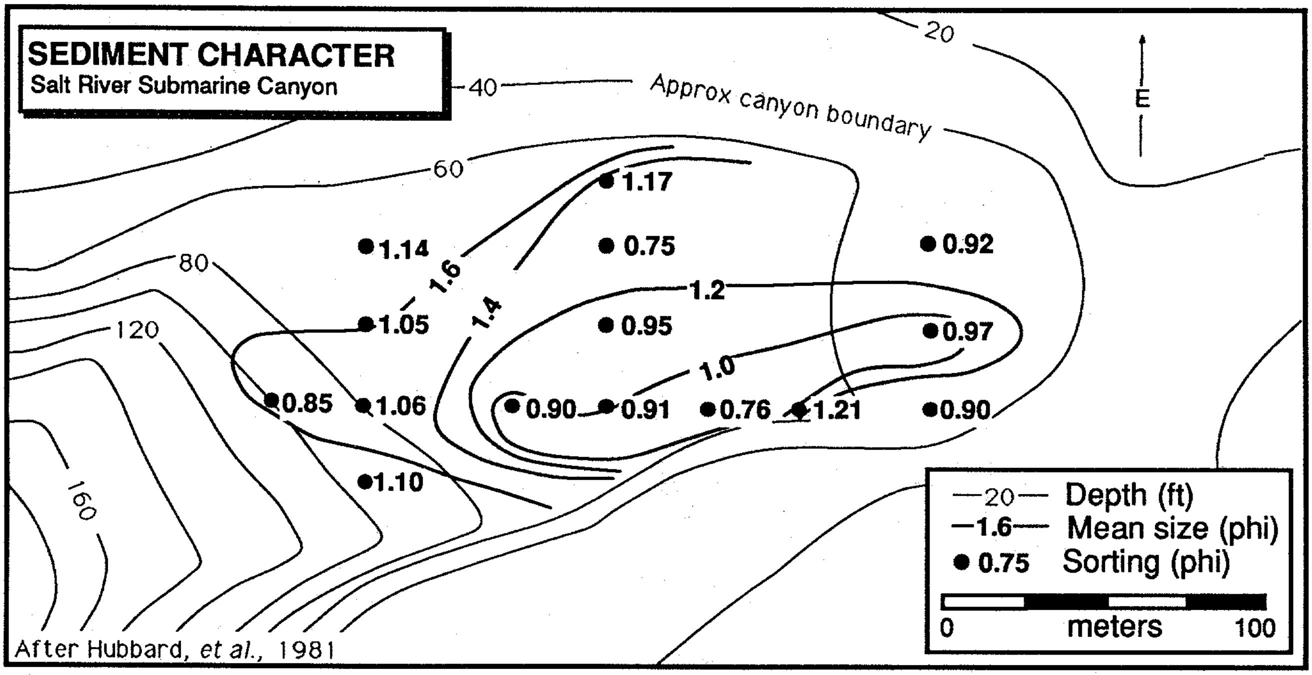

*Figure 12. Mean grain size (contours) and sorting (individual numbers) in Salt River submarine canyon. After Hubbard* et al. *(1981).*

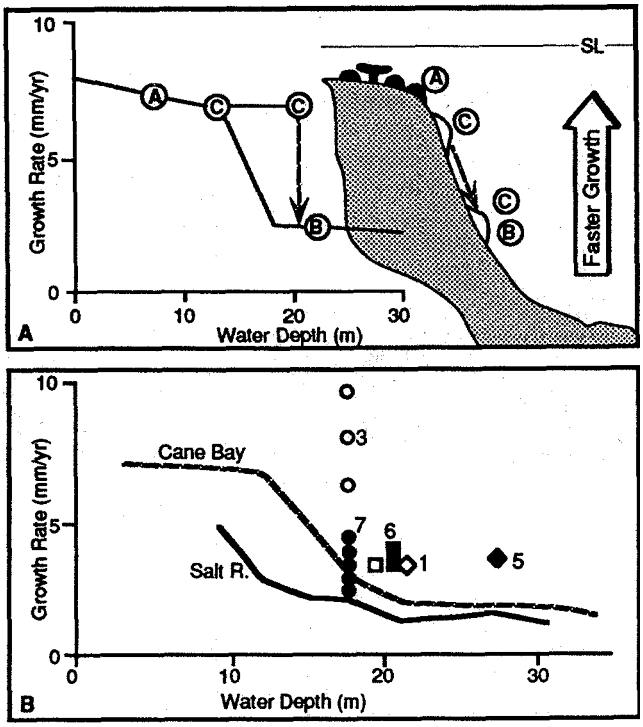

***Figure 13***. *A. Diagram illustrating the growth rates of modern and fossil corals in Salt River canyon. On the present reef surface, coral-growth rate (bold line) decreases with water depth (From Hubbard and Scaturo, 1985). In the fossil corals, in-place colonies in shallow water (A) will have growth rates faster than those in deeper water (B). Coral that grew in shallow water, but later slumped into deeper water (C) will have a growth rate faster than those growing near the final resting place of the slump block. B. Graph illustrating that most of the fossil corals have growth rates much faster than those growing today at similar water depths. The depths of the fossil corals have been "adjusted" using the radiocarbon ages of the corals and the sea-level curve of Neumann. Most of the fossil corals have growth rates faster than even those of open-water (Cane Bay curve) corals at the same depths. This, along with the date reversals seen in the cores, reflects the importance of slumping in the creation of the internal fabric of the west-wall reef. From Hubbard et al. (1985; 1986).*

sediment from the reef. Water depth over the reef crest was probably only a few meters. Water quality was probably much better at this time, as the shoreline was exposed to high wave action, and Salt *River* estuary had not yet flooded.

By 7500 ybp, vertical relief had *developed* along the western reef front. The A. *palmata* community continued to exist along the upper reef surface, while a head-coral community dominated by *Montastrea annularis* was developing along the reef front (Fig. 18). It *is* likely that sediment channels were a prominant morphological feature of the west wall.

Around 6,000 ybp, the processes that formed the reef over the previous 4,000 years changed abruptly. Two shallow-water cores (SR-8 and 9; Fig. 9) imply that development of the reef separating the canyon and the estuary started around this time, creating a quiet-water environment in which fine-grained terrigenous particles could settle out. As the estuary continued to develop, conditions within the canyon shifted from those of an open-shelf reef in clear water to those associated with regular tidal flushing of the adjacent, protected embayment (Hubbard *et al.,* 1986).

The increase in sedimentation gradually discouraged the rich *A. palmata* community that occupied the shelf edge, and more sediment-tolerant species gradually came to dominate (e.g. *Siderastrea and Montastrea).* Vertically oriented colonies of platy *Agaricia* that were able to *use* gravity and weak oceanographic processes to aid in sediment removal likely became important, and continue their dominance in the canyon today. The gradual *shift* away from *A. palmata* and the increasing disadvantages of coral colonization along the horizontal shelf shifted coral growth *to* the vertical reef face. At this point, an *active* lateral component of accretion rapidly developed, and the steeper slopes that resulted were often incapable of supporting their own weight. Continual bioerosion of the reef substrate combined with the somewhat open structure of the outer sections of the reef triggered continual breakage and slumping after about 6000 ybp. As these blocks piled up along the base of the slope they provided new substrate for *in situ* coral growth which would eventually be buried by later slumps from above. The continuation of this process has resulted in at least 26 m

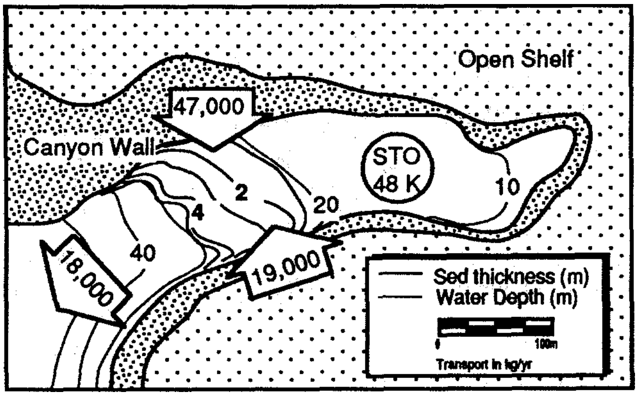

***Figure 14.*** *The "sediment budget" for Salt River canyon. Each year 47,000 kg of sediment enters the canyon along the eastern margin, most of that derived from the updrift shelf. An additional 19,000 kg of sediment are derived from the mainly biological breakdown of the reef on the west wall. With only 18,000 kg of sediment exiting the canyon under normal conditions, 48,000 kg of sediment is stored within the canyon each year. Over a 6,000 year period, this amounts to roughly three times the sediment that is presently contained within the canyon axis. Thicker contours are sediment isopachs thinner ones are isobaths. Periodic flushing by large tropical storms and hurricanes* is *proposed as the primary mechanism that removes excess sediment from the canyon, as well as many open-shelf reef environments. After Hubbard, 1986.*

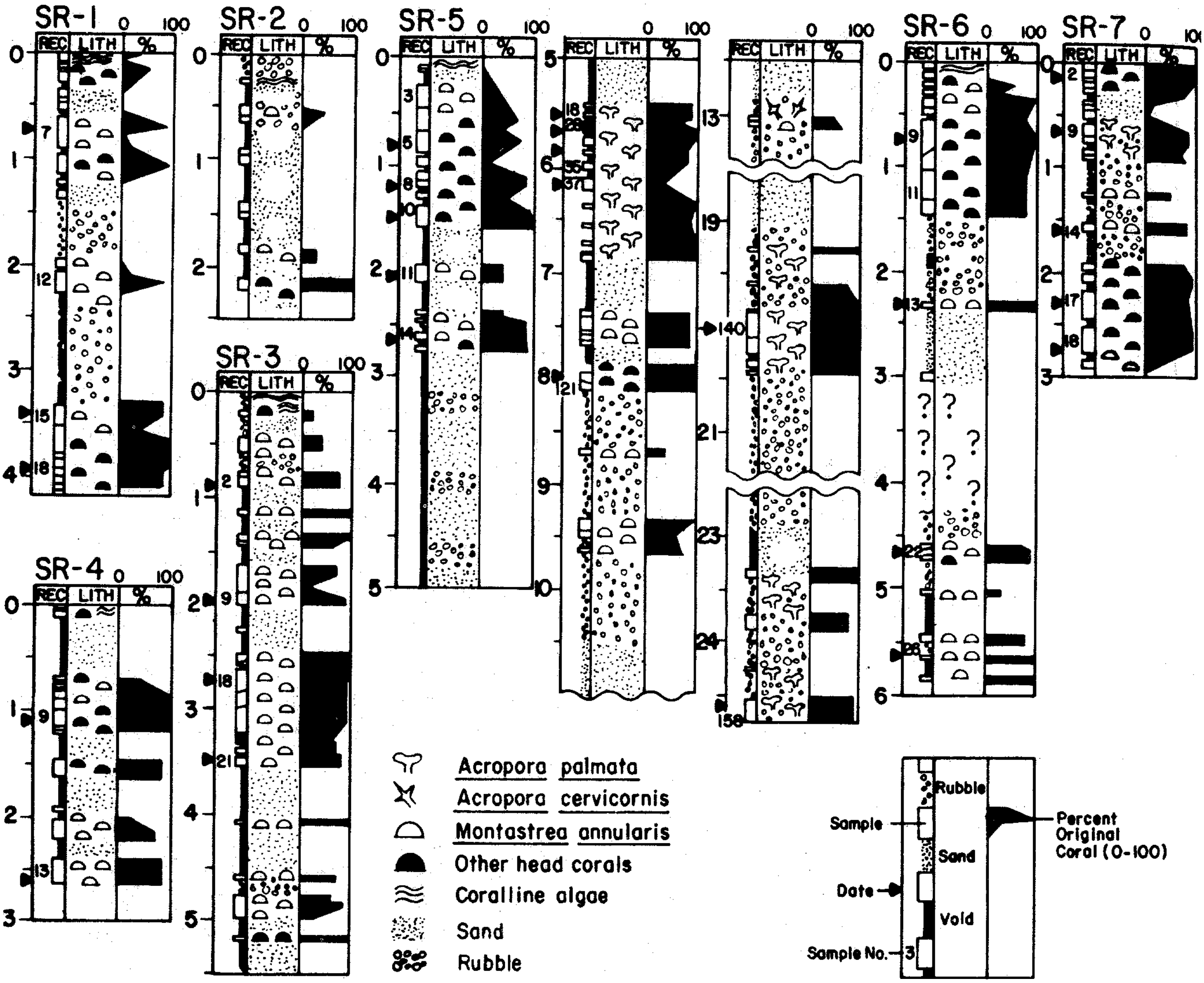

*Figure 15.. Logs for seven horizontal cores from Salt River canyon and the reef separating it from the estuary. The cores are located on Figure 9. Dates are listed in Table 3. Core measurements in meters.*

of lateral accretion along the west wall, the present limit of our coring capabilities.

It is interesting to note that the youngest material recovered from the five horizontal cores from the west wall is approximately 2,000 years old. This implies that while the present reef surface supports a moderate coral community, little if any of that ends up incorporated in the reef interior. Through either decreased carbonate production, increased bioerosion or both, little lateral accretion has occurred along the west wall over the past 2,000 years. This may be related to the dominance of *Agaricia* sp. which is quickly destroyed by bioeroders after death (Elizabeth Chornesky, pers. commun.).

Along the east slope, the alternating dominance of moderately to well-preserved corals and detrital sediment reflects the present-day pattern of localized coral

*Figure 16. (Facing page) Slabs and thin sections from the Salt River cores. A. Borings within Montastrea* annularis. *L =* Lithophaga; *W worm tube; C =* Clionagallery. *Sample SR7-17. Scale is in mm. B. Detrital infills within coral. Sample SRI-17. Photo is roughly 7 mm across. C. Slab of reworked* M. annularis. *Note the sedimentary drape (S) and worm tubes (w). Sample SR5-3. D. Radial cements of aragonite (?) in coral calices. Sample SR3-2. Photo is approximately 5 mm across. E.* Lithophaga *boring in coralline algae. Sample SR6-4. Shell is approximately 2 cm long. F. Sedimentary infills (S; ca. 1 cm across) of Cliona galleries. Sample SRI-11. G. Sediment-filled* Cliona *borings (arrows) in M.* annularis. *Sample SRI-12. H. Thin section of sedimentary infills of photo G. Photo is approximately 7 mm across.*

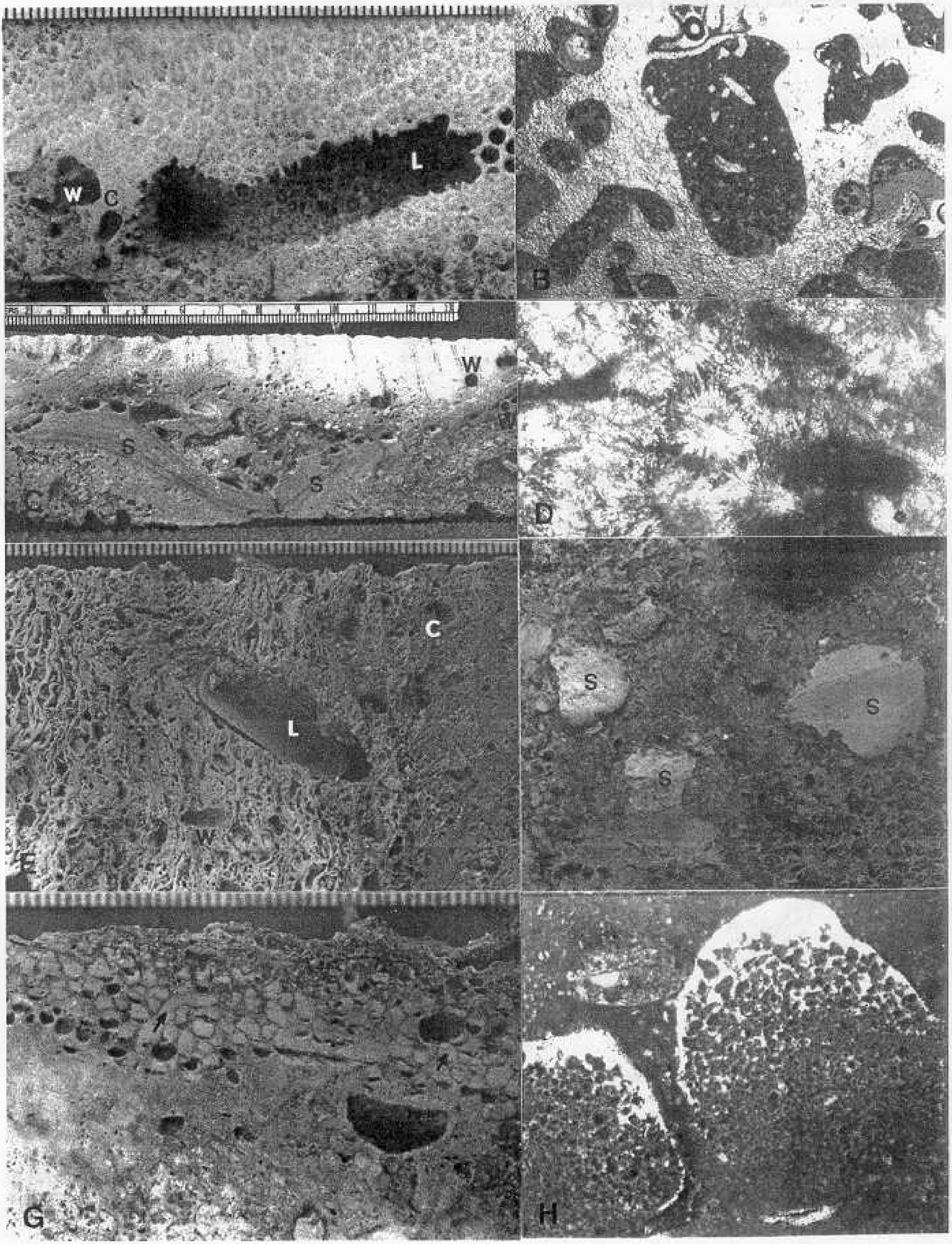
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***Table 3.*** *Radiocarbon dates for Salt River samples.*

| Sample | Age | % Calcite | Sample | Age | % Calcite |
|---|---|---|---|---|---|
| 1-08 | 4,170 ± 90 | 12.0 | 5-28 | 5,210 ± 100 | 0.0 |
| 1-15 | 4,290 80 | | 5-35 | 5,160 ± 90 | 0.0 |
| 1-18 | 4,650 70 | | 5-37 | 5,370 ± 80 | 2.6 |
| 1-07 | 4,560 100 | | 5-121 | 6,100 ± 100 | 0.0 |
| 2-07 | 2,550 ± 80 | 7.5 | 5-141 | 7,400 ± 220 | 0.0 |
| 3-02 | 3,790 ± 100 | | 5-160 | 9,650 ± 220 | 0.0 |
| 3-09 | 3,170 ± 120 | | 6-09 | 5,660 ± 90 | |
| 3-18 | 3,240 ± 80 | | 6-11 | 5,560 ± 70 | |
| 3-21 | 3,140 ± 80 | | 6-13 | 5,370 ± 100 | |
| 4-13 | 2,890 ± 80 | | 6-22 | 5,700 ± 100 | |
| 4-09 | 1,970 ± 60 | | 6-26 | 5,870 ± 100 | |
| 5-05 | 3,740 ± 60 | | 7-02 | 730 ± 60 | |
| 5-08 | 3,640 ± 90 | 5.0 | 7-09 | 1,730 ± 60 | |
| 5-10 | 2,400 ± 70 | 0.0 | 7-14 | 1,650 ± 80 | |
| 5-11 | 5,040 ± 80 | | 7-17 | 1,470 ± 60 | |
| 5-14 | 4,910 ± 60 | 5.0 | 7-18 | 2,010 ± 60 | 0.0 |
| 5-18 | 5,380 ± 80 | 0.0 | | | |

recruitment and short-term success, followed by rapid burial. Aside from one 700-year old head coral in core SR-7, most of the material in the eastern margin is very old, similar to the pattern seen in the west wall. The cessation of reef development in core SR-6 around 6000 ybp may reflect flooding of the eastern shelf. Today, the east slope receives the brunt of the sediment from the east. The flooding of the updrift shelf would have resulted in increasing sedimentation and reef degradation similar to that noted elsewhere on St. Croix by Adey *et al.* (1977) and Macintyre (1988).

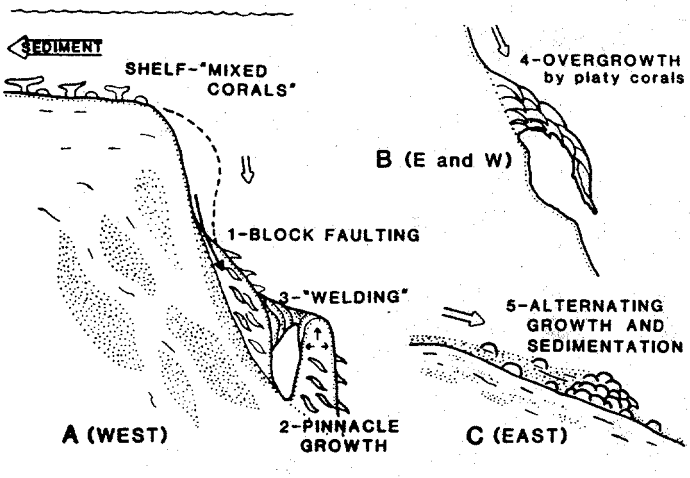

***Figure 17.*** *Styles of reef accretion in Salt River submarine canyon. Along the west wall, slumping, pinnacle growth and overgrowth by platy corals result in an open framework dominated by detritus and displaced reef blocks. On the east slope, the high rates of sedimentation discourage coral growth, and deposition is characterized by alternating intervals of in-place coral growth, detrital sediment and rhodoliths.*

## WHERE TO GO

Estuarine environments are accessible from several points along the shore. A public boat launch on the eastern side of Sugar Bay is convenient to all areas discussed above. Snorkeling is recommended, as is a walk through the extensive mangrove communities at the shore edge. Access is also possible through Columbus Landing Park on the western side of Salt River Bay. Most of the eastern shore is privately owned, and access must be arranged in advance.

The canyon environments are less accessible, and boat support is recommended. It is possible to reach either wall from shore, but the swim is long and strenuous. Several local operators run daily trips to Salt River, and this is the preferred course. Due to the varied visibility and the water depths involved, SCUBA is a must.

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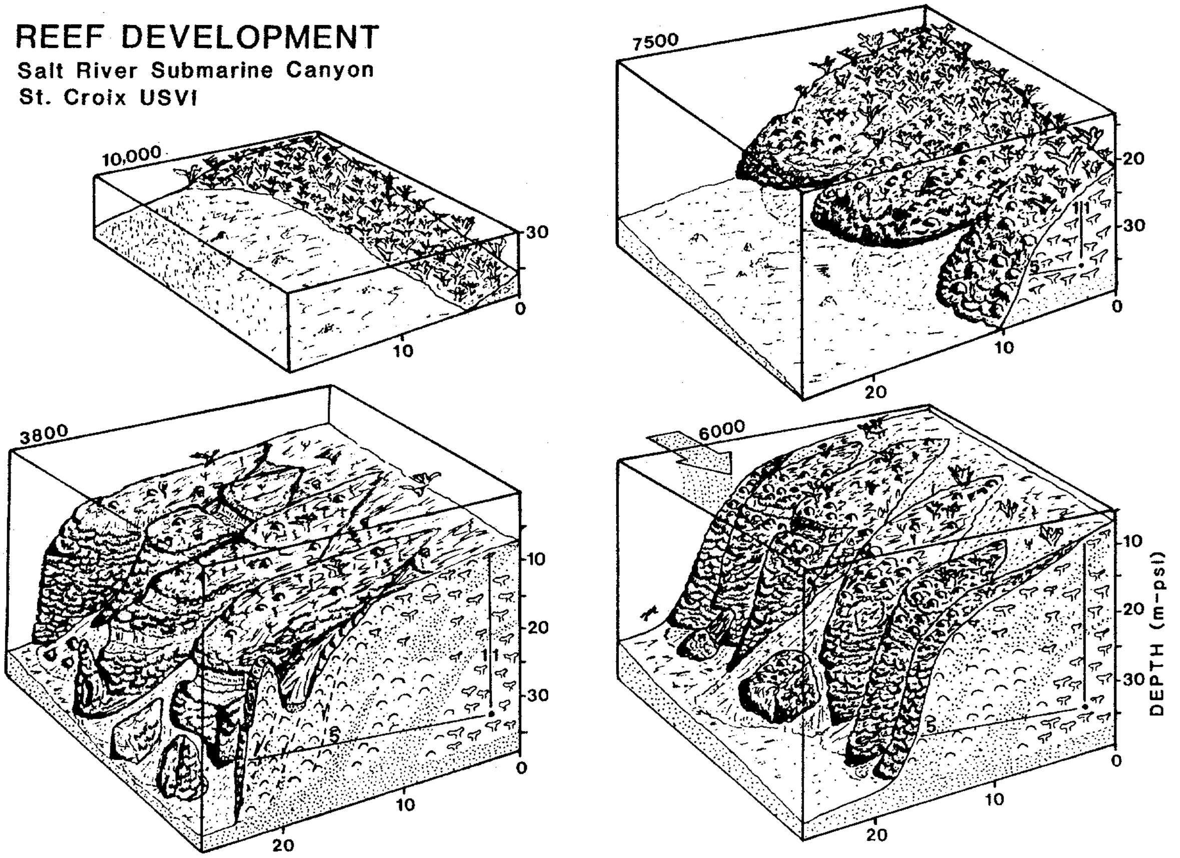

***Figure 18**. Accretionary history of Salt River submarine canyon. From 10,000 to 6,500 ybp accretion was dominated by A.* palmata. *The reef face gradually steepened during this time, and* M. annularis *formed a separate zone on the steepening reef front. By 6,500 ybp, the reef looked similar to today. Slumping dominated the accretionary style. Formation of the estuary at about this time dramatically changed the character of the reef as more sediment-tolerant species started to dominate. By 3,800 ybp the reef had reached a configuration very similar to that seen today. Since then, bioerosion has nearly kept pace with carbonate production, and net accretion has been very slow.*

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