Modern Carbonate Environments of St. Croix and the Caribbean: A General Overview

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INTRODUCTION

As you will see in the accompanying papers, St. Croix offers an impressive array of modern and ancient carbonate environments. This paper outlines general background information on meteorological and oceanographic processes within the Caribbean region. It also discusses variability in reef environments around St. Croix and the Caribbean within the context of local processes. Finally, it provides a brief overview of the wealth of carbonate depositional environments occurring on St. Croix. Hopefully, this will help the reader to put each of the individual, and more detailed descriptions that follow into the larger framework of St. Croix and the greater Caribbean.

METEOROLOGY AND OCEANOGRAPHY

Currents

Oceanographic currents in the region are driven by global circulation around the Equator, and can reach speeds of 0.5 to 1.1 knots (U. S. Naval Oceanographic Office, Sailing Directions, 1963). The North Equatorial Current is deflected along the outer margin of the Windward Islands to form the Antilles Current (Fig. 1). The South Equatorial Current passes into the Caribbean along the northern coast of South America, becoming the Caribbean Current. The latter moves westward into the Gulf of Mexico where it enters a clockwise loop that ultimately passes south of Florida. From there, it joins the Antilles Current and the Gulf Stream.

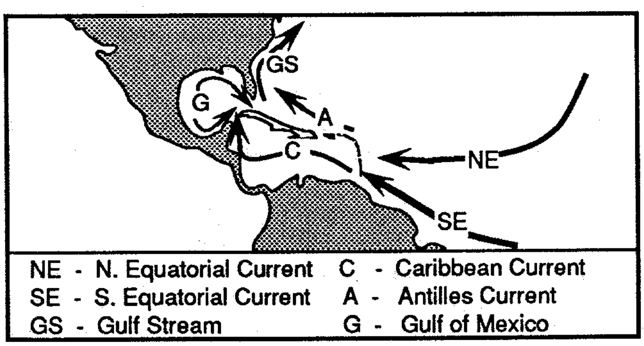


***Figure** 1. Map illustrating the major oceanographic currents of the Caribbean and western Atlantic. After von Arx (1967).*

Tidal range on St. Croix and most of the Caribbean islands is small (generally less than 20 cm; Fig. 2), and the predominant driving forces for shelf and coastal currents are wind and waves. Current speeds do not generally exceed 10 cm/sec, although several exceptions are worth mentioning. Along the northwestern and southwestern corners of St. Croix, strong currents are common. At Hams Bluff (Fig. 3), currents exceeding 15 cm/sec were measured on a very calm day. The current-swept character of the bottom reflects much stronger currents during periods of rougher seas which are more common in this area. Near Sandy Point (Fig. 3), Roberts *et al.* (1982) measured reversing tidal currents approaching 70 cm/sec (Fig. 4), attributing them to the refraction of the tidal wave around St. Croix. In the northern Virgins, tidal differences between the open Atlantic and the Caribbean result in strong tidal currents in the passes between adjacent islands. Between St. Thomas and St. John, currents in excess of 175 cm/sec have been measured (Island Resources Foundation, 1977).

Within enclosed bays and lagoons, current circulation is dominantly wind and wave-driven. In Lamb Bay, on the eastern end of St. Croix, water moved over the reef crest by breaking waves flows to the west and into adjacent Boiler Bay (Fig. 5a). In Christiansted Harbor

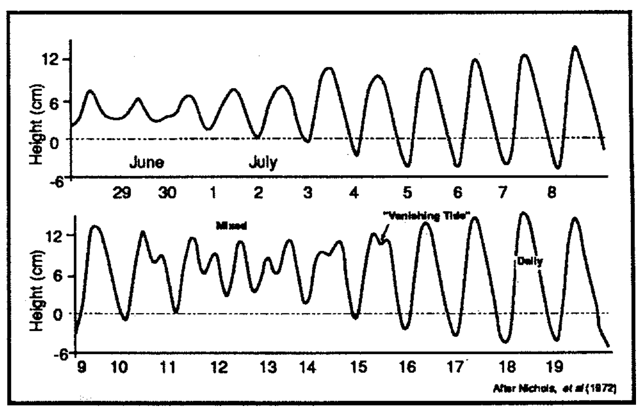
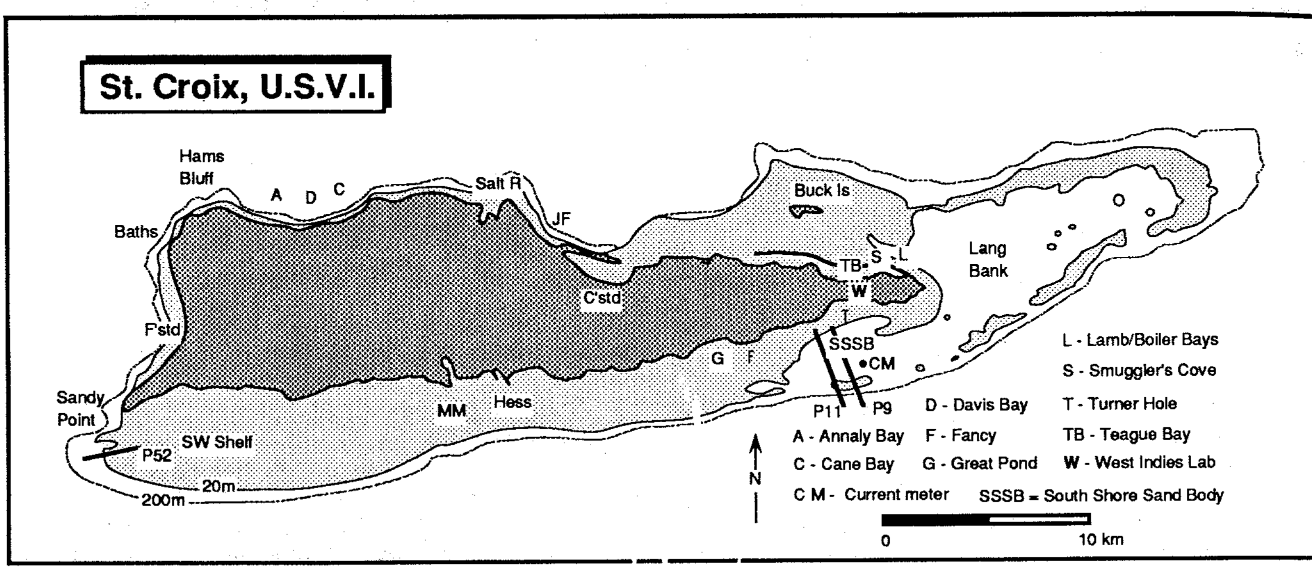


***Figure** 2. Typical tidal curve from Christiansted Harbor. From Nichols et al. (1972).*



Fieure 3. Man showing the locations of places discussed in this and other papers.

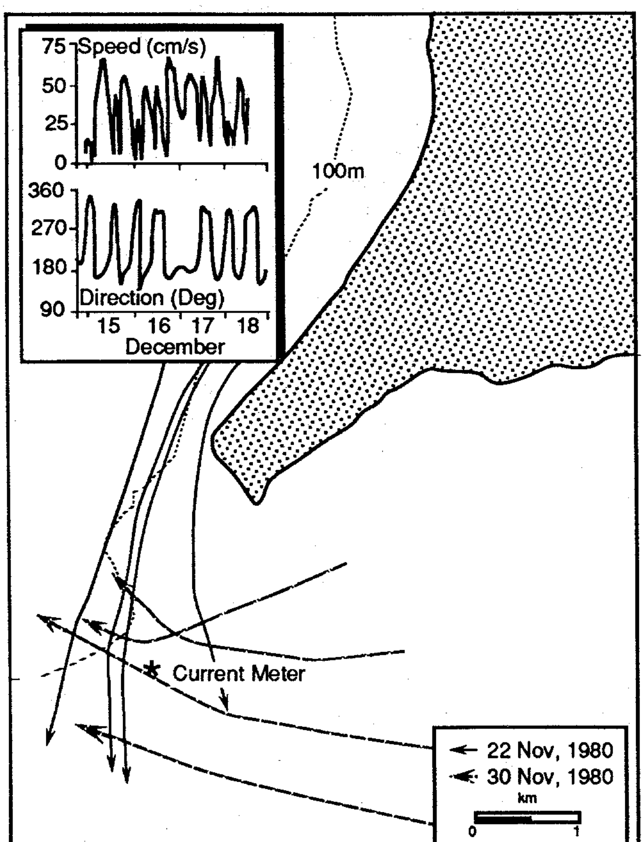


Figure 4. Current patterns in the vicinity of Sandy Point. The arrows are simplified flow paths based on drogue data. A four-day record from an offshore current meter (star) is shown in the inset. After Roberts et al. (1982).

(Fig. 5b) and Salt River Bay (see Figure 4 in the Salt River description), water passing over the reef crest drives a persistent circulation system within the lagoon.

Winds

Oceanic and atmospheric processes are strongly affected by the Bermuda High to the north and the Equatorial Trough to the south. Flow around these features drives the prevailing east-to-west trade winds. During the winter months, intensification of these features results in stronger winds and larger waves.

Roughly four seasons can be defined based on wind data from the U. S. Naval Oceanographic Office (1963; Fig. 6). During the winter months of November through February, wind speeds reach their maximum strength, blowing predominantly from the east and northeast. During the month of January, the Bermuda High to the north is intensified, and wind speeds exceed 20 knots nearly 25% of the time (Brown and Root, 1974). Usually during the month of December the locally named "Christmas Winds" blow at speeds exceeding 25 knots for periods of two to three weeks. These high winds occur when cold fronts are driven to the southeast and through the Caribbean by high-pressure cells forming over North America.

During the spring months (March-May) the trade winds decrease in their intensity, and their approach direction is dominantly from the east. During the summer months, the trade winds again increase in intensity, but a lowering of the barometric pressure within the Equatorial Trough increases the southeasterly wind component and reduces the contribution from the northeast. During the fall (September-November), winds reach their minimum. Warming of Caribbean and Atlantic waters during the late summer and early fall months also leads to the generation

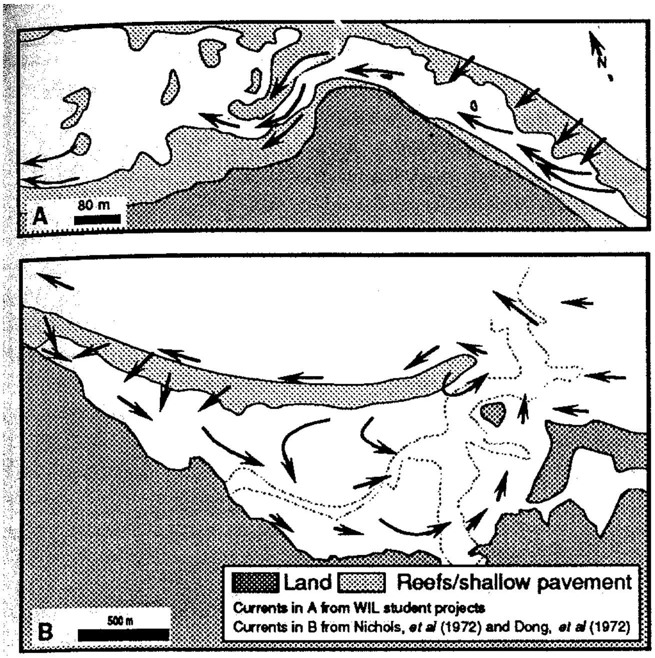


Figure 5. Current patterns in Lamb-Boiler Bay (A) and Christiansted Harbor (B). In both areas currents are driven primarily by waves breaking over the reef crest.

of tropical storms and hurricanes. Local custom celebrates Hurricane Supplication Day at the beginning of "hurricane season" and Hurricane Thanksgiving at its close.

Waves

Figure 7 summarizes the distribution of wave energy across the Caribbean. On an annual basis, waves from the east, northeast and southeast provide the majority of the energy expended on Caribbean shores. In general, total wind and wave strength decreases in a northerly direction from the Windward Islands toward the Bahamas.

In the Virgin Islands, waves come from the east nearly 60% of the time annually (Fig. 8). The calmest periods are during the spring months of March-April and the fall months of September-October. Starting in November, wave intensity gradually increases to a maximum in February, with strong northeasterly and southeasterly wave components added to the easterly Trades late in this period.

Due to its location behind the chain of islands to the north, St. Croix is largely protected from north Atlantic swell. Throughout the year, waves with heights less than one foot are consistently more important on St. Croix than further to the north (Fig. 9). During both the summer and winter months, the wave spectrum is narrower, excluding larger swell experienced in the northern, more-exposed islands of St. Thomas, St. John and the British Virgin Islands. Throughout the year, longer-period swell on St. Croix are confined to the southeast, with the exception of large waves that make it through the northern Anegada Passage about once a year (note: these are not reflected in Figure 9, but are common knowledge to local mariners).

The role of storms - Periods of heavy weather can occur throughout the year, and are related to either 1) the passage of low-pressure systems from the east, or 2) the westward movement of cold fronts driven by high-pressure systems on the North American continent. The period of greatest storm frequency occurs in the late summer and early fall months (maximum frequency is in late August and early September) when circumtropical waters are at their warmest. During this time numerous tropical storms and hurricanes are generated in the Atlantic Ocean and move westward through or near the Caribbean region. Over the past century, there have been only four major hurricanes that have passed directly through the U. S. Virgin Islands (U. S. Army, 1975). However, many have passed close enough to cause severe flooding, coastal erosion and reef damage. Notable examples within the past decade have been hurricane David and tropical storm Frederick in 1979, hurricane Allen in 1980 and tropical storm Klaus in 1984.

There are two dominant storm tracks through the region (Fig. 10). One passes to the north of the Antilles and into the northern Bahamas. Some of these storms are strong enough to pass up the east coast of North America as far as New England. The other track enters the eastern Caribbean midway along the Windward Island chain. From there, it passes to the south of St. Croix and into the southern Gulf of Mexico.

REEF TYPES OF THE CARIBBEAN

Despite the "standard reef models" published in most of the Caribbean reef literature, reefs in this region exhibit considerable variability. Some of the more recent discussions by Adey and Burke (1976) and Adey (1977) have dispelled old beliefs that algal ridges do not exist in

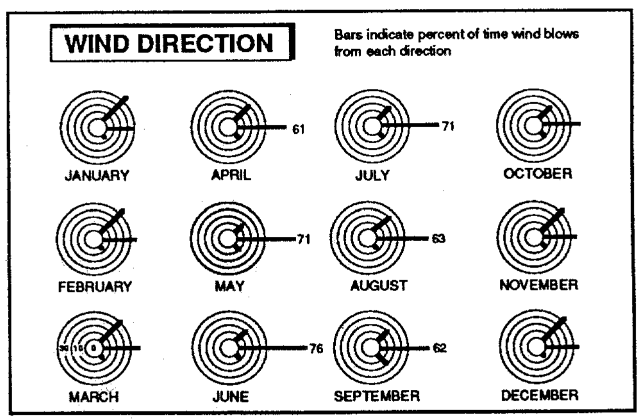


Figure 6. Wind data for the Virgin Islands. The length of each bar represents the percentage of the time that winds blow from that direction. Each concentric circle represents 19%. Note the dominance of easterly winds. In general, the strongest winds blow during the winter months. Data from the U. S. Naval Oceanographic Office (1963).

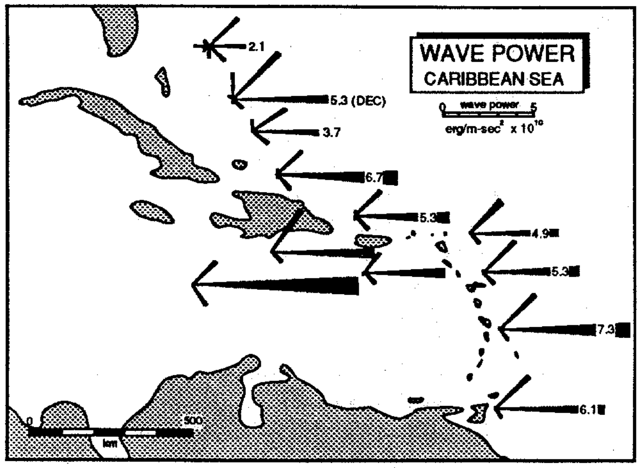


Figure 7. Wave-energy distribution throughout the Caribbean Sea. The length of each bar represents the total wave energy coming from each direction on an annual basis. Note the strong dominance of easterly waves. Also note that total wave energy generally decreases and spreads out among the different directions as one moves toward the northern Bahamas. Seasonal data are provided for the U. S. Virgin Islands in Figure 8. Data are from the U. S. Naval Weather Service Command (1970). Calculations of wave power are based on the methods of Walton (1973) and Nummedal (1975).

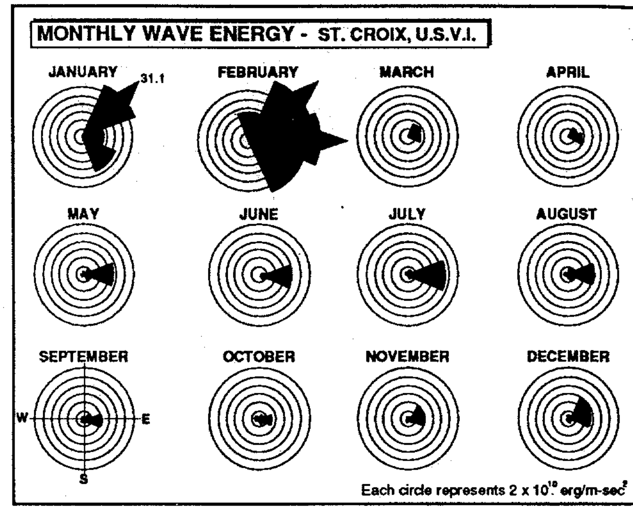


Figure 8. Monthly variations in the wave-energy distribution occurring in the U. S. Virgin Islands. Note the high wave energies in January and February associated with seasonal strengthening of the Bermuda High to the north and the Equatorial Trough to the south. Northeasterly waves are likely related to frontal passage. During the rest of the year, wave energy is much lower and comes predominantly from the east. Data are from the U. S. Naval Weather Service Command (1970). Calculations of wave power are based on the methods of Walton (1973) and Nummedal (1975).

the Caribbean (Milliman, 1974). Geister (1977) and Adey (1978) provided a preliminary discussion of the variability that exist in reefs of the region, and invoked a primary control by prevailing wave energy. Algal ridges prevailed in high-energy areas, *Acropora palmata* dominated the reef crest in areas of slightly lower wave energy, and *Acropora cervicornis* persisted only, inmore-protected settings. These ideas have been reinforced in a more recent discussion by Macintyre (1988).

A closer examination of the reef types, originally described by Adey, reveals that in addition to prevailing wave energy, major storms likely play an important role in the distribution of reef-crest communities throughout the Caribbean. Figure 10 summarizes the data on prevailing waves and storm frequency, as well as the reef types of Adey (1977) and Macintyre (1988). Algal ridges occur mostly in the eastern Caribbean where prevailing seas are larger and storms are more frequent (Table 1). Most of these reefs have deeper cores dominated by *Acropora palmata* (Adey, 1975). Before reaching sea level, the crests of these accreting reefs could sustain an *A. palmata* community as even slightly deeper water buffered the energy of destructive waves. Once the reefs reached sea level, however, frequent hurricanes reduced the large branching corals on the reef crests to rubble which was later bound together by algal overgrowth and submarine cementation. The coral rubble provided a substrate suitable for overgrowth by corallines, and the high prevailing seas discouraged grazing herbivores which could prevent the accumulation of thick algal crusts in a lower-energy setting. It is interesting that Adey and Burke (1976) noted the most spectacular ridge development on the island of Marie Galante. As hurricanes move westward, the anticyclonic circulation of winds around the low-pressure center results in the highest waves on the northern side of the storm track. Marie Galante sits just to the right of the southerly hurricane path through the Caribbean, and would receive the highest hurricane waves anywhere in the Windward Islands.

In the northern Bahamas, hurricane frequency is similarly high and *A. palmata* reefs are frequently destroyed by passing storms. Unlike the eastern Caribbean, however, this area is characterized by much lower prevailing wave energy. The resulting higher levels of sedimentation and predation, along with low water temperature, discourage the development of lush reef communities characteristic of the rest of the Caribbean (Table 1).

In the western Caribbean off Belize, Adey (1978) and Burke (1982) described luxurient A. *cervicornis* reefs in environments protected by offshore cays. Macintyre *et al.* (1977) documented a thick accumulation of this fast-growing coral and proposed that such assemblages are characteristic of these protected sites.

The reefs of St. Croix and the northeastern Caribbean are located midway between those of the northern Bahamas and the Windward Islands both geographically and from a standpoint of wave energy (Table 1). The dominant hurricane tracks are to the north and south of these islands, and severe hurricane damage is not a regular occurrence.

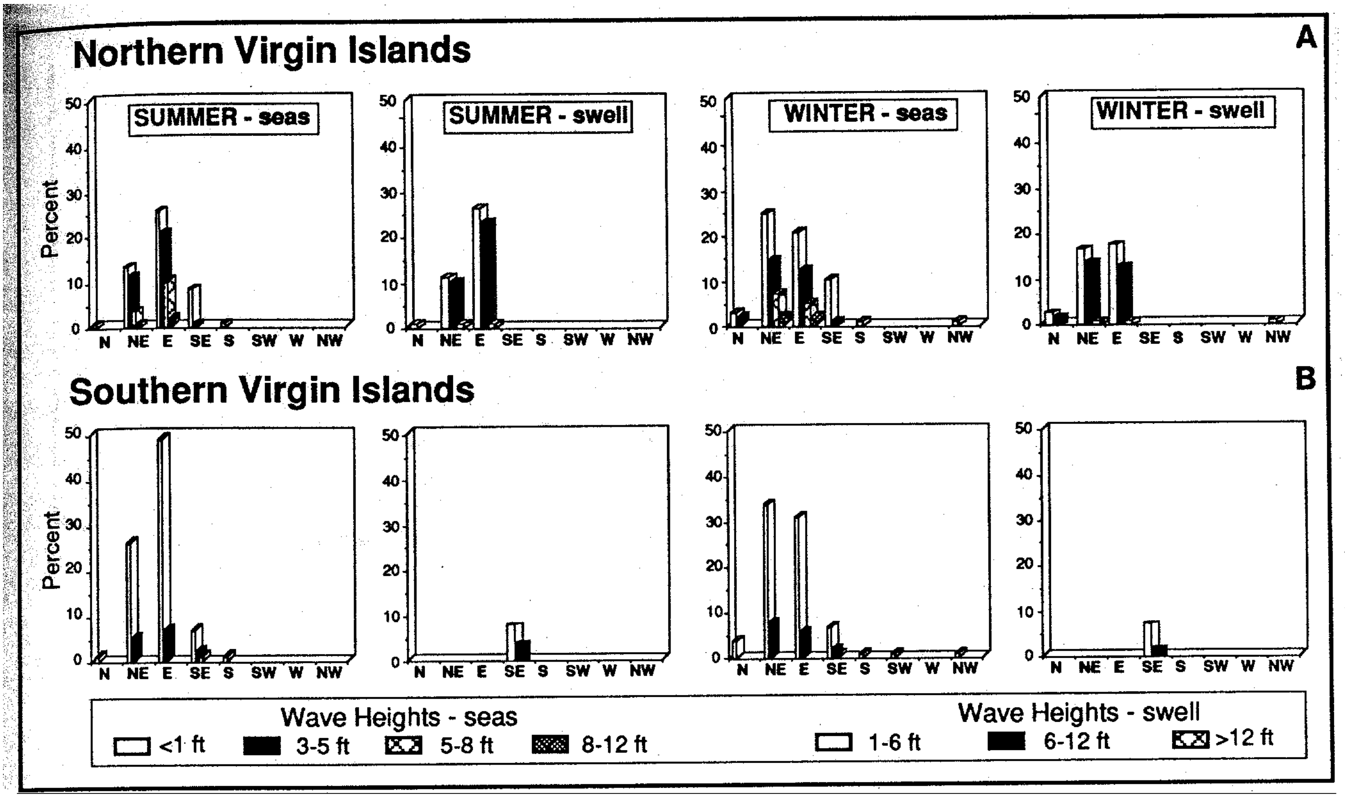


Figure 9. Variations in wave conditions between the more-exposed northern Virgin Islands (A) and St. Croix (B). In general, waves are higher in the northern Islands. The greater importance of swell to the north is related to exposure to the open Atlantic. On St. Croix, *swell generally approaches more from the south, compared to a more northerly and easterly approach on St. Thomas and St. John. Data from U. S. Naval Oceanographic Office (1963).*

Table 1. Prevailing wave energy and storm frequency as a control of reef type in the Caribbean.

REEF-CREST TYPE	WAVE ENERGY	HURRICANE FREQUENCY
Pavement Reef	Low	High
Acropora palmata	Moderate to High	Moderate
Algal Ridges	High	High
A. cervicornis	Low	Low

Prevailing wave energy is still adequate to remove excess sediment and biological wastes while also discouraging grazers. In this energetic environment, A. *palmata* flourishes. Its capacity for rapid calcification allows A. *palmata* to grow above the active traction carpet of sedimentcon the reef crest. Without the regular breakage by storm waves that frequent the northern and southern ends of the region, large colonies of this branching coral are common features around many of the islands, especially along the north coast of St. Croix where additional protection is provided by the islands to the north.

Less is known of the depositional processes of the deeper (20-50 m) reefs of the Caribbean. Descriptions in the literature are usually parenthetical, and detailed core investigations are few (Macintyre *et* al.,1982; Hubbard *et* al., 1985, 1986). The areal extent of deeper and more-exposed forereef settings (i.e. the shallow reefs drilled to date occupy less than 10% of the shelf) make them ripe targets for research in the near future.

MODERN CARBONATE ENVIRONMENTS OF ST. CROIX (FIG. 3)

Despite its small size, St. Croix boasts a surprising variety of shallow and deep-water carbonate environments. The following section provides a broad overview of several of these areas. More detailed descriptions of most of these areas immediately follow this paper.

Shallow Reefs

Most of the shallow, emergent reefs of St. Croix occur along the eastern (i.e. windward) end of the island. Differences in shelf orientation, exposure to wave energy, and substrate type have resulted in a wide variety of shallow-reef types within a relatively small geographical area.

Buck Island - Probably the best-known reefs in the area are located within the Buck Island National

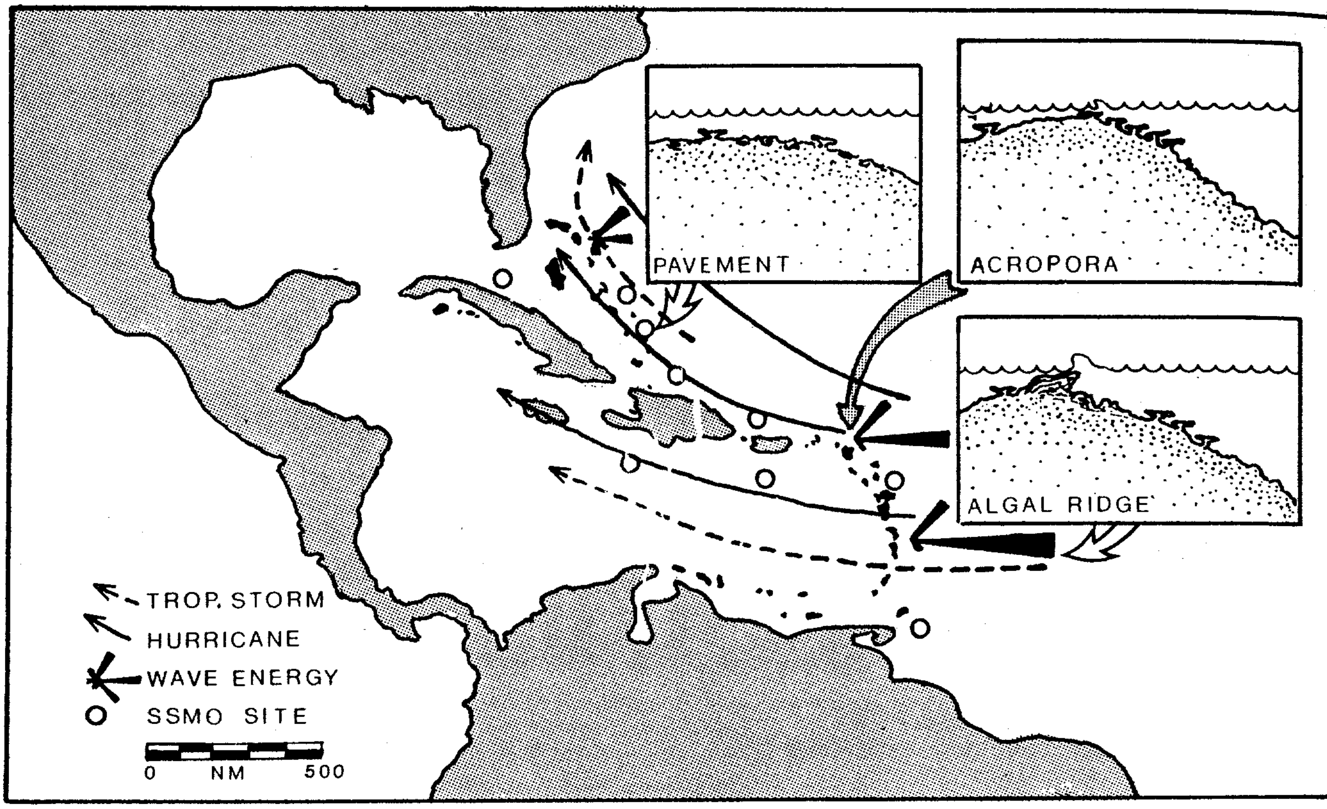


Figure 10. Reef type as a function of prevailing wave energy and hurricane frequency. Weather data are derived from Figure 7. Reef type is based on the work of Walter Adey of the Smithsonian Institution. Pavement reefs occur primarily in the northern Bahamas where hurricane frequency (and large, oceanic swell) is high, and intervening periods are dominated by calmer conditions. In the eastern Caribbean, hurricane frequency is again high, but prevailing seas are more powerful than to the north. As a result, the reef crest is dominated by coralline algae. In the northeastern Caribbean (including the north shore of St. Croix), both hurricane frequency and prevailing wave conditions are more moderate, and a coral community more dominated by Acropora palmata *is the norm.*

Underwater Monument north of St. Croix. Some of the largest and most impressive stands of the elkhorn coral *Acropora palmata* can be found in this area. Today, most of these stands have been ravaged by "white band disease", and dead colonies remain upright as a reminder of what the area once looked like (see the paper by Bythell *et al.* in this volume for details on short-term variability in the Buck Island area). The small size of this reef and lagoon makes it an ideal area for an introduction to reef systems. Snorkelers are afforded excellent access to a well-maintained "snorkel trail", and SCUBA divers can take advantage of the spectacular forereef and the unusual pinnacle reefs that dot the shelf to the north.

Tague Bay Reef System - Most of the northeast shore of St. Croix is protected by Tague Reef. At its eastern end, the reef is very close to shore, and small bays are formed between successive points of land (e.g. Lamb and Boiler Bays). Along the remainder of its length, the reef forms a continuous barrier that protects the lagoons in Smuggler's Cove and Tague Bay. These larger lagoons support a variety of marine flora and fauna, and provide an excellent setting within which to examine sedimentary processes and animal-sediment interactions.

Christiansted Harbor and Long Reef - Off the town of Christiansted, Long Reef protects a harbor that has been a center for commerce and trade throughout much of the five centuries since European "discovery" of the Caribbean. While Christiansted represents the earliest known attempt at "zoning", the present waterfront is the unfortunate site of numerous land and water-use conflicts. Intense development pressure provides all-too-good an opportunity to examine the effects of development on both the small-island infrastructure and the fragile carbonate environments of the harbor.

Long Reef forms a nearly complete barrier; to wave attack. The forereef area is characterized by variable and spectacular spur-and-groove topography. In front of the harbor, the reef channels are low (ca. 1-2 m) and are dominated by various species of head corals. To the west, near Judith's Fancy, relief on the channels exceeds 5 meters, and the dominant community shifts to *Acropora cervicornis* and species of *Agaricia.*

Southeastern St. Croix reefs - Along the southern shore of the island, the reefs and lagoons occur as somewhat isolated systems separated by Cretaceous headlands. Turner Hole, Robin Bay, Fancy Bay and Great Pond Bay are all excellent examples of small to moderate-sized lagoons fronted by well-developed barrier reefs. At Great Pond, terrigenous sediments drain from a large watershed, providing an excellent opportunity to examine a terrigenous-to-carbonate transition.

Because the southern coast faces into one of the dominant hurricane paths through the Caribbean, modest examples of algal ridges can be seen at a number of sites. Probably the most spectacular examples occur at Robin Bay. Cores through these ridges by Dr. Walter Adey (1975) of the Smithsonian Institution have documented the succession from early, A. *palmata* reefs to the present-day, coralline reef crest. Caves formed by coralline algae overgrowing former reef channels provide spectacular underwater vistas and a unique opportunity to directly observe the evolutionary sequence preserved in the interiors of these reefs.

The St. Croix Shelf Reefs

In general, emergent (i.e. barrier; fringing) reefs do not occur west of mid-island. Also, the eastern shelf is wide and does not support a shallow-water reef community at its edge. In these areas, a variety of "shelf-edge" reefs are found. Even though they do not occur in "shallow" water, and are often below fair-weather wave base, these reefs are actively accreting entities and exhibit all the criteria of card-carrying reefs. Further investigation may reveal that these kinds of environments are more analogous to some ancient systems than are the shallow reefs to which shelf-edge reefs have traditionally been compared.

Lang Bank - To the east and south of the island, a broad insular shelf extends offshore more than 5 km. To the east, Lank Bank extends nearly 15 km in water depths averaging 20-30 m. Just prior to Holocene flooding of the bank top 9000 years ago, the submerged margins were likely dominated *by A. palmata* reefs (Adey *et al.*, 1977). After flooding, the reefs along the southern margin were killed off, probably by sediment stripped from the updrift bank surface by wave action. Today the bank surface is predominantly a submarine hardground dominated by gorgonians, sponges and scattered head corals. This area is the site of a WIL-NSF study to hopefully document the internal character and Holocene development of the entire platform.

Southeastern Shelf - Along the shelf-edge to the south of St. Croix, a narrow reef persists in water depths of 30-50 m. This is probably an extension of a similar feature seen along the southern margin of Lang Bank. Coral cover is sparse on these reefs, owing to both the great water depth and the transport of detrital sediment into the area from the shelf to the east. The shelf-edge reefs are separated from a broad inshore hardground and sand flats by a broad moat of varying width (Fig. 11). A large sand body off Turner Hole (south-shore sand body; Fig. 3) serves as a major pathway for sediment moved from the more easterly shelf into the deep basin to the south.

Southwestern shelf - The last emergent reefs along the south shore occur near the Hess Oil Refinery. Most of the southwestern shelf is dominated by a broad, sandy plain with abundant stands of *Halimeda* and *Penicillus*. Sediment produced along this shelf is moved westward by surprisingly strong tidal and wind-generated currents (Fig. 4). Along the shore, littoral sediments have formed Sandy Point, the largest turtle-nesting area on the island. Sediments moving over the downdrift flank of the island have buried reefs that previously occurred in the area (Fig. 12).

Hams Bluff to Cane Bay - Along the northwest corner of the island the shelf is very narrow, and no emergent barrier reefs occur. Nevertheless, the benthic communities are widely varied and often quite luxurient. Off Hams Bluff, the bottom is current-swept and large basket sponges dominate the seascape. At Cane and Davis Bays, rich coral communities occur within easy reach from shore. Along the entire shelf break in this area, a vertical reef wall starts at water depths varying from 25 to 80 meters. A large slump in the shelf near Estate North Star provides a spectacular vertical reef wall in shallower (< 20 m) water more accesible to less-experienced divers. This 5-km long embayment is a site of continuing research by West Indies Laboratory, and is one of the best-studied shelf-edge areas in the Caribbean.

North-shore submarine canyons - Two excellent examples of submarine canyons can be found along the north shore of St. Croix. The larger of the two extends from the entrance to Christiansted Harbor into the Virgin Islands Basin. This canyon receives both sediment and organic detritus from the broad shelf to the east and serves as a conduit through which these are fed into the deep ocean (Hubbard *et al.*, 1982; Suchanek *et al.*, 1985).

A smaller canyon off Salt River likely occupies a relict river course cut during a previous lowstand of sea level. Associated with the canyon system is an upland estuary separated by a narrow, emergent reef. The luxurient mangrove community and strong terrestrial influence in the estuary make this an excellent area to view a dramatic terrestrial-to-marine transition. From an historical standpoint, Salt River was the site of Christopher Columbus' first landfall on his second voyage to the new world in 1493. Today, it is a focal point of a national research program funded by the National Oceanic and Atmospheric Administration and conducted by Fairleigh Dickinson University. Salt River submarine canyon has been a major center for reef research since this cooperative study was initiated by Dr. Robert F. Dill, the former Director of the West Indies Laboratory.

SUMMARY

The shallow-water carbonate environments of St. Croix are numerous and varied. In addition, the physical size of the island and its associated carbonate systems offer

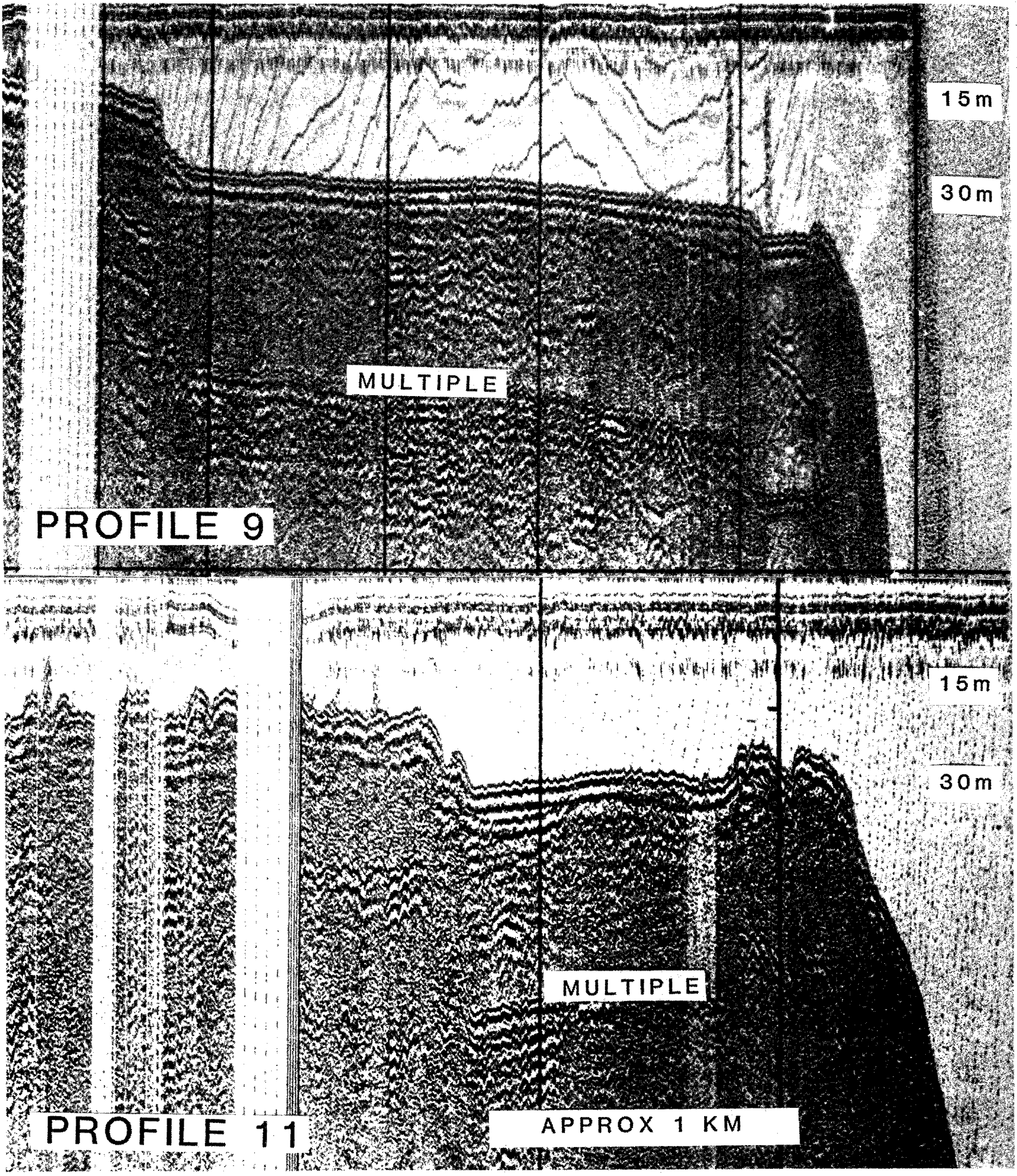


Figure 11. Seismic profiles across the southern shelf of St. Croix (see Figure 3 for locations). Profile 9 crosses near the axis of the South Shore Sand Body, a major sediment-transport pathway. Coral cover on the inner shelf is restricted and sediment thickness ranges up to slightly over one meter. To the west (profile 11), the shelf-edge reef is better developed, probably in response to lower levels of sediment stress. A broad, sediment-filled moat separates the outer reefs from the inner shelf where pavement and scattered reef communities occur.

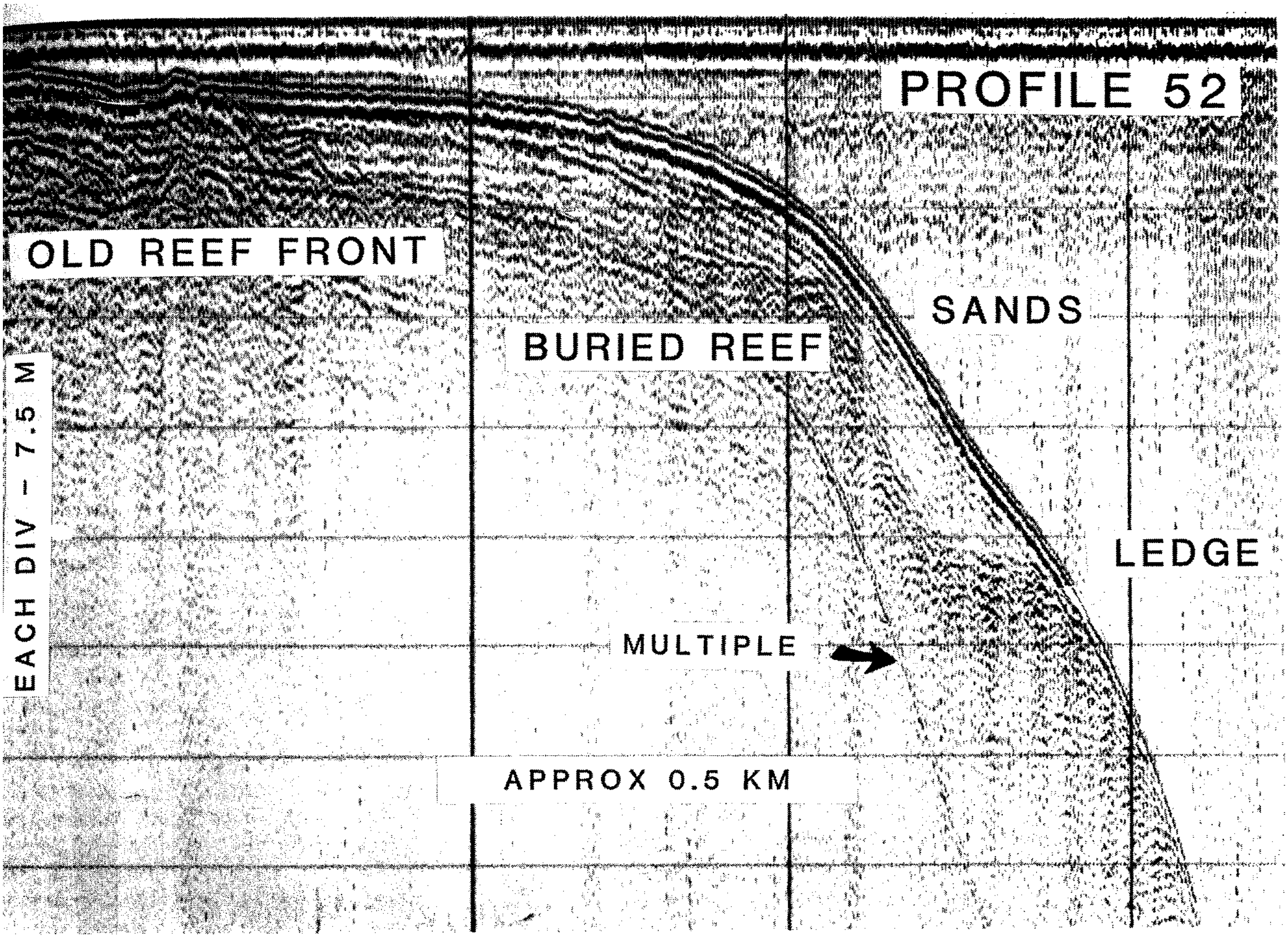


Figure 12. Seismic profile across the downdrf margin of St. Croix near Sandy Point. Sediments likely buried the reefs along this margin after the updrift shelf was flooded. This is similar to the downdrift margin described on Little Bahama Bank by Hine and Neumann (1977). The profile is located on Figure 3.

distinct advantages to the researcher trying to maximize efficiency in viewing and understanding the greatest number of environments in the least amount of time. Most environments are within a short boat or vehicle ride from one another. The modest size of the individual reef-lagoon systems permits the student or researcher to easily put each sub-environment within the framework of the larger system. On a somewhat larger scale, gradients in wave energy, sediment stress and other factors that control reef development, can be more easily understood than in places where these gradients occur over hundreds instead of tens of kilometers. And certainly not least of all, the close proximity of modern and ancient analogues (see papers by Gill *et al.* and Hubbard *et al.* in this volume) provides ample opportunity to compare modern carbonate environments to their ancient counterparts.

This guidebook is but a brief introduction to the vast array of environments available for study. It is hoped that within the following pages the reader will come to appreciate the value of St. Croix as a natural laboratory and will be inspired to visit not only the areas described below, but to seek out new areas as well.

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