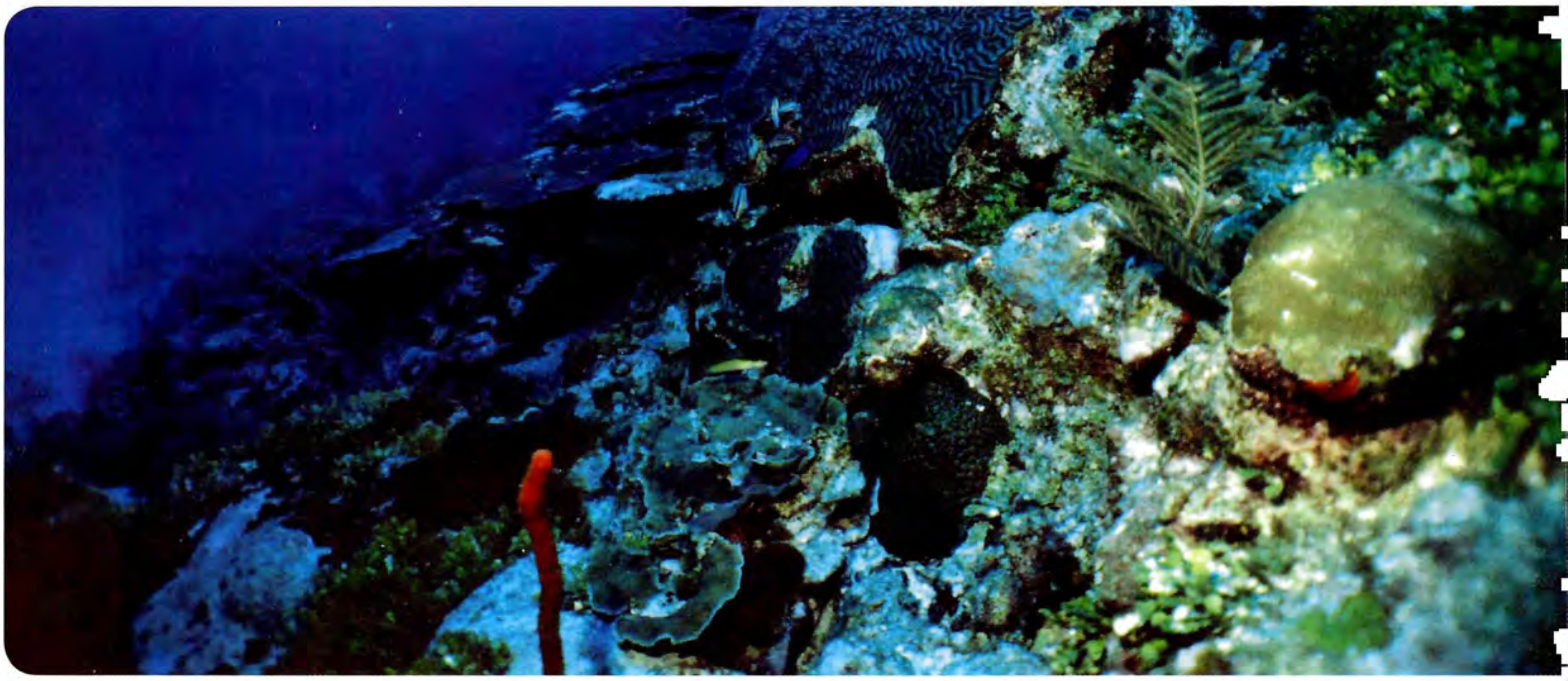
REEF ENVIRONMENTS AND GEOLOGY OF AN OCEANIC ARCHIPELAGO: SAN ANDRÉS, OLD PROVIDENCE AND SANTA CATALINA (CARIBBEAN SEA, COLOMBIA)

with Field Guide



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República de Colombia
MINISTERIO DE MINAS Y ENERGÍA

INSTITUTO COLOMBIANO DE GEOLOGÍA Y MINERÍA
INGEOMINAS

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Foto: Estación en el mar Cl. San Andrés: Pared vertical de Bocatora Hole a -30 m. El coral Montastraea sp. adoptó una forma plana. Agosto de 1998.

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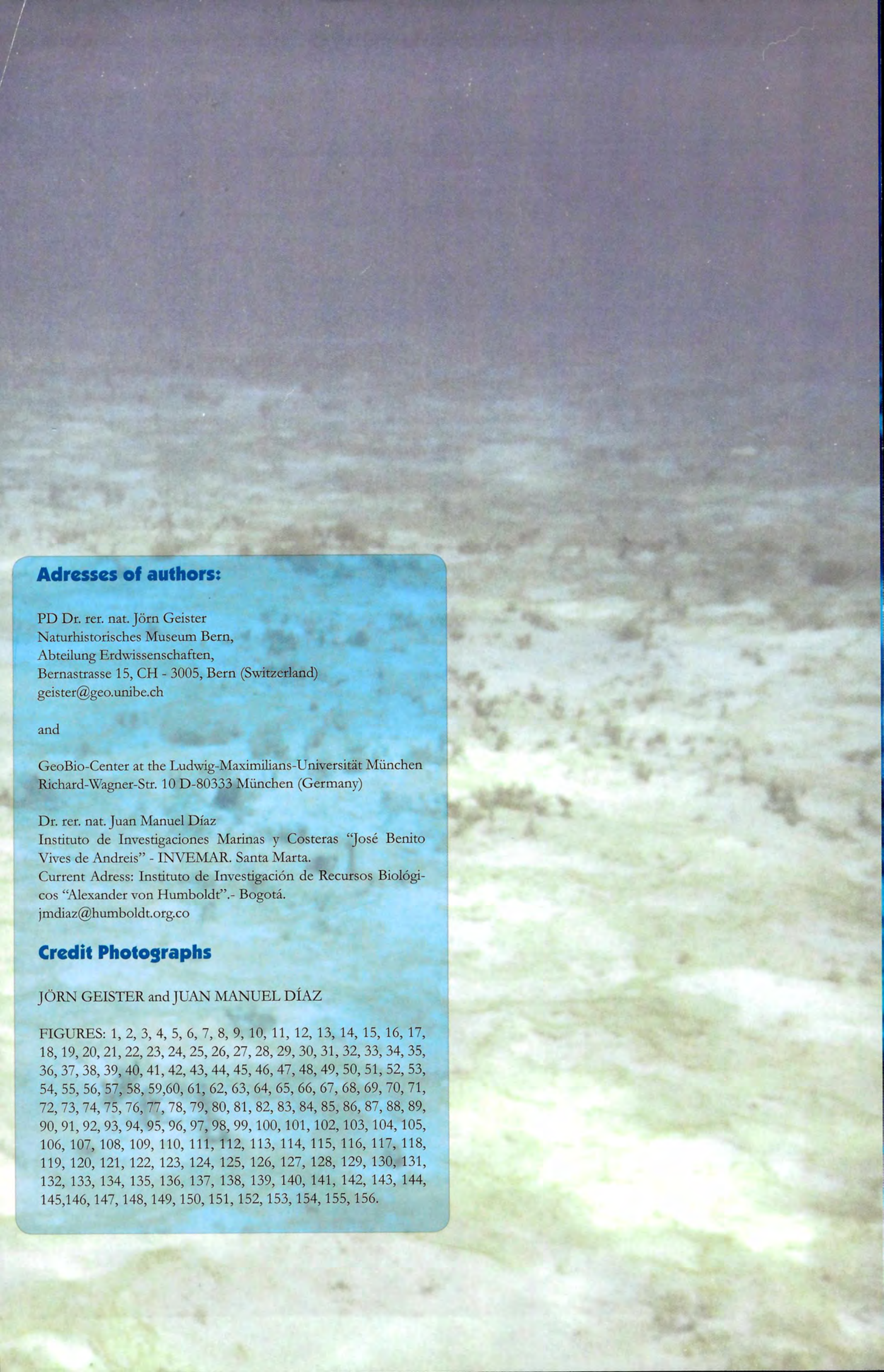
CONTENT



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PREFACE

This book compiles the results of studies carried out in the Archipélago since 1968 (J.G.) together with the results of more recent unpublished work. Early re-surveys of the reefs and reconnaissance studies in the volcanic rocks of Old Providence were carried out in 1979 in the company of Marion Frantz. Subsequent studies which focused on the degradation of San Andrés reefs and on the exploration of the four surrounding atolls (JMD) were supported by INVEMAR and COLCIENCIAS (Bogotá). The present book is based on a field-guide prepared and published for the "8th International Coral Reef Symposiurn" held at Panama City in 1996 (Geister & Díaz 1997). That guide and the present book were only possible after a joint re-survey of the reefs carried out by both authors in October 1994 at San Andrés and Old Providence; this survey was financed by COLCIENCIAS (Bogotá) and supported by INVEMAR, the Corporación CORALINA and the Swiss Ministry of Foreign Affairs (EDA/DEH). Subsequent (1998) studies in the Quitasueño Bank were financed by COLCIENCIAS (grant to J. M. D.) and supported by the Swiss Ministry of Foreign Affairs (EDA/DEH) (grant to J.G.). The "Dr. Karl Bretscher Foundation", Bern (grants to J. G.), financed supplementary research carried out at San Andrés in 1996, 1998 and 1999. In 2000, a topographic survey of the North Cliff and May Cliff areas at San Andrés was carefully performed by local governmental topographer Mr. McLean in order to facilitate reconstruction of paleo sea-levels from old intertidal notches. Finally, the volcanic rocks of Old Providence and Sta. Catalina were studied in more detail during two weeks of fieldwork in August 2002; this investigation was carried out with the active participation of Alvaro Nivia and financed by the Geological Survey of Colombia. The authors are especially grateful to INVEMAR and COLCIENCIAS (Bogotá) and to the direction of INGEOMINAS and CORALINA for the support offered to them over many years of field studies.

Claudio Scarcia (Bern) contributed mapping results from the southern part of Old Providence and geochemical data of volcanic rocks. Geochemical analyses of volcanic rock samples were carried out by the Institut de Minéralogie et de Pétrographie of the University of Fribourg and the Institut de Minéralogie et de Géochimie of the University of Lausanne (both Switzerland). We are grateful to Nan Mercolli (Bern) for his advice on volcanic rock samples and comments on the text concerning Old Providence. Photographic work was financed by the Institut für Geologie of the University of Bern .

Graphic support and drafting was done by GEOTEC Ltda. (Bogotá). Much encouragement came from Fabio Cediel (GEOTEC, Bogotá), who reviewed the manuscript and edited the book. Stylistic suggestions for the English text were provided by Charles Monson (Iowa City, U.S.A.).

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Jörn Geister and Juan Manuel Díaz

1. GENERAL BACKGROUND

The Archipélago of San Andrés, Old Providence and Sta. Catalina is situated on the Lower Nicaraguan Rise in the western Caribbean Sea. It comprises two high-standing oceanic islands and a series of atolls and coral banks which are aligned in a NNE direction (figs. 1 and 2). Although it is geographically closer to Central America than to the South American continent, the Archipélago has been part of the Republic of Colombia since 1822. A Carib Indian aboriginal population never settled on the islands, but San Andrés and Old Providence were visited now and then by Miskito Indians from the Central American coast, who came to catch fish and turtles. The islands were "discovered" early in the 16th century by Spanish sailors. The first settlers on the islands at the beginning of the 17 th century were Dutch smugglers and English Puritans. The islands changed hands between English and Spanish rulers from 1641 to 1822, with occasional conquests by pirates from Jamaica and Haití (Parsons 1956, 1964).

Only the two major islands, San Andrés and Old Providence (with Sta. Catalina), are permanently inhabited. San Andrés, which has a tourist industry and a population of 60,000-90,000, is the administrative and commercial center. With a surface area of only 25 km^2, San Andrés is probably the most densely populated high-standing island in the Caribbean. By contrast, immigration from the mainland to Old Providence (in Spanish, Providencia) has always been low. Its 4,500 inhabitants are mostly English-speaking. They live predominantly through subsistence farming, fishing, cattle breeding and small-scale tourism. Several tiny cays exist close to the major islands and on most of the atolls of the Archipelago. These are visited regularly by fishermen and by chartered tourist boats from San Andrés and Old Providence. Military posts of the Colombian Navy exist on certain sandy cays of the atolls.

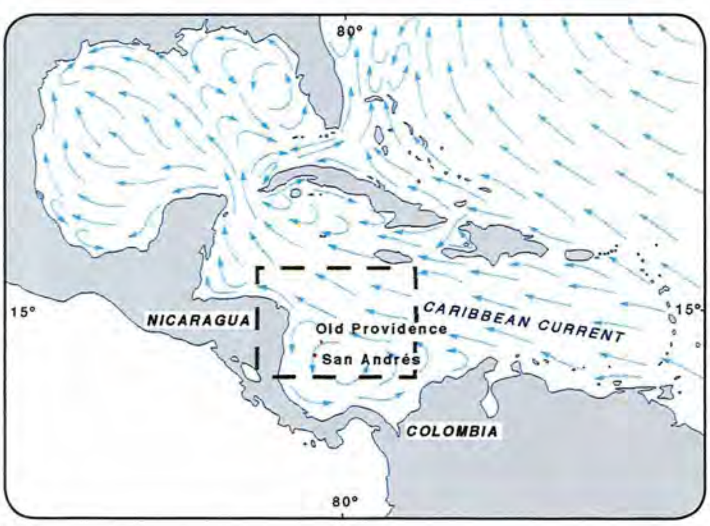


Figure. 1 Map of the West Indies showing the location of the Archipelago of San Andrés, Old Providence and Sta. Catalina in the western Caribbean Sea (inset). Surface current pattern prevailing during summer is indicated by arrows (based on U.S. Naval Oceanogr. Off. Publ. 700, 1965).

Figure. 2 The islands and atolls belonging to the Colombian Archipelago of San Andrés, Old Providence and Sta. Catalina (in italics) lying off the Middle American continental shelf. The Lower Nicaraguan Rise covers much of the slope between the Upper Rise and the Colombia Basin. It corresponds approximately to the area occupied by the archipelago.

2. STRUCTURAL SETTING AND REGIONAL GEOLOGY OF THE ARCHIPELAGO

The atolls and high-standing islands of the Archipélago have a long geological history which is tightly linked to the formation of the Caribbean Sea and thus dates back to at least early Cenozoic times. Known geologic history of the wider area is limited to Mesozoic and Cenozoic time (with the possible exception of the Upper Nicaraguan Rise, which may be underlain in part by a core of pre-Mesozoic rocks (Holcombet al. 19901).

2.1 Caribbean Plate

During late Mesozoic times, most of the Caribbean seafloor formed a Pacific Plate segment which was moving toward the Atlantic. The Caribbean Plate decoupled from the Eastern Pacific Plate by the beginning of the Oligocene, when a new subduction zone (Middle American Trench) arose connecting the subduction zone bordering western North America with the one bordering western South America. Since then, the Caribbean sea floor has bounded the north coast of South America, while the Atlantic Plate was subducted beneath it (Malfait & Dinkelman 1972). Today, the Cocos Plate is subducting beneath the thicker and more buoyant Caribbean Plate along the Middle American Trench. The Lesser Antilles Trench delineates the eastern leading edge of this plate. The western edge of the Caribbean Plate adjacent to the Archipélago is formed by the Chortis Block, which comprises part of northern Central América. This tectonic unit is characterized by pre-Mesozoic continental basement rocks. It is delimited to the S by the Santa Elena-Hess Escarpment fault zone, which crosses the isthmus from the Caribbean side to the Santa Elena Peninsula on the northern Pacific coast of Costa Rica (Muñoz et al. 1997).

Evolution of the Caribbean Plate through Cenozoic times has been controlled largely by accumulation of sediments, structural deformation of the existing crust, and volcanism. The core of the Caribbean Plate is comprised of oceanic crust which apparently constitutes remnants of an oceanic plateau. Recently, drilling during Leg 165 of the Ocean Drilling Program has penetrated the Caribbean crust. The drilled units are thick, coarse-grained basaltic sills or flows with intercalated foraminiferal limestone dated as Coniacian (89.0-85.8 Ma) from samples taken in the Venezuela Basin. The extraordinary thickness of the crust (15-20km locally) may indicate a flood basalt event. At site 1001 (about 800km NI3 of San Andrés), the basaltic basement was drilled in the southernmost edge of the Lower Nicaraguan Rise along the Hess Escarpment. The overlying Campanian limestones indicate a minimum age of 77 Ma for the basalts. Site 999 lies closest to the islands, some 300 km E of San Andrés Island. The drilled basaltic sequence can be divided into 12 distinct units that probably represent individual lava flows and associated hyaloclastic beds (Sinton et al. 2000).

The present-day motions of the Caribbean Plate relative to its neighbors - North America, South America, Cocos and Nazca - are known from earthquake focal studies and from active strike-slip fault zones that bound the northern and southern margins of the plate. At present, the Caribbean Plate is moving eastward at rates of 2 to 4 cm/yr relative to North and South America (Mann & Burke 1984).

In order to provide a better understanding of the regional framework, the geological history of several regions of the Caribbean Plate will be discussed in more detail.

2.2 Upper and Lower Nicaraguan Rises

The Nicaraguan Rise in the western Caribbean Sea, which is due to a broad submerged belt of crustal thickening (Arden 1969), forms an important physiographic division on the Caribbean Plate. It extends from the Honduras/Nicaragua coast eastward to Jamaica. Its northern boundaries are the Swan Island Fracture Zone in the NW and the Walton Fault Zone in the NE (Mann et al. 1990). The left-lateral Hess Escarpment, a formerly active fracture zone (fig. 3), defines the southern boundary of the rise.

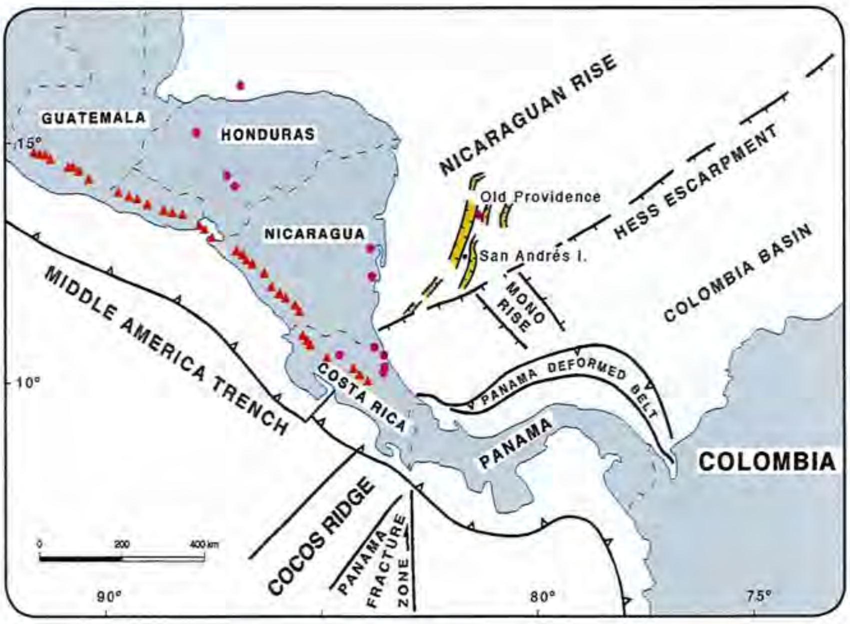


Figure 3. Neotectonic map of Central America and the Western Caribbean.
Red triangles: Quaternary calc-alkaline volcanoes in western Central America.
Red circles: Neogene alkaline volcanoes in eastern Nicaragua, Honduras and Old Providence.
Yellow areas: active fault-controlled graben formation with recent sediment fill.
The northern extension of the archipelago is not represented on this map!
Adapted from Mann et al. (1990).

The complex geological history of the Nicaraguan shelf immediately W of the Archipélago is detailed in Muñoz et al. (1997). According to these authors, the Miskito Basin which underlies much of the shallow eastern Nicaraguan shelf encompasses the back-arc region of the Caribbean side of Nicaragua. The breakdown of the major part of the platform presumably occurred in the Early Cenozoic along a NE trending wrench fault zone. Extension rift-like features formed in the Early Miocene with volcanism induced by wrench faulting. A series of four structural highs and depressions runs in a NE direction. Thicknesses of marine sediments reach up to 7 km in the central Miskito Basin.

The Upper Nicaraguan Rise extends from Honduras in an ENE direction. It comprises the shallow shelf area between Central America and Jamaica as well as a series of carbonate banks (including Pedro Bank, Thunder Knoll, Rosalind Bank, Serranilla Bank and Alice Shoal) lying within the 200 m isobath. The smaller banks are separated from the Upper Rise by NW-trending channels ranging in maximum depth from 400 to 1,500 m. These may correspond to a deeper-seated horst-and-graben structure.

The geological history of the Upper Rise is not known in detail. Pre-Mesozoic rocks of the continental Chortis Block of northern Central America may underlie at least its western part. Earliest occurrences of volcanic deposits in Honduras suggest that the area became an active island-arc subduction zone beginning in Late Jurassic time. Intensity of deformation was at a maximum along the island arc during the latest Cretaceous and again during the early Eocene. From the Late Paleocene to the Early Eocene, there was extensive faulting beneath the Nicaraguan/Honduran portion of the rise, and NW-SE trending grabens were formed by extension. In Middle Eocene time, tectonic activity ceased along the arc and submergence was general, as testified by the wide distribution of an Eocene limestone cover (occasionally with porous reef rock and traces of lignite). Evaporites occur near the present coastline of Honduras. Oligocene strata are missing or very thin. Miocene strata are marly and gypsiferous to the N and W and grade to carbonaceous to the S and E. Pliocene and Pleistocene rocks are karstic limestones with breccias in cavernous zones of reef complexes (Holcombe et al. 1990; Hine et al. 1994; Duncan et al. 1999).

The Lower Nicaraguan Rise lying to the SE of the shallow shelf area of the Upper Rise is more deeply submerged. It appears to be a crustal block bounded by the Pedro Bank Escarpment in the NW and the Hess Escarpment in the SE. It seems to be of oceanic origin and was probably created in the Pacific Ocean during the late Mesozoic before becoming part of the Caribbean Plate. Faults, ridges, troughs, scattered seamounts and volcanoes are found everywhere on the floor of this part of the rise. Seismic reflection data appear to indicate that most of the deposits that cover the Lower Nicaraguan Rise are pelagic (Bowland & Rosencrantz 1988, Holcombe et al. 1990, Mann et al. 1990).

In contrast to the NW trending escarpments of the Upper Nicaraguan Rise, rift grabens, ridges, and escarpments on the Lower Nicaraguan Rise show a clear NE trend similar to the Hess Escarpment (fig. 3). This trend seems to be related to the eastward movement of the Caribbean Plate. Most of the tectonic activity was probably Neogene to Recent in age. One of the more prominent of these features is the San Andrés Trough, which lies to the W of San Andrés Island and continues northward to the Old Providence Trough trending 15° NNE. It separates the southern part of the Archipélago in the E from the Nicaraguan shelf area of the Upper Rise in the W (fig. 4). The trough is filled with highly stratified deposits (probably turbidites that formed a small abyssal plain). Under the surface of the plain, the strata are folded by recent tectonic activity. The islands of San Andrés and Old Providence are seamounts that rise above sea level from the eastern shoulder of the graben. Similar young rift basins occur also to the E of San Andrés and Old Providence and E of Roncador Bank (figs. 3 and 4) (Holcombe et al. 1990).

According to Christofferson (1983), a zone of shallow earthquakes near the San Andrés /Old Providence Trough suggests that a plate boundary is forming there beneath the Caribbean Sea. A broad belt of extension faulting runs from W of Albuquerque Cays to the area W of Quitasueño Bank, from which it abruptly changes trend to NE. The extension faults connect with the old fracture zone of the Hess Escarpment near Albuquerque Cays. Sinistral transform motion is obvious between southern Central America and the part of

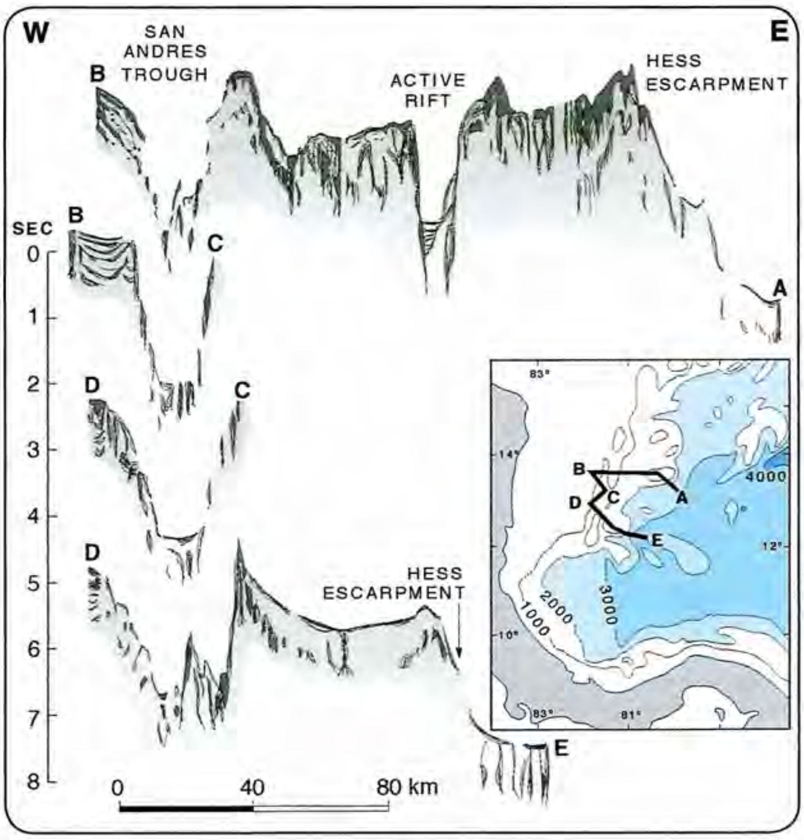


Figure 4. Seismic E-W sections taken across the San Andrés /Old Providence Trough and the Hess Escarpment. It illustrates the active rifting that is going on E and W of the islands. San Andrés and Old Providence are situated on the high ridge rising immediately E of the San Andrés /Old Providence Trough. Adapted from Holcombe et al. (1990).

the Caribbean Plate lying to the E. The offset of the sinistral motion is creating pull-apart basins in the form of the San Andrés /Old Providence Trough, resulting in collapse of the continental slope of Nicaragua.

2.3 Hess Escarpment and Colombia Basin

The Hess Escarpment forms a prominent bathymetric break between the Lower Rise and the Colombia Basin in the S. It extends for 1,000km in a southwesterly direction with a highly variable relief of 100 to 3,000m. The overall depth of the rise lies between 2,000 and 4,000m. This escarpment is of probable transcurrent-fault origin and may be as old as Late Cretaceous. It appears to be related to plate movements that were active during the early phase of the formation of the Caribbean Sea (fig. 3).

The crust of the Colombia Basin adjacent to the escarpment is dominated by Mono Rise, which is situated some 150 km ESE of San Andrés Island (fig. 3). Mono Rise is similar to aseismic oceanic rises known from the western Pacific Ocean. Seismic reflectors within Mono Rise are interpreted to be Late Cretaceous basalt flows with sedimentary interbeds. This basement complex was built by widespread, interise Middle and Late Cretaceous intraplate volcanism. It is probably underlain by the normal oceanic crust of possibly Late Jurassic or Early Cretaceous age, similar to that encountered to the E of Mono Rise (Bowland, 1984).

Open marine sediments were deposited from Middle to Late Cretaceous times until the mid-Eocene. These sediments were subsequently overlain by thick mid-Cenozoic volcanoclastic turbidites, which originated N and NW of the basin and partially filled the relief around Mono Rise. Since the Middle Miocene, interise tectonic and magmatic activity in southern Central America has resulted in a dominance of sediment sources from the western margin of the basin. The shedding of these volcanoclastic sediments led to the formation of an eastward prograding deep-sea fan complex which was active until Quaternary time (Bowland 1984).

According to Bowland (1984) and Holcombe et al. (1990), three episodes of deformation have been recognized in the Colombia Basin and at its northern and western margins:

1.) Latest Cretaceous transcurrent motion at the northern margin of the basin formed the Hess Escarpment.

2.) Paleogene structural deformation and rifting during the formation of a NE-SW trending wrench-fault zone at the NW corner of the basin gave rise to the mid-Cenozoic turbidites in the basin.

3.) From mid-Miocene to the present, a NW-SE trending transpressional zone was formed within the basin and gave rise to the North Panama Deformed Belt. During this deformation, the eastern edge of the Nicaraguan shelf was pulled apart as a system of Quaternary grabens along a zone of pre-existing crustal weakness. The most prominent of these graben structures is the above mentioned San Andrés/Old Providence Trough .

An alternative interpretation of the bathymetry of the SW Caribbean Sea came from Christofferson & Hamil (1978). They discuss a number of discontinuous bathymetric lineaments and faults disposed radially and (to a lesser extent) concentrically about San Andrés Island and the neighboring seamounts. The area in discussion includes more than 350.000km^2 of sea floor on the Nicaraguan Rise and in the Colombia Basin. The center is taken for the probable deformation center; however, nothing is known or suggested of the character, age and duration of the presumed deformational event.

2.4 Islands and atolls of the Archipelago

Milliman & Supko (1968) gathered geomagnetic data during a cruise to the San Andrés area. When superimposed over the submarine topography (fig. 5), their geomagnetic profiles show a direct relationship that is especially pronounced at Courtown Cays atoll. This indicates possible deep-seated volcanic cones under the limestone caps of the atolls and of San Andrés Island. Their volcanic origin is further supported by a basaltic pebble that was dredged from a depth of about 700m at Albuquerque during the same expedition. In addition, a prominent -400m platform was recognized throughout the entire area. According to Milliman & Supko (1968), this platform may represent the remmants of wave-cut volcanoes covered by a thick cap of sediment.

From the limited evidence presently at hand, it is concluded that the atolls, islands and coral banks of the southern group may have originated in Early Cenozoic times as volcanoes. Subsidence and simultaneous capping of the volcanoes by shallow-water carbonate deposits from Cenozaic through Quaternary times gave rise to the formation of the shallow banks and atolls of the Archipélago. Subaerial and submerged terraces and intertidal notches that were cut into coastal limestone by advancing sea-cliffs testify to Quaternary sea level oscillations on both islands and the atolls. Pleistocene sea-level lowstands (marked by a distinct unconformity within Pleistocene coral rock and by paleosols) are known from San Andrés Island.

Most coral banks, atolls and islands (Serrana Bank, Quitasueño Bank, the northern branch of Courtown Cays atoll, San Andrés, Old Providence) trend in a NNE direction, as does the SE margin of the Upper Nicaraguan Rise. Several of these structures and island shelves (see fig. 1 and Geister 1992:fig. 6) are aligned in the same NNE direction (Albuquerque Cays atoll, San Andrés, Old Providence, Quitasueño Bank), suggesting a possible NNE trending submarine fault zone which gave rise to localized volcanic extrusions on the sea floor. The NW trend of elongated atolls and islands equally suggests the presence of NW trending fault zones underlying these structures. Courtown Cays atoll, San Andrés, and Serrana Bank appear to lie over triple points of intersecting fault zones (Geister 1992). Serrana Bank is underlain by a horst structure (Munar 2000).

From the evidence at hand, it appears that most of the islands and atolls of the Archipélago have a common geological origin. Nevertheless, each one lived a geological history of its own. This may be summarized as follows, but will be detailed in Chapter 6 (fig. 6):

1.) Volcanic cones formed during early Cenozoic time along NNW and SW trending fault zones on the Lower Nicaraguan Rise. These volcanoes rose to near or above contemporary sea level.

2.) Slow subsidence of the volcanoes and subsequent colonization of their submerged tops by reef corals and other calcareous encrusters resulted in the formation of shallow reef-rimmer carbonate platforms surrounding "primary volcanic islands," while carbonate production kept pace with slow subsidence. According to Darwin's subsidence theory

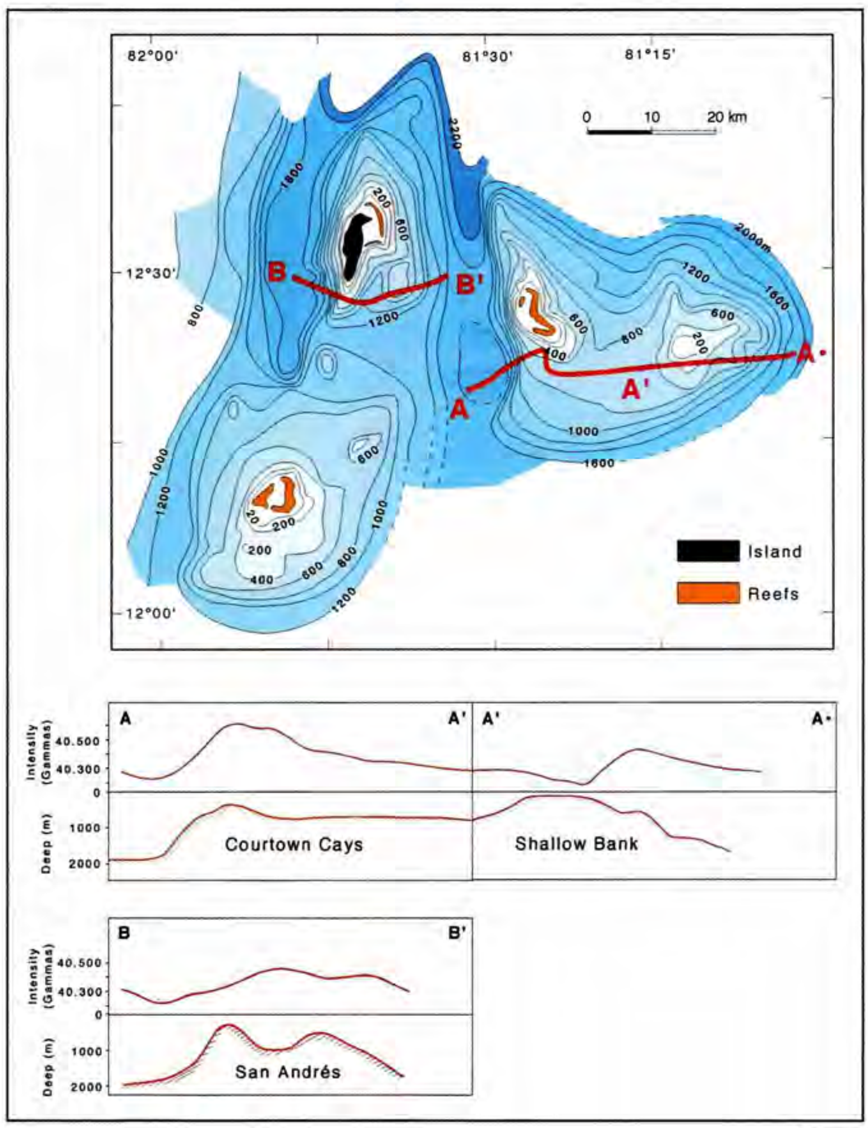


Fig.5

Fig. 5 Top: Bathymetric map of the seafloor between San Andrés Island and the atolls of Courtown Cays and Albuquerque Cays. Magnetometer/fathometer tracks are marked.
Below: Total magnetic intensity curves superimposed on bzzathymetric profiles. Note that correlation of curves is best at Courtown Cays atoll. Adapted from Milliman & Supko (1968).

(Darwin 1851), these barrier reef complexes became atolls after complete submergence of the central volcano.

3.) Too-rapid subsidence of some of these atolls during Cenozoic times led to "drowning" due to reduction and final disruption of carbonate production in aphotic depths. A flat-topped seamount (or "guyot") mapped SE of Courtown Cays atoll in 200m of water depth (Milliman & Supko, 1968; see also fig. 5) is thought to be such a drowned Cenozoic atoll.

4.) San Andrés also originated from such an ancient atoll. However, it began to tilt to the E when the eastern shoulder of the San Andrés /Old Providence Trough began to rise in Late Miocene time. Thus, the western atoll margin was gradually uplifted to form a "high-standing" limestone island. Though continuously eroded by subaerial weathering, the island top today reaches up to 100m above the sea. As a result of this tilting, the eastern atoll margin continued to subside until present, remaining a productive carbonate platform. This is the modern shallow bank-barrier reef complex E of San Andrés Island (Geister 1975: fig. 29).

5.) At Old Providence, the atoll stage ended abruptly in Miocene time, when recurring volcanism formed a new volcanic cone near the southern margin of the carbonate bank. Today, Old Providence is a "secondary barrier reef island," i.e. a volcanic barrier-reef island that evolved from an atoll. It is surrounded by a modern barrier reef complex.

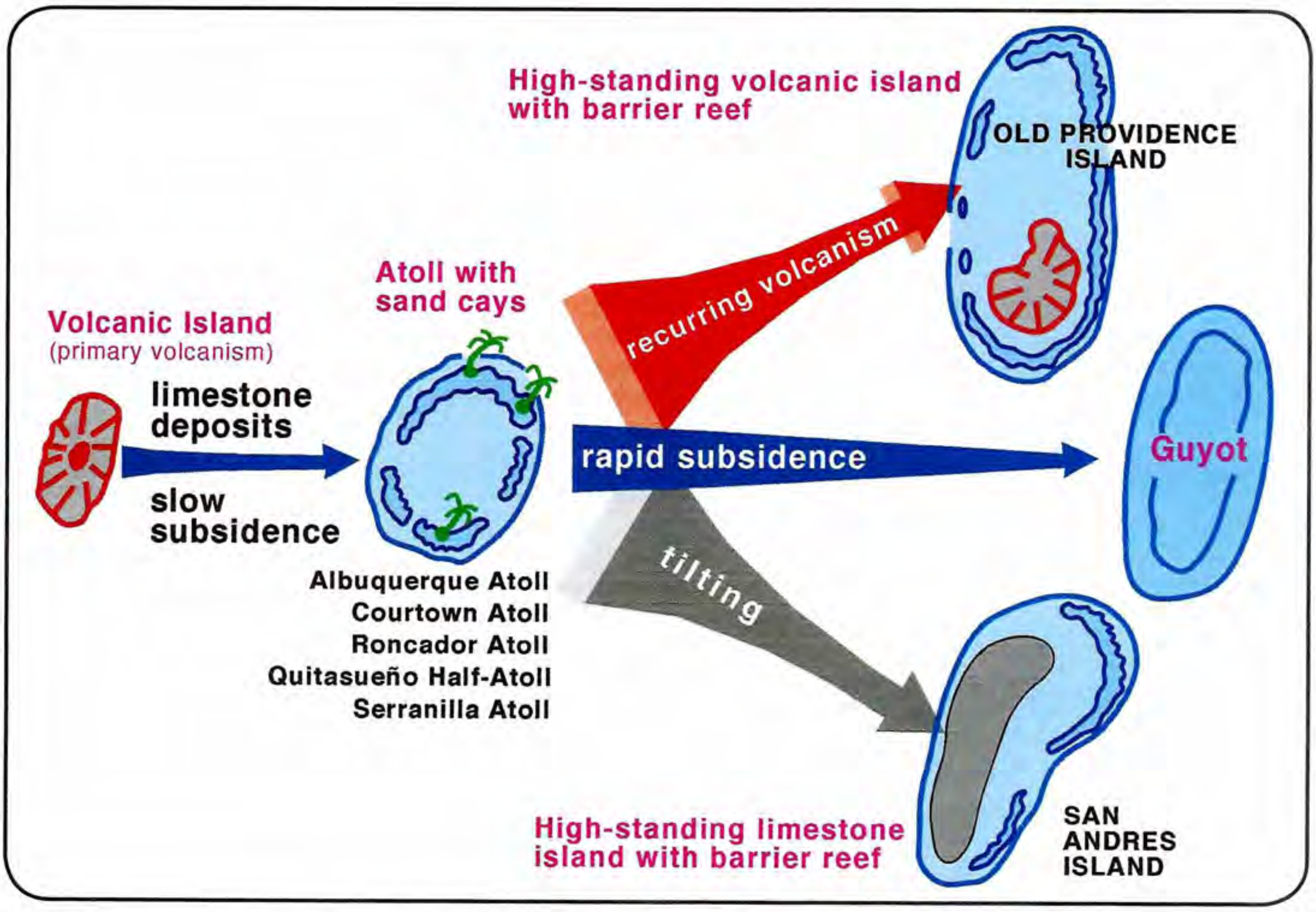


Figure 6. Genetic relationship between islands, atolls and guyots in the Archipelago of San Andrés, Old Providence and Sta. Catalina.

3. CLIMATE AND OCEANOGRAPHY

Since the Archipélago lies in the belt of the NE trades, wind directions are primarily from the ENE, with mean monthly variations between 4 m/s (May, September-October) and 7m/s (December-January, July). Sporadic storms with westerlies or northwesterlies attaining speeds over 20m/s do occur, mostly in the second half of the year. Hurricanes occur at irregular intervals near the Nicaraguan Rise. Five major hurricanes have been recorded at San Andrés and/or Old Providence in the past century (1932, 1935, 1961, 1971, and 1988). The mean annual air temperature is 27°C, with a 1°C, range between monthly values. The rainfall is irregular and varies greatly from one year to another. The mean annual value at San Andrés is close to 1900mm. There are no published records on rainfall from Old Providence and the atolls.

The reefs of the Archipélago suffer the almost permanent impact of long-periodic oceanic swells generated by the trade winds over an effective wave fetch that extends for nearly 2000 km (almost the entire width of the Canbbean Sea). The considerable energy released on these reefs by the swell and surf episodic storm waves is an essential factor that structures their benthic communities and controls their morphology and sedimentology.

The prevailing surface current in the Caribbean Sea is from E to W (Canbbean Current). It forms a large counterclockwise eddy in the SW Caribbean (fig. 1). A persistent northward flow of the

Caribbean Current through large gaps and narrow open seaways across the top of the Nicaraguan Rise is the single most important oceanographic and environmental factor controlling sedimentation on the western platforms of the rise (Hallock et al. 1988). It has been suggested that restriction of the northward flowing Caribbean Current by the carbonate platforms on top of the Nicaraguan Rise creates topographic upwelling, which promotes sponge-algal dominance of bank-margin benthic communities. Consequently, some of these platforms have not kept up with rising sea level and lie today in 20-40 m of water depth (Triffleman et al. 1992a).

The sea surface temperature around the major islands averages 27.5° C with mean monthly values ranging between 26.8 (February-March) and 30.2°C (August-September). Surface salinity fluctuates between 34.0 and 36.3 ‰. Terrestrial run-off is limited to the immediate vicinity of the two high-standing islands. In Providencian reefs, turbidity from fresh-water run-off is negligible, because most of the reef complex lies well offshore and up-current of the mouths of the few ephemeral streams that drain the comparatively small watershed.

4. GENERAL FEATURES OF WESTERN CARIBBEAN OCEANIC REEF COMPLEXES

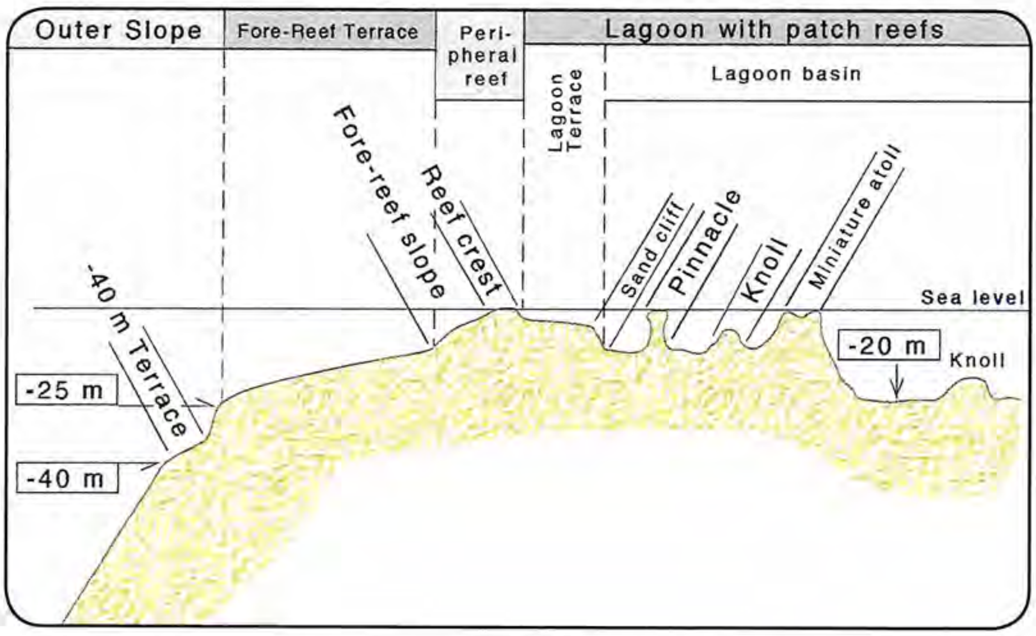


Figure 7. Generalized section across a bank-reef complex of the western Caribbean and terminology. The peripheral reef may be either from a barrier or an atoll.

4.1 Gross geomorphology of reef complexes (fig. 7)

The complex geomorphology of West Indian coral reefs has been detailed in Geister (1983), which provides a trilingual terminology (English, Spanish, German) of geomorphological terms that may be directly applied to the reefs of the Archipelago. In contrast to shelf-edge reefs characteristic of the Indo-Pacific, the oceanic reef complexes of the Western Caribbean are typically of the bank-reef type, i.e. in front of the shallow peripheral reef there is a fore-reef terrace up to several 100 m wide which slopes gently seaward from 8m to 20-30 m of water depth. From there, the sea floor drops off steeply to the outer reef slope. Frequently, a shallow bench ("-40 m terrace") between-35 and -40m marks a rather young sea-level lowstand.

The fore-reef terrace (or "-20 m terrace") of barrier reefs and atolls was formed by intertidal limestone thought to be of erosional origin. It formed in the late Pleistocene but is today covered by Holocene sediments and reef growth. Additional low-stands of Quaternary sea level are indicated by submerged intertidal notches or submarine terraces and by the occurrence of drowned coral reefs and lagoons. Drowned stream valleys also occur on the island shelf at Old Providence (Channel Mouth and Tinkhams Cut). Lagoon basins have a Pleistocene history of karstification. At present, Holocene sediments (mostly derived from the peripheral reefs) are rapidly filling them.

Windward peripheral reefs are generally continuous with only a few passes. An oceanic fringing reef is found exclusively along the SE coast of San Andrés. An ocean-facing reef in the lee of islands and atolls is hardly ever developed in the Archipelago. Exceptions are occasional short reef segments that close the lagoons incompletely to the W. Groove-and-spur systems are generally well developed in ocean-facing fore-reef situations. Towards the lagoon, the peripheral reef is fringed by a wide lagoon terrace which descends gently from the rear of the reef to about 4 to 5 m of water depth at its lagoonward margin. From here, the sea floor drops off steeply to the bottom of the lagoon basin as a "sand cliff". Sediments derived mainly from the reef and transported during storms to the lagoon basin cover the lagoon terrace. Depths of lagoon basins range between 12 and 20 m. San

Andrés, Old Providence, and most of the atolls have more than one lagoon basin within its reef complex.

In addition to the shallow reef complexes, drowned barrier reefs with drowned lagoons exist locally near the outer margins of the fore-reef terraces at -25 m and more of water depth. From here, their steep seaward slopes plunge to great oceanic depths. Drowned barriers are known from San Andrés (Pallat Bank) and from Old Providence (Northeast Bank). Similar features were previously described from the Lesser Antilles (Macintyre 1972).

Patch reefs occur both on the lagoon terraces and in the lagoon basins. Some of the deeper patch reefs thrive well below wave base at water depths greater than 15 m. Other patch reefs reach the surface and emerge during spring low-tides. Pinnacles and reef knolls that break the surface are occasionally found on the fore-reef terrace seaward of the main reef tracts, where they grow up from depths of about 5 to 10m. The best-studied examples include the "Rocky Cay" reefs of Old Providence. Pillar-shaped pinnacle reefs are common at Old Providence, where they form a wide discontinuous windward barrier belt for many kilometers. They seem to be essentially of Holocene origin but may rest on an antecedent high of Pleistocene age.

The wide distribution of anastomosing patch reefs is a unique characteristic of western Caribbean atoll lagoons.(Diaz 2005) These reefs form an immense continuous meshwork of connecting reef ridges that rise a few meters above the Bottom of the lagoon basin. The width of the meshes ranges from a few meters to more than 20 m. These reefs cover a significant proportion of the lagoon floor in some of the atolls; their continuous honeycomb-like reef structures can attain widthis of more than l km. Lagoonal fringing reefs occur at the coasts of the two larger islands and some nearby rocky islets.

4.2 Recent erosional and depositional processes

Constructional and erosional processes control present reef topography. Sediment production and active growth of Holocene reef framework can both be observed in the southern part of the Archipélago (San Andrés, Old Providence, Albuquerque, Courtown, Roncador, Serrana, Quitasueño), where the framework and sediments reach estimated thicknesses of several meters. Many of the modern reefs rest visibly on an inherited topography of Pleistocene limestone, but modern shelf carbonate production (especially reef growth) is fairly modest in the N of the Archipelago (Serranilla, Alice Shoal and Bajo Nuevo). Exceptions to this trend include huge "biohermal" mounds of the green alga *Halimeda opuntia* which line the deep channel that crosses the northern Nicaraguan Rise E of the Miskito Bank. The tops of these features lie in about 40-50 m of water depth (Hine et al. 1988). Local relief of the *Halimeda* bioherms is generally 20-30 m, though it attains 140m in one instance. These bioherms form a nearly continuous band bordering the channel.

Shallow seaward terraces are exposed to abrasion by storm waves. They are cleaned of sediment by the waves, but abrasion inhibits permanent growth of fiame-builders. True abrasional hardgrounds are found in Pleistocene bedrock down to - 15m of water depth. There is only negligible overgrowth by hard corals (fig. 8). Rarely is sediment deposited on windward fore-reef terraces shallower than -15m. On the other hand, thick loose sediments frequently cover some terraces deeper than 8m in leeward settings.

Shallow-water sediments are skeletal sands, with an important addition of larger coral clasts in the vicinity of reefs. *Halimeda* plates are abundant both in near-reef and shallow lagoonal environments. At San Andrés, *Halimeda* plates are extremely abundant in deep fore-reef settings below 40m, where they may entirely cover the steeper slopes. Lagoonal sediments are relatively fine organic sands and muds. Some of the fine sediments found at the outer slope and in the lagoon basins may have originated from abrasion and bioerosion on the fore-reef terrace. Many of the non-skeletal constituents, notably cryptocrystalline lumps, ooids and peloids, are only known from the western lagoon of Serrana Bank where patch reefs are absent (Milliman 1969b). Mixed siliciclastic-carbonate sediments are observed in the immediate vicinity of Old Providence and Sta. Catalina Islands.

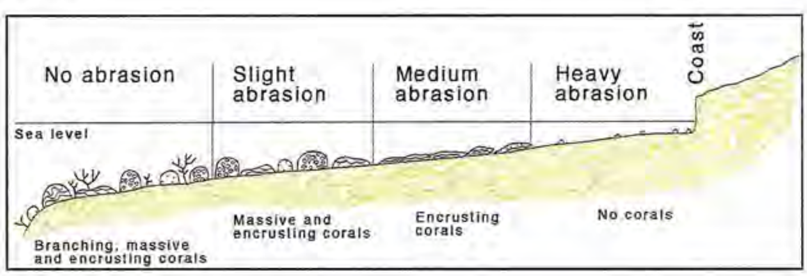


Figure 8. The influence of periodic abrasion caused by storm waves on the growth form of corals and the composition of reef coral associations. The intensity of periodic abrasion decreases gradually seaward. This phenomenon is well visible on the Holocene -4m terrace N of Poxhole. Schematic. From Geister (1983), modified.

Sediment transport in the oceanic reef complexes of the Archipélago is mainly controlled by the exceptionally high oceanic swell and by the resultant strong currents and extraordinary hydrodynamic energy (see Geister 1975: fig. 14). As a result, we observe a continuous flow of open-sea water over the peripheral reefs, into the lagoons, and out to the sea through the leeward gaps of the reef tracts. The following mechanisms for sediment transport and deposition have been distinguished (Geister 1983):

1 .) Coral fragments and sediments are washed by storm waves from the fore-reef onto the reef flat and over the reef crest onto the lagoon terrace. Rubble is deposited in a broad band in the lee of the reef along the outer margin of the lagoon terrace. The finer sediments prograde towards the lagoon basin. The fronts of these prograding sand slopes appear as steep "sand cliffs" where sediments are deposited in the natural angle of repose (fig. 9).

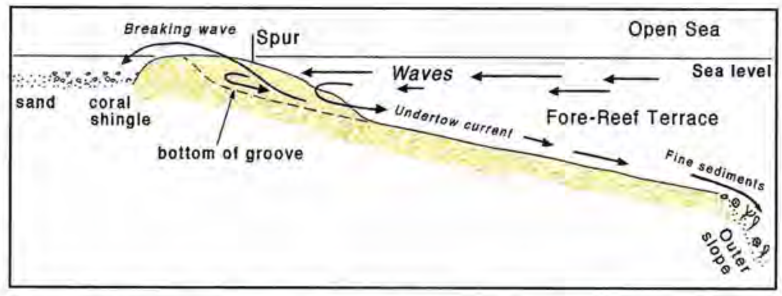


Figure 10. Transport of sediments by breaking waves and surf currents in a barrier reef (or fringing reef with boat channel). Reef crest shallower than - 1m below sea level. Reefs of this type are generally characterized by well-developed groove-and-spur systems direzcted to the open sea. Strong vertical exaggeration. See also Sea Stop C3..

2.) Although most sediment from seaward reefs is driven to the lagoon by the breaking waves, some of the sandy material is transported in the opposite direction by undertow currents. These currents occur when some of the water rushes back to the open sea on the bottoms of grooves. The fine sediment from the groove area is carried over the fore-reef terrace in very shallow sandy channels to the steep outer slope (see fig. 10). From there, the sand is transported down into deeper water. Channel heads are about 10 to 20m apart at the outer margins of the fore-reef terraces. Between them, reef buttresses rise up to several meters above the level of the adjacent channel floors.

3.) A rhythmic current towards the lagoon is produced by the overflow of breaking waves above seaward reef crests deeper than about 1.5m. As a result, practically all the coarse and fine sediments from the reef are transported to the lagoon (fig. 11).

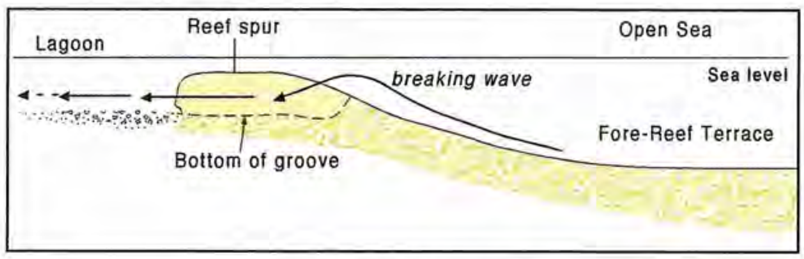


Figure 11. Transport of sediments by breaking waves and surf currents in a barrier reef (or fringing reef with boat channel). Reef crest lies more than 1.5m below sea level. Note that here the spurs and grooves are directed towards the lagoon. Strong vertical exaggeration. See also Sea Stop B1.

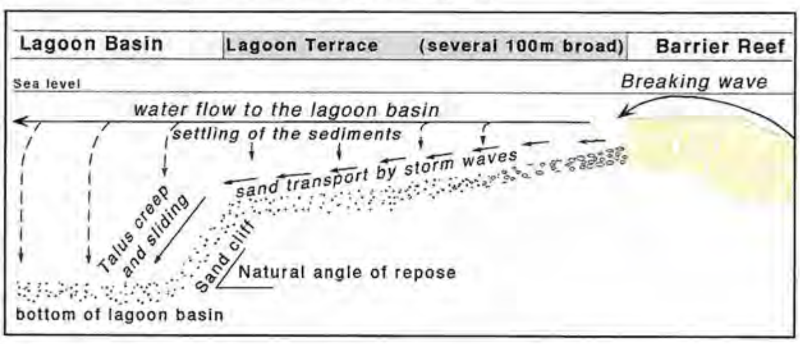


Figure 9. Process of sand-cliff formation in the lagoon basin. Combined lagoonward sediment transport by breaking waves, currents and the force of gravity. Very shallow-water sediments prograde into the lagoon basin, where they are deposited in a natural angle of repose. Strong vertical exaggeration, schematic. One such sand cliff will be visited at Sea Stop C5.

4.) Low islets may be formed shallow reef flats and lagoon terraces by accumulation of storm- derNed coral shingle and sand (fig. 12). Sediment accumulation is favored in areas where storm waves are refracted around seaward convex topography.

5.) Along unprotected cliffy coasts (fig. 13), breaking hurricane waves throw up storm beach deposits onto the tops of the cliffs, several meters above sea level. They consist of coral shingle, sand and occasional blocks. A storm beach lines the west coast of San Andrés several meters above sea level and reaches up to 100m inland. During storms, much of the stirred-up fine material in the water column is carried seaward by ripcurrents. It falls out in transit over the -20m terrace and the outer slope. In air photographs, sites of sediment outfall on the -20 m terrace appear as whitish pointed lobes formed by the loose sediment. The points of these lobes are directed seaward. They are sites where rip currents return water from the coastline to the open sea. Landward water transport by surges causes heavy abrasion in headlands onto which the incoming waves are refracted. Backflow to the sea occurs from re-entrant sectors of the coastline.

6.) Swift currents from waves washing over the peripheral reefs carry stirred-up fine sediments across the lagoon. Transport of fine sediments in the water column tends to bypass the northern and southern points of the high-standing islands. Outfalling sediments form wide sedimentary aprons or tongues on the leeward -20 m terrace where strong currents leave the lagoon. A considerable amount of the sediment ma-

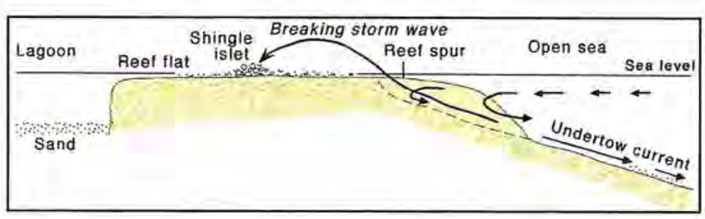


Figure 12. Transport of sediments by breaking waves and surf currents in a fringing reef or barrier reef with very broad (>50m) and very shallow (<1m deep) reef flat or lagoon terrace. Seaward reefs of this type frequently exhibit a well-developed groove-and-spur system directed to the open sea. Locally, the formations of sandy islets can be observed. Strong vertical exaggeration.

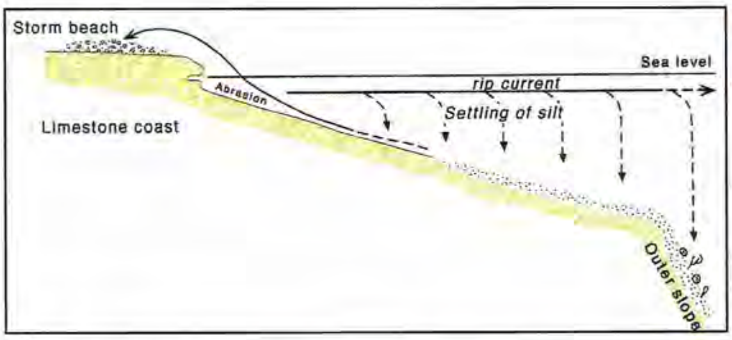


Figure 13. Transport and deposition of sediments by storm waves and rip currents in front of a sea cliff with seaward abrasional terrace. Strong vertical exaggeration. Best examples are found along the west coast of San Andrés. See Land Stop A8 (Lynton Rock).

terial produced on the platform is deposited on the adjacent island slope and in the deeper sea. In fact, South End Bank at San Andrés may have formed as a Pleistocene (or older?) accumulation of sediments that bypassed the South Point of the island. The general absence of a leeward reef tract in the atolls favors major sediment transport by storm-induced currents from the lagoon to the leeward terraces and down the outer slope. Sediment deposition and downslope transport is spectacular at the leeward atoll slopes of Serrana and Roncador Banks. Coarse and fine skeletal material is transported by the force of gravity to greater depths by avalanching, sediment creep or sediment falls (fig. 14).

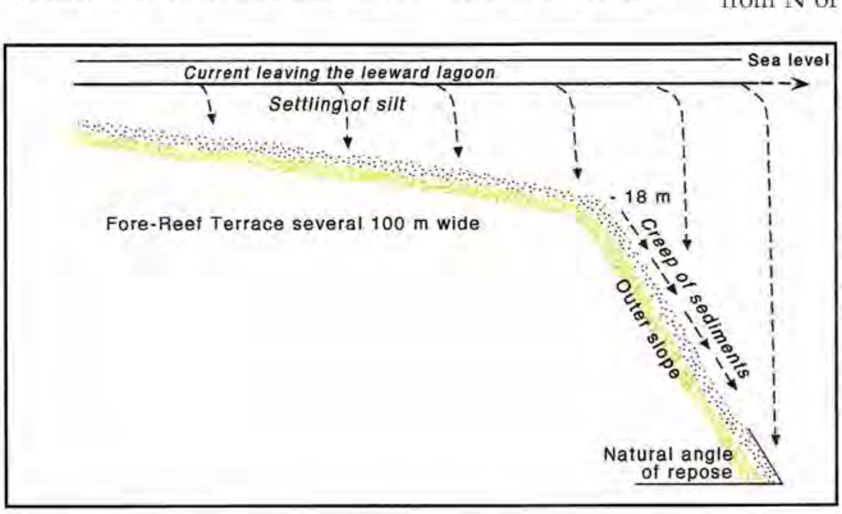


Figure 14. Combined sediment transport by strong currents leaving the lagoon, and by the force of gravity producing sediment creep and sand falls down the outer slope. Strong vertical exaggeration. Best example: Fore-reef terrace and outer slope NW of German Point, San Andrés. Sea Stop B3.

The transport by currents and waves generally results in the sorting of the sediment components according to size, in rounding of larger coral fragments, and in the local formation of an imbricated texture of platy components in storm deposits. These features are characteristic of very shallow-water deposits. Sediment transported by avalanching at the outer slope forms chaotic, unsorted accumulations of unrounded coarse coral fragments intermingled with fine reef detritus. These reef talus deposits are characteristic features below storm-wave base at more than 30m of depth.

4.3 Collapse of carbonate platforms

Large, convex-bankward embayments with precipitous high-relief escarpments can be observed in most of the shallow carbonate banks of the Archipélago. They are crescentic in map view and extend from several hundred m to several km along the platform rims of islands and atolls. After the study of sea charts and on-site examination of some of these features, we believe that they were formed as a result of collapse of unstable oversteepened seaward platform rims as described by Mullins & Hine (1989)

4.3.1 Platform margin failures in the Archipelago

"Bocatora Hole" in the southeastern sector of the San Andrés island shelf (map fig. 15; see also Sea Stop C1) is the best studied of these features in the Archipelago. Divers and even snorkelers can easily visit its extremely shallow outer rim. Swimming along the outer edge of the fore-reef terrace from N or from S towards the inner bulge of the drowned embayment, we observed that the edge shallows gradually from about 18 m to a minimum depth of 5 m. The seaward slope steepens gradually to become a vertical wall at the inner bulge. Gaping NNE trending clefts, up to 1m wide, are visible in the outermost platform margin near the drop-off. The wall was examined during dives down to a depth of 55 m. It appeared essentially vertical and had significant overgrowth of the green calcareous algae *Halimeda* and very sparse overgrowth of encrusting organisms. No intertidal notches were found that might indicate Pleistocene sea-level lowstands. Based on these observations, we believe that the break off of the platform must be very young geologically, postdating these sea level lowstands. This conclusion is corroborated by the observation of still-open and uncemented extension fractures of similar strike at the nearby island coast.

The available data suggest that Bocatora Hole collapsed not earlier than latest Wisconsinan/earliest Holocene time (20,000 to 10,000 years ago) when the sea level was 50-100+ m below present datum. Young fractures at its outer edge indicate that the collapse may have been triggered by earthquake shocks. A minimum waste of about 10 million m3 of rockmass can be estimated from the 200m height of the escarpment wall and the surface area of the 1000 m-long by 500 m-wide erosional scarp. During latest Pleistocene/earliest Holocene time, this mass fell suddenly into the deep sea from a steep coastal cliff that may have been up to 100 m high. This must have been a truly catastrophic event at the island scale, producing huge waves that washed up the ancient shoreline.

The deeply convex-bankward embayment at "Entrance" is thought to be another collapse feature of the San Andrés insular shelf. This very steep to almost vertical dropoff plunges from the -20 m deep shelf margin into the abyss in the S. The width of the embayment is approximately 1000 m and the maximum bankward bulge extends to about 700m. Assuming a minimum height of the scarp on the order of 200 m, a rockmass exceeding 50 million m^3 would have slid into the deep ocean during the collapse. This event probably occurred in Pleistocene time, before the formation of the "fore-reef terrace" ("- 20 m terrace").

On the Providencian island shelf (see map fig. 31), "Blue Hole" is a most spectacular crescentic escarpment frequently visited by divers. At the southern end of this scalloped embayment, between about -50 and -20 m of water depth, the shelf edge is transected by a gaping extension fracture clef that is over 1 m wide ("Broken Ground"). At the inner bulge of the embayment, the shelf edge lies at about -20m of water depth. It is overgrown by scleractinian corals, octocorals and sponges. Below an almost vertical drop-off from the -20 m edge, there is a steep sedimentary slope covered by coral growth between -35 m and -40 m, followed by a subvertical cliff. The sandy slope suggests a narrow -40m terrace covered by sediments. The presumed collapse of the shelf margin at Blue Hole would necessarily predate the formation of both the -20 m and the -40 m terraces and would thus be considerably older than Bocatora Hole of San Andrés. The entire embayment is about 3 km wide from N to S and bulges into the insular shelf for about 2 km. Assuming a minimum height of the subvertical wall of about 200 m, a mass flow of more than 500 million m^3 of limestone blocks to the abyss can be conservatively estimated.

There are several additional submerged embayments of smaller size along the western shelf margin of Old Providence, as well as two considerably larger "scallops" indented into the northeastern and southern island shelf. These were not examined during our dives but show up well on the hydrographic chart. The surface area of the northeastern embayment is more than twice the size of Blue Hole, indicating that more than one billion m^3 (109 m^3 or 1 km^3) of rocks fell off the island shelf and settled on the deep-sea floor. In addition, it is worthwhile to note that the northern deep lagoon basin of Old Providence ("Point Blue") is completely open to the W suggesting the failure of the entire western platform rim in this area.

Even longer, precipitous platform margins were located and visited by one of us (JMD) at the western rims of Serrana and Roncador Banks. At Serrana, the sand masses of the lagoon basin are emptied into the abyss to the W. At Roncador Bank, the western platform margin is formed by an almost continuous vertical to overhanging cliff plunging from a 18m deep shelf-edge into the ocean. These features also appear to have formed by break-off of the outer shelf margins. If leeward peripheral reefs had ever existed at Roncador and

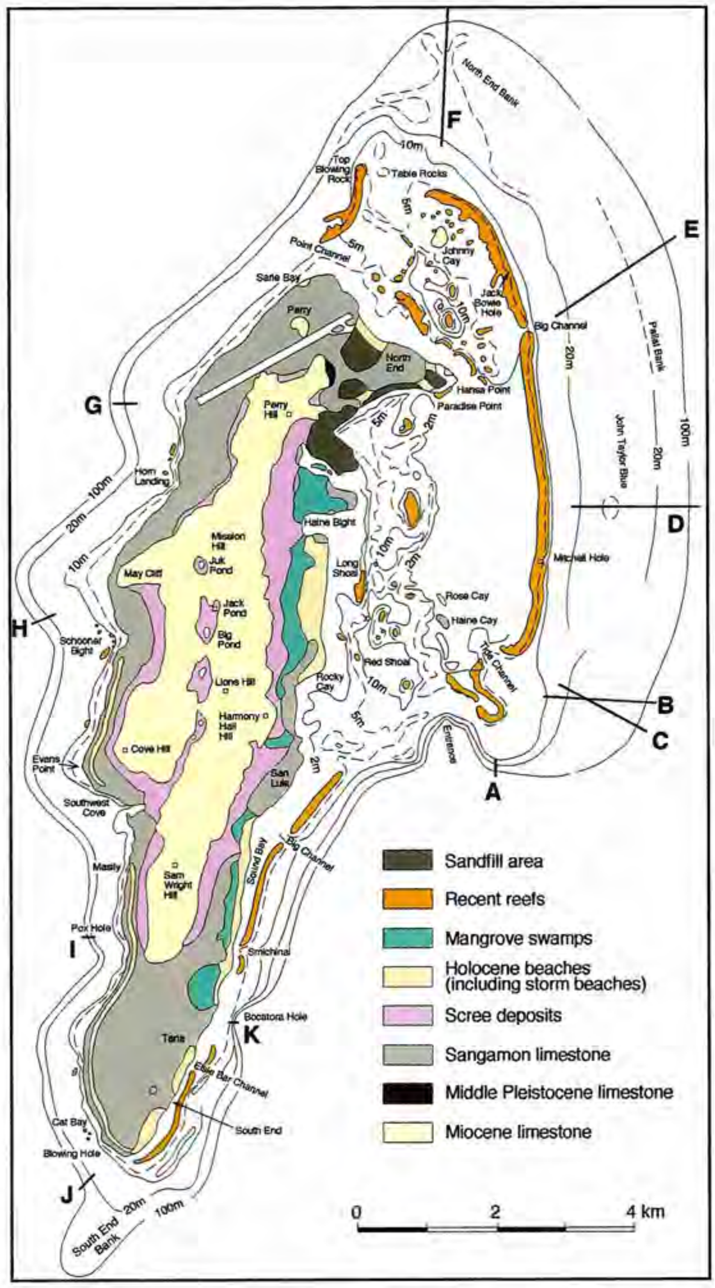


Figure 15. Map of San Andrés featuring island geology, submarine topography and distribution of reefs on the surrounding insular shelf. Contour lines are in meters. Letters A to K indicate locations of fathometer profiles shown in fig. 16. From Geister (1975), modified.

Serrana, they might have been ripped-off by the collapse of the western shelf margins. The mass wasting during failure of both platforms would amount to several km^3 each.

4.3.2 Shedding of megabreccias

Previous seismic studies on the northern Nicaraguan Rise discovered platform margin failure which resulted in the shedding of a megabreccia. This particular breccia included blocks almost 300 m across and more than 110m high (Hine et al. 1992) and was formed during 10 individual collapse events. A large and steep erosional escarpment at Bawihka Bank with a headwall scarp 180m high indicates its source area. Most of the megabreccia was deposited on the floor of nearby Diriangen Channel, which traverses the Upper Nicaraguan

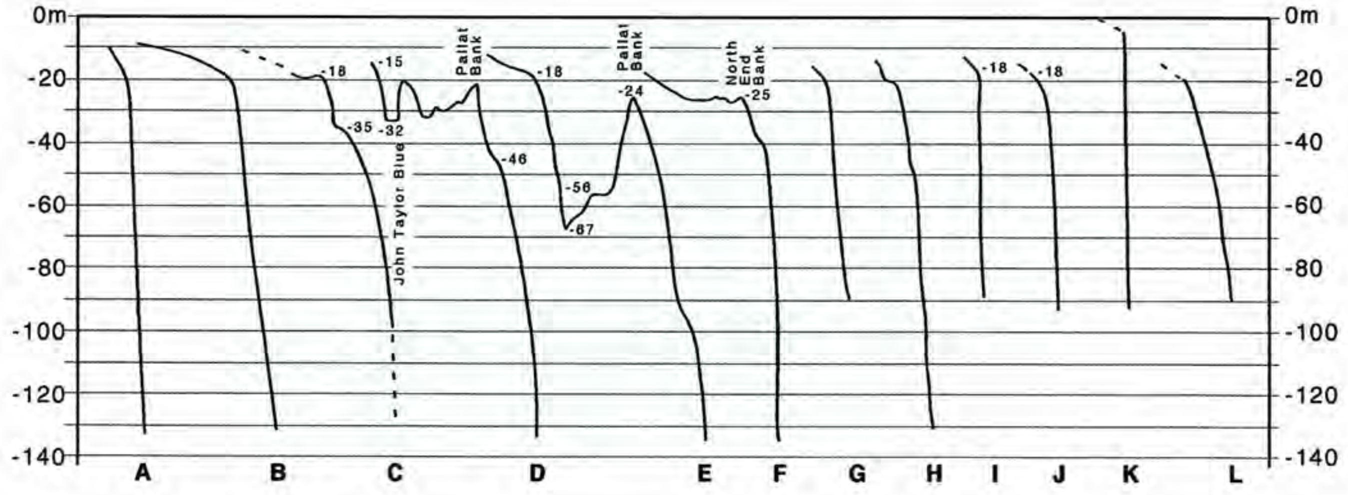


Figure 16 Fathometer profiles run from the fore-reef terrace to the outer slope of the San Andrés insular shelf. Vertical exaggeration is about 50 times. For location of profiles see fig. 15. Water depths in meters.

Rise. Enormous blocks were transported several kilometers. The platform margin retreated an estimated 2 km.The total volume of the block deposit is around 10 km^3. The age of these mass wasting events has been dated as Pliocene.

The collapse of numerous platform margins on the Lower Nicaraguan Rise must have generated huge mass flows of rock material to the deep sea. The resulting breccias are today expected to cover extensive surface areas of the sea floor surrounding the atolls and islands of the Archipélago. Until now, we had no opportunity to verify the existence of the breccias and the presence of megablocks on the deep-sea floor in the study area.

4.3.3 Causes of collapse

Collapse of the platform margins seems to be tightly linked to the tectonic activity on the Nicaraguan Rise. It may be episodically triggered by earthquake shocks resulting in faulting (clefts in Bocatora Hole/San Andrés and Broken Ground/Old Providence) and was probably not simultaneous at the different sites. Rifting movements with the formation of pull-apart basins (fig. 4) were certainly accompanied by earthquakes. These movements date back to Miocene time, when the seamounts and atolls were already installed.

4.3.4 Recurrence time of collapsing margins

The process of rifting continues today, so collapse of platform margins will go on in the future.

Resulting huge waves might not only devastate nearby sandy cays but also inundate the low-lying terrain of the high-standing islands. Repeated break-off will destroy carbonate platforms step by step over geologic time and even affect high-standing islands.

The recurrence time for major break-off events in the Archipélago seems be fairly long compared to a human lifetime, but these events are probably not evenly distributed in time. About 30 of the scalloped shelf margins in the Archipélago are probably no older than Quaternary (1.8 million years). If each break-off was separated from the preceding event by an equal length of time, the mean recurrence interval would be on the order of 60,000 years; however, some of the events will probably be less than 60,000 years apart. The population might face huge, catastrophic flood waves resulting from collapsing platform margins at irregular intervals.

4.4 General reef and lagoon ecology

The Bottom facies in modern reef complexes is characterized by the prevailing regimes of sedimentation and reef growth. We may distinguish areas of framework growth and sediment accumulation and areas where neither framework growth nor sediment accumulation occurs.

Framework growth by scleractinians, hydrocorals and melobesioid encrusting algae on hard substrates is the most obvious aspect of the reef facies. Variations in reef facies may be observed mostly in relation with increasing water depth and variable exposure to waves and abrasion, which find their expression in the distribution and growth forms of frame builders and other key organisms.

The most important factor controlling the distribution of frame-builders in the western Caribbean Sea is the considerable wave energy released in unprotected windward reefs by the breaking of high oceanic swells. The latter is generated by the NE trade winds over an exceptionally long fetch which extends across almost the entire width of the Caribbean Sea. The predominant framework associations of the reef crests (see Geister 1977a, Díaz et al. 1997) reflect the intensity of exposure to swell of individual reefs. From highest to lowest wave exposure, the reef crest associations are dominated by the following taxa: 1) An algal ridge (formed mainly by encrusting red melobesioid algae); 2.) the fire coral *Millepora complanata* and the colonial zoanthid *Palythoa*; 3.) the moose-horn coral *Acropora palmata* and the brain coral *Diploria strigosa;* 4.) the staghorn coral *Acropora cervicornis;* 5.) the finger coral *Porites porites*; and 6.) the star corals *Montastraea* spp.

By contrast, the sand facies (lagoon facies) is characterized by sediment accumulation which results in a loose, predominantly sandy or muddy substratum. Sediment may be derived from the reef or be autochthonous. It is of skeletal (coral and algal fragments, foraminifera, etc.) or non-skeletal (ooids, oncoids etc.) origin. In the lagoon, most benthic animals are vagile or burrowing, as exemplified by echinoids, pelecypods and gastropods. A regime of currents and waves is indicated by characteristic sedimentary textures (ripples, foreset bedding) in shallow lagoonal areas. Absence of distinct bedding and abundant bioturbation is more characteristic of deeper and/or protected lagoonal settings.

The absence of both framework growth and permanent sediment accumulation is the most prominent feature of hardground facies, while periodic abrasion of the hard substratum by sand and coral shingle during seasonal storms may occur. Boring and encrusting organisms are the most characteristic biotic elements surviving in this environment.

For the purpose of mapping, both reef and lagoon facies have been subdivided in a number of smaller units, which reflect in detail the physical forces and biological environments by which these units are controlled. The units have been defined by Díaz et al. (2000: 31-45). Here they will be briefly described again and the definitions adapted to geological needs. They form the basis for the ecological mapping in the Archipélago. At San Andrés, they have also been used for the reconstruction and mapping of Sangamon paleoenvironments.

4.4.1 Shallow reef facies

The shallow reef facies in the Archipélago is characterized by the presence of specific shallow water species such as the pillar coral *Dendrogyra cylindrus* and or the moose-horn coral *Acropora palmata*. Neither coral is found in water deeper than about 20 m. The shallow reef facies is equally characterized by the absence of certain deeper water reef corals (*Scolymia* sp., *Agaricia undata* etc.). The shallow reef facies is potentially exposed to permanent wave action, which grades from very high to extremely low. The following shallow reef assemblages, from very exposed to very protected settings, were recomized:

- Melobesieae (algal ridges)
Most notable is the presence of true algal ridges on limited segments of the barrier reefs at San Andrés (Geister 1983: plate 33/1-3) and Old Providence (Geister 1992: plate 1/1). These are massive encrustations by melobesioid calcareous algae (mainly *Porolithon* sp.) jointly with other encrusting organisms such as the foraminifer *Homotrema,* vermetid gastropods, serpulids, bryozoans and occasional *Millepora* colonies. Algal ridges may be more than half a meter thick. They form 30 cm-high crests at the outer rim of the reef flat. As the ridges are subject to maximum wave energy by refracted long-periodic oceanic swell, divers may only visit them during a few days every year. The most easily accessible algal ridge of the area is the Top Blowing Rock N of San Andrés Island. Local algal ridges emerging at low tide also occur on some of the atolls.(Diaz et al. 1996).

- *Millepora complanata*, red algae and zoanthids
Crests of ocean-facing windward reefs in the Archipelago are characterized by an immense and intricate framework of the fire coral *Millepora complanata* and red algae. The pale colonial zoanthid *Palythoa mammilosa* is very common here. Thin reddish crusts of coralline algae are ubiquitous on dead coral surfaces.

- *Acropora palmata* and *Diploria strigosa*
Dense stands of the moosehorn coral *Acropora palmata* and massive heads of the brain coral *Diploria strigosa* are common in lagoonal patch reefs but also form a discontinuous zone in 8- to 10m-deep water in front of the windward reefs.

- *Acropora cervicornis*
Near-monospecific thickets of the staghorn coral *Acropora cervicornis* characterize certain lagoonal patch reefs. According to observations between 1969 and 1980, this was formerly the reef facies with the widest distribution in lagoonal patch reefs of Old Providence Island (Geister 1992). Since the bleaching events of the 1980s, most of these patch reefs are barren coral rock overgrown by soft brown algae (see: Dead reef overgrown by algae).

- *Porites porites*
Dense, almost monospecific stands of the finger coral *Porites porites* are prevalent on tops of patch reefs of rather protected lagoonal settings.

- *Montastraea* spp.
Very mixed stands of mostly massive scleractinians, in which the star corals *Montastraea annularis*, *M. faveolata* and *M. franksi* become co-dominant, are characteristic of this assemblage. It is observed in deeper water of the fore-reef and in very protected lagoonal settings. Quiet-water communities dominated by octocorals and the scleractinians *Montastraea annularis* and *M. faveolat*a form continuous coral carpets on the leeward -20m terraces where not inhibited by abrasion and sediment deposition. This assemblage has the widest distribution in the lagoon patch reefs of the atolls.

- Mixed scleractinians

Closely resembling the *Montastraea* spp. unit, but the *Montastraea* species are not dominant. The unit is mainly found on seaward facing terraces more than 10m deep.

- Mixed scleractinians with octocorals
Octocorals (mainly gorgonids and plexaurids) dominate the mixed scleractinians assemblage. This unit is only found in settings well flushed by oceanic currents. In outcrops of fossil reefs, it would not be possible to separate it from the mixed scleractinians facies.

- Dead reef overgrown by algae
These are barren areas of reefs which died during the bleaching events of the 1980s and whitch were subsequently overgrown, mostly by soft algae but also by some calcareous (*Halimeda* sp.) algae. At Providencia, most barren lagoonal patch reefs are former *Acropora cervicornis* thickets.

4.4.2 Deep reef facies

Deeper-water associations of hermatypic scleractinians are found on the outer slope, generally below 20 m of water depth. They are dominated by platy corals (*Agaricia lamarcki, A. undata* etc.) and encrusting growth forms of otherwise massive scleractinians (*Montastraea* spp., *Porites astreoides* etc.). The appearance of solitary mussids (*Scolymia lacera* and *S. cubensis*) below about 20 m of water depth is very characteristic of this facies. The total absence of shallow water corals such as *Acropora palmata* and *Dendrogyra cylindrus* is notable. Sponges often become dominant below 30 m. Though individual encrusting scleractinian colonies were seen well below 55 m, the lower limit of active reef growth in the Archipelago is probably shallower than 40m.

The deep reef facies can be further subdivided into depth zones which are based on coral distribution and controlled by ambient light availability (see Geister 1975: 104-106, fig. 18). In the present publication, only one facies unit was defined. This unit characterizes very steep substrates at the outer slope down to 60m of water depth:

Agaricia spp. with mixed scleractinians
The assemblage of platy agaricids, most notably *Agaricia undata, A. lamarcki* and *A. grahamae*, dominates the outer slope, generally below 15 to 20m. *Mycetophyllia* spp. and *Montastraea* spp. Are also frequent, and the solitary scleractinians *Scolymia lacera* and *S. cubensis* occur.

4.4.3 Hardground facies

Rocky windward flats are generally shallower than 15 m. They are kept free of sedimentation by permanent or occasional wave action and show only negligible coral growth. Locally, sea fans, sea whips, and soft algae colonized these flats. Rock surfaces are polished during storms by wave-driven coral shingle. Only some encrusting scleractinians and hydrozoans survive. In addition, the surface of the flats is drilled by boring organisms such as clionids and lithophagan pelecypods. Though hardground facies may be further subdivided on ecological grounds), in this publication only one facies unit was defined. This unit characterizes all the rocky flats kept free of sediment by the waves:

- Encrusting scleractinians on rocky flats
Dominated by the brain corals *Diploria clivosa* and *D. strigosa, Siderastrea siderea* etc. and octocorals.

4.4.4 Shallow sand facies

Lagoon facies (or sand facies) may be divided on topographical and ecological grounds into deposits of shallow lagoon terraces and deeper lagoon basins. Lagoon terraces fringe the inner margins of seaward reefs and certain lagoonal patch reefs. They are very shallow (1 to 3 m in the vicinity of reefs, from where they dip slightly towards their outer margin at 3 to 6 m). From here, there is a steep natural slope prograding to the deep lagoon basin. The lagoon floor on the terrace and in the basin is covered by reef- derived coarse and fine debris and may be dotted with coral patches. Coral fragments, coralline algae and *Halimeda* are the main components.

Sediment of shallow lagoons in the Archipelago is almost exclusively carbonate, with the exception of some nearshore areas of Old Providence, where an admixture of siliciclastic sediment derived from the island has been noted. Carbonate sediment is predominantly of skeletal origin, though a major non-skeletal fraction consisting of ooids, pelletoids, cryptocrystalline lumps and aggregates is present in the lagoons of some of the atolls. Most notable is the presence of an appreciable amount of ooids in the western shallow lagoon of Serrana Bank. This has been explained by the lack of patch reefs, which elsewhere provide a great amount of detrital carbonate sand which "dilutes" the concentration of ooid grains in the bottom sediment (see Milliman 1969b).

- Seagrass beds
Dense beds of marine phanerogams stabilize the loose sediment and serve as a sediment trap. Sea grass beds are found in the Archipélago from the shallowest subtidal down to about 10 m of depth in the shallow lagoon basins. In the atolls, their distribution is restricted to a few patches in the lagoon.(see Diaz et al. 2003).

- Algal beds on sand
Dense macroalgal beds consisting mainly of the genera *Halimeda, Penicillus, Rhipocephalus,Lobophora* and *Dictyota* cover the lagoon floor locally between 4 and 10 m of water depth.

- Octocorals with sponges
This unit consists of plexaurid and pseudoplexaurid octocorals with numerous large sponges on a sandy or shingle bottom. It was only mapped on the insular shelf of Old Providence Island.

- Rhodolith beds

At Quitasueño Bank, numerous rhodolith cover shallow flats and flanks of certain lagoonal ribbon reefs in the windward lagoon from about 1 to 10 m of water depth.

- Red mangroves
Thickets consisting mainly of the red mangrove *Rhizophora mangle* are found in very shallow sheltered sectors of the lagoons of San Andrés and Old Providence.

4.4.5 Shallow to deep sand facies

-Sand and coral shingle
Coarse sand and coral shingle is derived from nearby reefs mainly by wave activity or the force of gravity. A belt of wave transported coral shingle is characteristic of the lee of ocean facing reefs but is also found around patch reefs in the deeper lagoon basin.

4.4.6 Deep sand facies

The lagoonal basins in the archipelago are generally up to 12m and rarely up to 20 m deep. Their bottoms are covered by autochthonous carbonate sand and mud as well as by some calcareous algae (mostly *Halimeda* spp.). Bioturbation by *Callianassa* shrimps is common here. Locally, soft algae form extensive mats on some lagoonal bottoms. The deep sand facies is also found on non-lagoonal seaward terraces below wave base.
-Bioturbated sediments with calcareous algae
Carbonate sands and lime mud are not reworked by currents; rather, they are structured by intensive bioturbation. This unit is found in sheltered positions mostly below 10 m of water depth.

- Sand overgrown by soft algae
The sandy bottom of the lagoon basin at San Andrés is patchily overgrown by soft algae (*Dictyota* sp., *Padina* sp., etc.).

4.4.7 The fauna of stony corals and mollusks of the archipelago

The shallow-water fauna of stony corals recorded from the archipelago comprises approximately 50 species (Geister 1975, 1992; Díaz et al. 1995). Four scleractinian genera (*Cladocora, Oculina, Solenastrea, Tubastrea*) known from the Colombian mainland coast are missing or locally missing in the archipelago. This may be due to the isolated geographic position of the archipelago and the short larval stages of the corals in question.

The mollusk fauna collected in the reefs (Geister 1973b) seems to be equally impoverished with respect to the mainland coast, as it shows a predominance of species with long pelagic larval stages (Díaz 1995). Moreover the gastropod fauna of the archipelago shows a greater similarity to that of the Antillean region than to the adjacent Central American coast (Diaz 1995).

5. STATUS OF REEF ENVIRONMENTS IN THE ARCHIPELAGO

The reference basis for comparisons between current and earlier conditions of reef environments are the comprehensive observations made at San Andres in 1968 - 1973 (Geister, 1973, 1975), 1977 and 1979 (Geister, unpubl. data), 1992 (Garzón & Kielman, 1993; Díaz et al., 1995), and at Old Providence in 1969, 1970, 1973, 1977 and 1979 (Geister, 1992) and in 1994 (Diaz, Geister, Sanchez & Zea, unpubl. data). The Marine Research Institute INVEMAR at Santa Marta, Colombia, has assessed the degree of reef degradation in some of the atolls belonging to the archipelago. Zea et al. (1998) and Geister (1999, 2000 and 2001) studied and documented the biotic changes that have occurred over nearly three decades at San Andrés. Modern syntheses of the reefs in the archipelago and in Colombia as a whole are given by Díaz et al. (1996, 2000). A video Clip documenting the 1970 state of the reefs at San Andrés and Old Providence is accessible at the following Internet site:

http://www.palaeo.tv/modern/moderncoral.html#geister
x

Also time series of underwater photographs from San Andrés covering the degradation of reef sites over more than 30 years are available on this Internet site.

5.1 Natural versus anthropogenic degradation

As in the Atlantic and most tropical seas of the world, reef degradation in the Archipelago of San Andrés, Old Providence and Sta. Catalina has resulted in widespread, recently dead reef surfaces which are mostly covered by algae. Reef degradation, algal proliferation and large surfaces of recently dead corals can be observed even in the most remote and uninhabited oceanic atolls such as the Quitasueño Bank. Therefore, we believe that regional coral mortality cannot have its principal origin in local coastal pollution but rather in worldwide bleaching events, Black Band Disease (BBD) and White Band Disease (WBD) (see Geister 1999, 200la and 2001b). These phenomena caused generalized reef deterioration throughout the wider Caribbean Sea. Anthropogenic factors, nevertheless, play an important role in the degradation of reef communities at some localities. These factors include dredging, overfishing, sewage pollution and shipping activities. In addition, Hurricane Joan caused damage in 1988 at San Andrés, especially to near-shore coral communities along the unprotected west coast (see also Zea et al. 1998).

5.2 Mortality rates of corals

High levels of recent coral mortality have been recorded from San Andrés in depths between 0.5 and 20 m. Overall, Living coral has declined more than 50% in recent years in San Andrés. Most affected, with up to 80% coral mortality, are lagoonal patch reefs dominated by one or two branching species (*Acropora, Porites, Millepora*). They are situated near the highly populated areas of the northern part of the island. Equally affected are coral communities along the NW shores close to the area where sewage and solid waste are discharged into the sea. Lowest mortality levels were observed in the groove-and-spur system of the barrier reef, where the dominant species is the hydrocoral *Millepora complanata*. From a total of 49 species of scleractinian corals so far recorded for San Andrés, 19 were found to be affected to some extent by recent coral mortality (Díaz et al., 1995). Among them, 14 species exhibit maximum mortality levels of at least 50%, and some up to 80% (e.g. *Acropora* spp., *Agaricia* spp., *Porites furcata*, *Eusmilia fastigiata*, *Montastraea* spp.).

The condition of reefs around Old Providence and at the other reef complexes of the Archipelago is marginally better than at San Andrés. As at San Andrés, high levels of coral mortality have occurred in most of the lagoon, especially in patch reefs dominated by *Acropora cervicornis* and *Montastraea* spp. The staghorn coral *Acropora cervicornis* was the most widespread coral species from 1970 until the mid-1980s, when it covered extensive areas in lagoonal patch and ribbon reefs. Today (2002) this species is is almost entirely absent from the whole insular shelf of Providence. Many of these reefs are now heavily overgrown by algae, mainly *Dictyota* and *Lobophora*. On the other hand, the condition of reefs in many wave-exposed and non-lagoonal settings seems to be healthier around Old Providence and in the atolls than at San Andrés.

Sea fans of the genus *Gorgonia* suffered a recent mass mortality of more than 90%, not only at San Andrés and the southern atolls of the Archipelago but also on most shelf reefs along the continental coast of Colombia. The effects of this mortality were first observed in the islands during field work in 1992, but the mortality itself probably dates back to the late 1980s (Díaz et al., 1995:103-104). A similar mass kill of gorgonians was observed along the Caribbean coast of Central America (Guzmán 1984).

Encouraging signs of local recovery of San Andrés shelf reefs since about 1993 suggest that the degradation has essentially come to an end (Geister 1999, 200la and b). The recovery of a number of thickets of *Acropora palmata* on lagoonal patch reefs through 2002 has been spectacular.

5.3 Increases in macroalgae

As in most Caribbean reefs, algal cover and biomass have increased dramatically during the last two decades in San Andrés. Early encroachment by algae has been documented by time series of photographs since the late 1970s (see Geister 1999, 2001a). Subsequent algal growth has become more evident since the mass mortality of the sea urchin *Diadema antillarum* in 1983. Dense algal cover (mainly *Halimeda*, *Dictyota*, *Lobophora* and *Amphiroa*) can commonly be found today on dead coral surfaces and even on adjacent portions of the coral tissue.

These algae frequently overgrow healthy coral heads (mainly *Montastraea annularis*) gradually from the sides to the top, forming a dense felt of algal growth. Polyp tissue covered by the felt will bleach, and finally the entire colony will die when completely covered by the algae. It is interesting to note that representatives of 3 algal phyla (Chlorophyceae: *Halimeda sp.*, Phaeophyceae: *Dictyota* sp., Rhodophyceae: Amphiroa sp.) almost simultaneously assumed a similar strategy of invasion of new rocky surfaces from where they densely overgrow adjacent Living corals and suffocate the coral tissue.

5.4 Effects of overfishing

Populations of certain commercial species such as lobsters, queen conchs, groupers, and snappers have been overfished in San Andrés to such an extent that it is very difficult today to observe even a single individual of these species when diving. In 1968-1970, big fishes such as barracudas and reef sharks were commonly sighted around San Andrés, often in small groups. During Intensive field surveys carried out for several days in 1992 to 2001, only occasional solitary individuals of these fishes were seen.

In spite of heavy increases in fishing pressure around Old Providence and at the atolls in recent years, market-sized lobsters, queen conchs, groupers, snappers, barracudas and reef sharks can still be commonly sighted.

5.5 Recovery

Long-term monitoring (more than three decades) of San Andrés reefs points to a slow degradation with partial mortality of coral colonies and gradual algal encroachment in the late 1970s, followed by catastrophic coral mortality and massive algal invasion in the 1980s. This was followed by slow but accelerating recovery of reefs in the 1990s. Although algal infestation remains a major hazard, especially to massive corals, some patches of *Acropora palmata* have attained lush growth comparable to the 1970s. Some of these patches, however, did not recover at all due to the lack of surviving colonies. *Acropora cervicornis* became almost completely extinct during degradation, and the few surviving fragments of this species did not show promising signs of recuperation (Geister 1997, 2001a 2001b).

5.6 Natural reserves and protection

A limited area off the north and east coasts of San Andrés (essentially "Little Reef") was selected as a "Zona de Reserva Natural de San Andrés" in 1971 by the INDERENA, a former office of the Colombian government responsible for protection and management of the environment and natural resources (for zonal limits see fig 8.1 in Díaz et al. 1995). The "Parque Nacional Manglar de McBean", which has representatNe submarine environments, was established at Old Providence in 1995 by the Ministerio del Medio Ambiente. Besides the mangroves, this park includes part of the lagoon around Crab Cay, the nearby sector of the barrier reef, and a large piece of land above the landing strip and the adjacent main road.

In November 2002, UNESCO officially declared the entire Archipelago of San Andrés, Old Providence and Sta. Catalina the "Seaflower Biosphere Reserve". Though the island surface is only about 50km, the total area of the Archipélago comprises about 10% of the Caribbean Sea.

6. ISLAND GEOLOGY AND REEFS OF THE LOWER NICARAGUAN RISE

The available scientific information on the islands and atolls of the Archipelago is highly biased. The geology of the high-standing islands of San Andrés and Old Providence is the best-studied in the area. There has also been some geological work on the southern group of atolls including Courtown, Albuquerque, Roncador, Serrana, and Quitasueño, and there is some published information on Serranilla Bank. By contrast, hardly anything is known from Alice Shoal and Bajo Nuevo (fig. 2). Due to their remoteness from the inhabited islands of the Archipélago, the reefs and low islets of the northern group of coral shoals have hardly ever been visited by scientific expeditions. A distance of almost 500km from the administratNe center at San Andrés precludes their visit on a regular field trip by boat.

Though San Andrés is a pure limestone island and Providencia is almost entirely volcanic, early reports on the geology of the two main islands were largely erroneous. Collett (1837:206) considered the island rocks of Old Providence "to be chiefly limestone due to the presence of small but deep caves near the water's edge," but he also observed "fine black sand on the western side, which is attracted by the magnet" and thus could "be the remains of decomposed basalt". In addition, he mentions the spectacular "basaltic columns" of Basalt Cay lying to the N of Sta. Catalina Island. On the other hand, San Andrés was thought to be a volcanic island. On regional grounds, Schuchert (1935: 63 and 731), who has never been on these islands, considers San Andrés to be entirely basaltic. Mitchell (1955) never visited San Andrés personally, but he gave a description of a collection of magmatic rocks which were erroneously believed to come from San Andrés. Nevertheless, by 1931 the malacologist Pilsbry had already given the first correct geological information on both islands in his report on the occurrence of recent land mollusks. He recognized that the range of hills terminating in the high escarpment of North Cliff at San Andrés is a "limestone formation, probably an ancient elevated reef. He also stated that Providencia "is a volcanic island, the rock andesitic with some basalt". Milliman (1969a) was the first to point out that some of the large reef complexes of the Archipelago were in fact true oceanic atolls with a volcanic basement.

The geology of the Archipelago will be described in more detail in chapter 6. In the field trip section, it will be discussed jointly with outcrop photographs (chapter 8). To facilitate reading, relevant field stops will be mentioned in the following descriptions. Aerial views featuring islands and reef complexes will be presented in the overflight section (chapter 9). They give important additional information on the geomorphology of the islands and on the geometry and distribution of the modern reefs.

6.1 Island geology and reefs of San Andrés

The elongate San Andrés Island has a N-S extension of 12.6km and is only 3-km wide. It covers a surface area of 27km^2. The center of the island is a limestone ridge ("The Hill") up to 100 m high, formed by Miocene (Bürgl 1961) lagoon and reef deposits ("San Andrés Formation"). This ridge is an erosional relic of the rising western flank of a Miocene atoll. The periphery of the ridge was eroded during Pleistocene transgressions, but its core persisted as an island.(fig 15, for island topography see fig 25)

Today the Hill is fringed by a broad platform of terraced Pleistocene reef limestone. This platform emerges from the sea only around the central ridge, where it forms the flat lowlands of the present island. The peripheral areas of this terraced platform were flooded towards the end of the Holocene sea-level rise and remain submerged today. They form the modern insular shelf on which the Holocene barrier reef complex became established.

"San Luís Formation" is the name given to the Pleistocene limestone deposits cropping out on the terrestrial terrace around the island and underlying the Holocene reef complex and beach deposits (Geister 1975). It consists of at least two superposed stratigraphic units separated by an unconformity: the "Older Low Terrace Limestone Member" of uncertain Middle Pleistocene age has limited outcrop area and is widely overlain by the Sangamonian "Younger Low Terrace Limestone Member". Each unit belongs to an ancient coral reef complex which formed during an important transgressive event in Pleistocene time. At the entrance of Schooner Bight Cave, the horizontal contact of both Older and Younger Low Terrace Limestones is marked by a distinct paleosol indicative of a period of prolonged emergence, when soil formed between the two transgressions. The spatial relationship between the two limestones can also be studied in detail at May Cliff.

Holocene deposits of the modern reef complex overlie most of the Pleistocene San Luís Formation where submerged. The fore-reef terrace is an erosional hardground cut into the San Luís Formation. It is frequently transected by extension fractures of Wisconsinan age. The fractures seen in this hardground are laterally overgrown and covered by the Holocene reef facies.

The geomorphology of the island shelf is depicted in fig. 15, with fathometer profiles of the outer island slope shown in fig. 16. The geological evolution of San Andrés is represented schematically in fig. 17. A more detailed description of reefs and geology of San Andrés Island was previously given in Geister (1975).

6.1.1 Early island origins

A positive magnetic anomaly on the sea floor (fig. 5) points to the presence of a volcanic structure underlying the limestone cap of San Andrés. Both the outline of the island and present submarine topography suggest that this primordial volcano formed as an elongate NNE trending ridge. It is lying on the intersection point of two differently trending fault zones of the western Caribbean fracture system (see Geister 1992: fig. 6).

The age of this deep-seated volcano must have been Pre-Miocene. A Pre-Miocene (most likely Paleogene) age of the volcanism would also be compatible with the geological history of the western Caribbean crust. Subsidence coupled with shallow-water carbonate production till late Miocene time resulted in the deposition of a thick carbonate bank of the atoll type on top of the submerged volcanic ridge.

A tilting movement towards E began in latest Miocene time at the eastern shoulder of the San Andrés/Providencia graben structure. Persisting tilting of the atoll structure resulted in the continuous emergence of the western atoll rim giving rise to the present high-standing limestone island, while the eastern rim experienced faster subsidence with more continuous carbonate deposition (fig. 17).

Gradual uplift for about 500m of the western atoll margin during the last +-10 million years was largely offset by simultaneous erosion, subaerial weathering, and lateral truncation by advancing sea cliffs. Today, a 500 m thick stratigraphic section of limestone is accessible in an E-W section across the center of the island (fig. 18a). The oldest karstic features of the modern island, the dolines of the "Ponds" lined up in central Duppy Gully, may already have begun to form in late Neogene time along a zone of tectonic fracturing in the rising limestone mass. At present, these dolines are filled with clay and seem to be inactive.

6.1.2 Miocene lagoon and reef environments

The facies distribution within the Miocene deposits documents the atoll stage that the island went through and which lasted at least till late Miocene time. Most, if not all, of the outcropping rocks are of Miocene age, predominantly late Miocene. An erosive unconformity is seen in a lagoon section of probable Miocene age at Perry (see also Land Stop E6) near "Little Cliff" just N of the landing strip. Either this "Perry unconformity" documents the temporary failure of carbonate production on the ancient reef platform and accompanying erosion, or it is just the truncation plane of a sea-level lowstand (see Land Stop E6). The peripheral reef tract of the former Miocene atoll is not exposed today because it was truncated during several Pleistocene transgressions and overlain by reef complexes of Pleistocene and Holocene age.

Miocene lagoonal limestones of the central and northern part of the Hill are lithified calcareous muds deposited on a rather level lagoon floor. They show indistinct stratification in vertical outcrops. True foreset bedding was observed only in the road cut at the locality of Linval. It indicates shifting of sands in the ancient shallow lagoon. A rather monotonous fauna of thick- shelled pycnodontid oysters dominated parts of the deeper lagoon basin in the wider Duppy Gully area. In the large quarry of Duppy Gully (see Land Stop E2), it can be shown that the Pycnodonte beds are 0.5 to 1m thick and occur in cycles interbedded with limestone bearing an abundant and highly diverse fauna of medium-sized and small mollusks (pelecypods and gastropods). Bivalves are predominantly burrowing genera. The latter beds are from one to several meters thick. With the exception of oysters and pectinids, the mollusc shells of the Miocene lagoon are only preserved as molds. Geister (1975) listed the Miocene mollusk fauna collected. A complementary and more detailed study of the Miocene mollusks of San Andrés is given by García-Llano (1998).

Burrowing sea urchins (Clypeaster spp.) are frequently found in lagoon deposits at Mission Hill and elsewhere. Bioturbation by crustaceans is locally common in lagoonal sediments. An intricate meshwork of *Thalassinoides* burrows is exposed in a road cut at Lever Hill (see Land Stop E3).

Coral carpets of branching and massive species frequently intercalate with beds of mollusk-bearing sediments of the shallow lagoon floor. Only scattered coral communities are found in outcrops of the deeper lagoon facies of the central Hill. By contrast, rich Miocene coral faunas crop out in the southern hills in patches and thickets. These developed only a low relief, barely rising above the seafloor.

As indicated by distribution of sediment and coral fauna and by the overall shape of the ancient atoll, the Miocene lagoon was widest and deepest in its northern and central outcrop

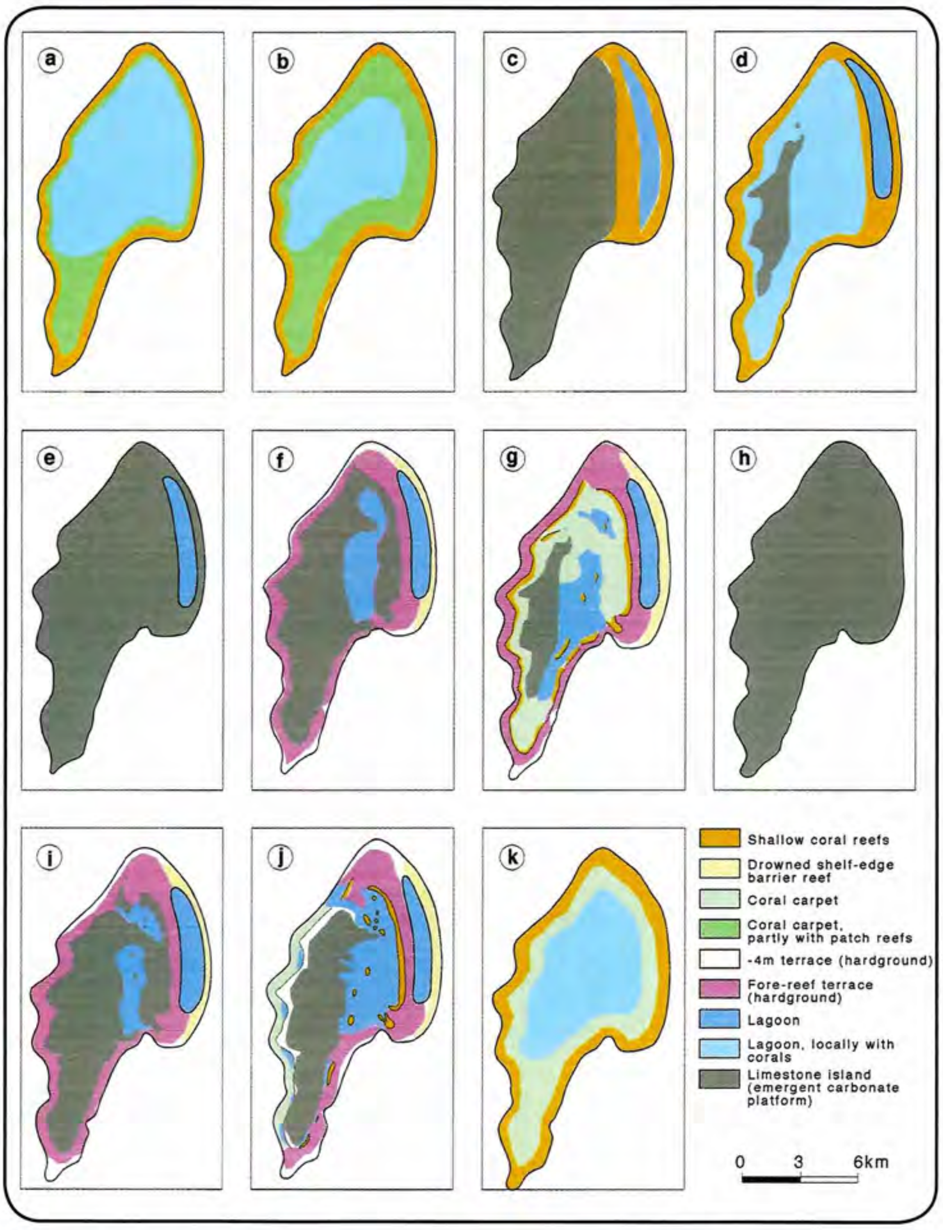


Figure 17. Geological evolution of San Andrés (revised from Geister 1975)
The San Andrés carbonate platform became established on top of a hypothetical elongate subsiding shield volcano (probably of Paleogene age) that formed along an intersection of two major fractures in the Caribbean oceanic crust. A succession of the following major evolutionary stages of the carbonate platform and of the shaping of the island may be reconstructed from field data (relative sea-level stands recorded in insular and submarine geomorphology and geology) as well as from the eustatic sea-level curve.

a) Early Miocene about 20 million years ago
Atoll stage with a lagoon wider and deeper in the N and narrower and shallower in the S.

b) Late Miocene about 10 million years ago
Persistence of atoll stage. The deep central lagoon basin is surrounded by a gradually widening, shallow lagoon dotted with coral carpets and patch reefs. Skeletal material is shed from the peripheral reef ring to fill the lagoon basin.

c) Latest Miocene about 5 million years ago
Beginning of tilting of the Miocene atoll to the E: A limestone island is rising at the western atoll margin, whereas a barrier reef with lagoon is forming along its subsiding eastern rim.

d) "Middle Pleistocene" (Aftonian?, Cromerian? complex): several sea-level highstands between 800,000? and 500,000 years ago
One or several major transgressions truncate many of the preceding Pleistocene terraces and the periphery of the uplifted atoll, leaving just the elongated central Miocene ridge of the present Hill. The latter is surrounded by a wide transgressional terrace bounded on the landward side by conspicuous high cliffs and escarpments (May Cliff, North Cliff, etc.). A shelf-edge barrier reef complex with lagoon basin in the W formed around the island on top of the transgressional terrace. The ancient eastern lagoon probably persists as a separate basin in the E (John Taylor Blue).

e) Early Yarmouthian (?) -25 m sea-level highstand ca. 220,000 years ago
Emergence of entire carbonate platform at the beginning of the Yarmouthian transgressions. Early truncation at seaward cliffs. Possible re-establishment of coral reef associations along the eastern shelf margin (Pallat Bank).

f) Late Yarmouthian (?) -8 m sea-level highstand ca. 170,000 years ago
Truncation ends along the west coast at a conspicuous high cliff ("Poxhole Cliff"), leaving a deeply undercut terminal intertidal notch at the present –8 m level. Truncation platforms of the Yarmouthian (?) transgressions will become the fore-reef terraces (modern –20 m terrace) of the Sangamon and Holocene reef complexes. Formation of a Yarmouthian reef complex on the –20m terrace is uncertain, because terraces are covered by younger sediments today.

g) Sangamonian +8 m maximum sea-level highstand 125,000 years ago
The great Sangamonian transgression re-floods the emergent Yarmouthian terrace and drowns Poxhole Cliff reaching the Hill escarpment at May Cliff. Establishment of the Sangamon barrier and fringing reefs on top of the Poxhole Cliff escarpment. Formation of a bank-barrier reef complex around the island, which covers the Yarmouthian (?) reef complex on the fore-reef terrace and Middle Pleistocene reef complex (Older Low Terrace Limestone), with exception of some topographic high areas near the Hill escarpment.

h) Wisconsinan -125 m maximum lowstand 20,000 years ago
Immersion of the entire carbonate platform and outer reef slopes during the –125m sea-level lowstand of the Wisconsin glaciation.

i) Late Holocene –5 m sea-level stand 5,000 years ago
Re-flooding of low-lying parts of Sangamon reef complex and of the ancient lagoon basins towards the end of the Holocene transgression. Gradual re-establishment of an active carbonate platform.

j) Latest Holocene modern 0m sea-level stand The last 3000 years
Submergence of peripheral Sangamon reef complex. In the past 3000 years, a modern bank-barrier reef complex has become established on top of the antecedent topography of the Sangamon barrier reef complex. Truncation of Poxhole Cliff will result in the formation of the –4m terrace.

k) Far geological future
Continued subsidence and general sea-levzel rise will lead to final truncation of the present island. Submersion of truncation platform may revert the former highstanding limestone island to an atoll complex established on top of a truncation unconformity.

sectors. Preliminary paleobathymetric analysis of coral distribution was carried out in the quarry near the landing strip ("Cantera de San Andrés"). The results suggest a lagoon floor between 20 and 55 m deep (Geister 1975: 145). True lagoonal coral build-ups are generally missing. However, at least one local build-up of branching poritids and one of massive corals (*Montastraea* spp.), both several meters high, rose here above the level floor of the ancient deep lagoon (see Land Stop E7). In the same extensive outcrop numerous large (some > 1 m), isolated, hemispherical coral colonies (mainly *Colpophyllia* sp.) became embedded in a top-down position on the level lagoon bottom, suggesting effects of seismic shocks during deposition time (Land Stop E7).

The lagoon was narrower and the water shallower in the S than in most of the central and northern outcrop area of the Hill. Between Lion's Hill in the N and Pepper Hill in the S, dense carpets of branching corals (*Acropora* spp., *Stylophora* spp., Porites sp.) are common (Land Stop E5). At Sam Wright Hill in the very south of the Miocene outcrop area, dense patches of massive corals (mainly large *Montastraea* spp., *Astreopora* sp., *Siderastrea* sp.) and stout branching corals (*Porites* sp.) may be seen under rather poor outcrop conditions. The distribution and ecology of the Miocene reef coral fauna is discussed in Geister (1975:140-148), where the species are also listed.

At irregular intervals, ashfall deposits several centimeters to decimeters thick suffocated the carbonate production of the Miocene atoll. The tephra, today mostly altered to smectite clay, have been as yet neither dated nor analyzed geochemically. Pebbles of such altered volcanic ashes in deposits of the Miocene lagoon were first recorded from Lions Hill (Geister 1975: 139).

Today, distinct but heavily altered tephra beds can be seen in fresh outcrops at Lever Hill and in Duppy Gully quarry. A succession of several clay beds, representing tephra layers, was recently encountered in cores recovered from a 100 m deep drill hole beside Big Pond in Duppy Gully (cores examined by courtesy of Corporación CORALINA, San Andrés, see also report by Rojas-Barahona 2001).

The tephra beds may correspond to Miocene ash layers recovered recently from three boreholes of the Deep Sea Drilling Project (including site 999 lying 300 km to the E). According to Sigurdsson et al. (2000) those tephra layers constitute a major episode of Miocene siliciclastic explosive volcanism in the Caribbean region with characteristics of co-ignimbrite fallout deposits. The distribution and thickness of the Miocene tephra on the ocean floor indicate a general fall-out axis trending easterly out of Central America, which was the nearest major source of ignimbrite volcanism at that time. The Miocene tephra episode recorded in the Caribbean deep-sea sediments seems to represent the distal fall-out equivalent of the thick ignimbrite formations of Central America (Sigurdsson et. al. 2000).

6.1.3 Pleistocene terraces and marine environments

Reef terraces originate from truncation of limestone coasts during slow transgressions. During a later stage of a transgression, a new reef complex will be deposited on top of the truncation plane (Geister 1983:235-239). Multiple reef terraces were formed in areas of slow but permanent uplift during Quaternary sea-level oscillations (Mesolella et. al. 1969, Chappell 1974; see also Geister 1984). As a result of tilting of San Andrés, flights of uplifted terraces can only be observed along the rising western margin of the island, while submerged reef terraces are more frequent and better developed along its subsiding eastern shelf. Ancient sea-level positions are indicated by old terraces and intertidal notches. Their present elevation reflects the effects of both eustatic sea-level oscillations and gradual uplift (west coast) or subsidence (east coast) in the near geological past.

a) The "High Terrace" and "Middle Terraces"
Erosional relics of a "High Terrace" (+80 to +95 m) occur at Sam Wright Hill, in the Cove Hill area, and possibly at May Mount. These terraces are preserved only in the heavily weathered flattened tops of the highest hills. No limestone deposits from the time of their formation were found. Considerable platform lowering due to limestone dissolution by rainwater was active over a long timespan. Successively younger and lower terrace levels occur near the rising west coast. The uplified terraces ("Middle Terraces") and associated cliffs on top of the "May Cliff' promontory are rather well preserved. They are less weathered than the "High Terrace" but still intensely karstified, showing solution caves and speleothem deposits. The bedrock of the terraces appears to be hard Miocene limestone, though no fossils have been found. Pleistocene reef rock was probably also deposited on these terraces, but is not preserved due to prolonged limestone dissolution by rain precipitation over periods of several hundreds of thousands of years. Two terrace levels have been recognized: The "Upper" (+55 to +65m) and "Lower Middle Terraces" (+25 to +30 m). Both levels are separated by a heavily weathered sea cliff, which is locally formed by two successive morphological steps (fig. 18b). Each of these terrace levels corresponds to a major transgression event, probably of early or middle Pleistocene age. Crosscutting relationships suggest a partial truncation of the Upper Middle Terrace by the transgression of the Lower Middle Terrace, which consequently should have a younger age. The 20 m high flat top of Little Cliff (NW of landing strip) rises almost to the level of the Lower Middle Terrace and thus might have been truncated by the same transgressive event.

b) The "Older Low Terrace" (+ 12 m Terrace) and the "Fore-Reef Terrace" (-20 m Terrace)
Outcrops of the reef complex of the Older Low Terrace ("Older Low Terrace Limestone") are almost restricted to the North Cliff and May Cliff areas. Some of the rocks cropping out at Little Cliff and on the topographic ridge to the

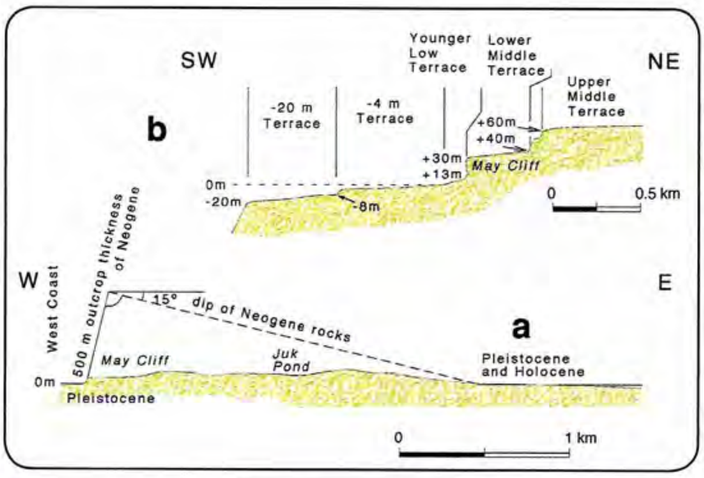


Figure 18 a) Geological section across San Andrés Island (vertical scale not exaggerated). The bedding planes of the Miocene rocks clearly indicate a tilting of the island to the E.

b) Topographical section across the May Cliff area. The section reveals several major terrace formations (vertical exaggeration 5:1). The -20m terrace (presumably Yarmouthian) is the fore-reef terrace of the modern barrier reef. The -4m terrace was formed by the Holocene transgression. The "Middle Pleistocene" Older Low Terrace or +12m terrace (presumably of Aftonian, Cromerian age) is not seen in this section. It corresponds to the +13m notch in May Cliff. The Younger Low Terrace is of Sangamon age. The corresponding +9m notch is not shown. Oldest are the Middle Terraces, which are preserved as purely morphological features cut into Miocene limestones of the San Andrés Formation. Penecontemporaneous limestone deposits are not preserved. See also fig. 20. Adapted from Geister (1975).

SW of it may also be of this age. Elsewhere, this limestone is currently hidden under the younger Sangamon and Holocene carbonates. The "Older Low Terrace" was formed as a wide truncation terrace in Miocene limestone around the rising island ridge and covered by a penecontemperaneous reef complex. The final sea level corresponding to this terrace is marked by a deeply cut terminal notch in the ancient coastal cliffs of North Cliff (fig. 19) and May Cliff (fig. 20).

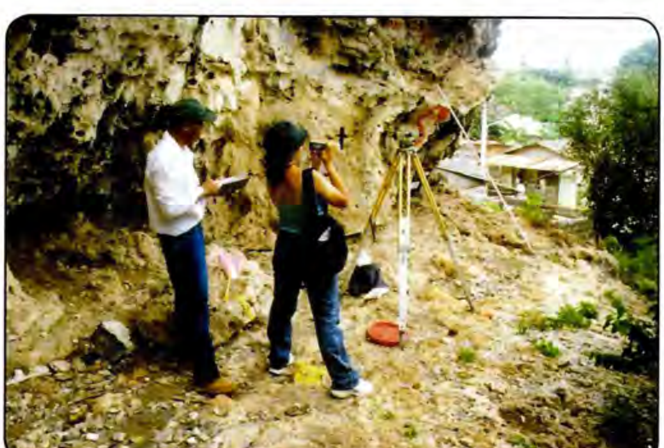


Figure 19 San Andrés: Geodetic survey at North Cliff by Mr. McLean, topographer of the local government, and geologist Betty Rojas of CORALINA. The inner margin of the Older Low Terrace was determined to be exactly 11.37m above modern sea level on this spot (yellow blotch below Betty). Note weathered intertidal notch to left just above the terrace. Terrace formation took place several hundred thousand years ago in the "Middle Pleistocene"(presumably Aftonian, Cromerian age). Rain dissolution of limestone in areas that are not protected by the overhanging cliff has since lowered the terrace level by about 3m. The houses in the background are standing on this lowered terrace, which was flooded again towards the end of the great Sangamonian transgression. Photo taken on September 11, 2000.

It lies today at the + 13m level. Two heavily weathered, less conspicuous additional notches without preserved relic sediments are visible higher in the May Cliff face. They may have formed during relatively short sea level pulses subsequent to the formation of the terrace and cliff (see fig. 20).

At both North Cliff and May Cliff, the inner margins of the terrace relics lie about 12m above modern sea level. Erosional relics of this Older Low Terrace are best preserved along the ancient +13 m intertidal notch (see fig. 19), where they are protected from subaerial erosion by the overhanging cliff face. Only a narrow landward margin of the original terrace surface can be observed today. It reaches a maximum width of only 2.5 m at North Cliff. The notch is locally filled with relic sediments, including beds of coral shingle and small mollusk shells (Geister 1975: plate 11 b and c), at May Cliff only. These sediments and the coral limestone at the foot of the cliff date from the final stages of a great transgression that must be of Middle Pleistocene age (fig. 20).

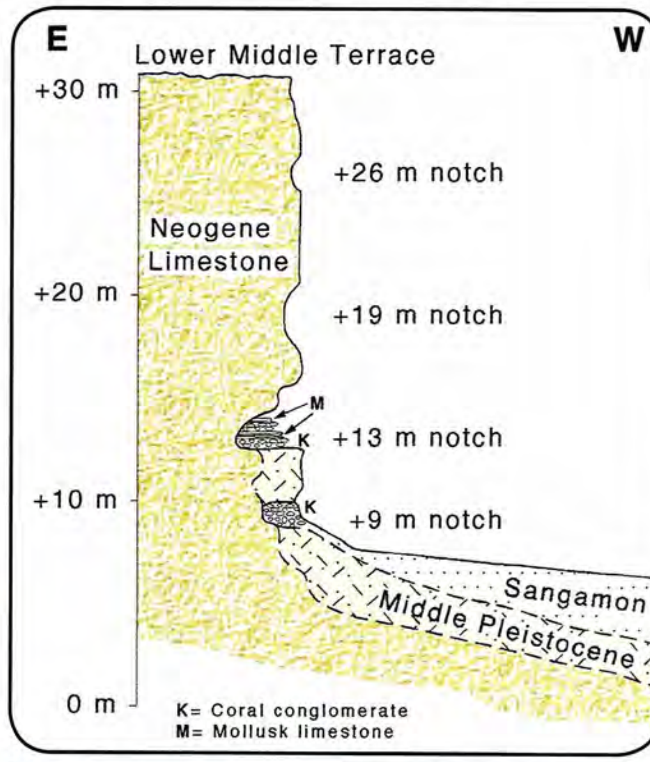


Figure 20. Topographic profile of May Cliff, San Andrés. Note fossil intertidal notches. The +13m notch contains marine deposits which record the end of the "Middle Pleistocene" transgression (presumably Aftonian). The higher and heavily weathered notches at +19m and + 26m are somewhat younger, but may also be of Middle Pleistocene age. The 3m-high vertical cliff wall below the +13m notch consists of Middle Pleistocene coral limestone of the Older Low Terrace. This wall was formed by limestone dissolution of areas of the +12m terrace that were not sheltered by the overhanging cliff. During the recent geodetic survey, the inner margin of the Older Low Terrace at May Cliff (flat below the +13m notch) was determined to lie exactly 12.16m above modern sea level in one particular spot.

The +9m notch cut into the Older Low Terrace Limestone marks the sea-level maximum reached by the Sangamon transgression. It is filled with lithified coral rubble and some Strombus gigas shells overgrown by thick encrustations of red algae. The Sangamon coral limestone ("Younger Low Terrace Limestone") in front of the cliff overlies Middle Pleistocene coral rocks of the "Older Low Terrace Limestone". Where seen along the +9m notch, limestone dissolution by rain was around 1m outside the shelter of the notch. Land Stop D3. Modified from Geister (1975). Levels of notches were adapted according to the topographic survey in 2000.

In the limestone wall of May Cliff, just below the notch, well developed, flattened, unusually large *Diploria strigosa* colonies crop out in vertical sections. They reach several meters in horizontal diameter and are up to l m high. Several large colonies grew in a superposed position. Locally, thickets of unusually thick *Acropora palmata* were associated with the *Diploria* colonies (see also Land Stop D3). The corals must have grown in very shallow water (less than 2 m deep) along the high coastal cliff, where they were shaded from morning till mid-day by the west-facing and overhanging wall of May Cliff Partial shading may explain the unusually flattened growth habit of these normally massive corals. Elsewhere, the older Low Terrace Limestone is rather devoid of very large (more than l m diameter) reef corals.

The seaward rim of this "Older Low Terrace" reef complex was partly truncated by Pleistocene time due to a transgression which formed the -20 m terrace (fore-reef terrace) and ended at a landward cliff. The terminal notch of this transgression is today found under water at the -8 m level. This second high sea cliff of San Andrés ("Poxhole Cliff') is submerged with its base 8 m deep, but it rises 15 m locally above the inner rim of the fore-reef terrace, or 7 m above present sea level (at Masily and Morgan Jump). Reef deposits penecontemporaneous to terrace formation probably underlie Sangamonian and Holocene carbonates deposited on the fore-reef terrace.

The formation of both May Cliff and North Cliff, as well as the "Older Low Terrace Limestone," was probably contemporaneous with that of the very similar but higher-uplifted "Second High Cliff of Barbados (Mesolella et al. 1969). A similar conspicuous high cliff exists to the E of the town of Santo Domingo (Geister 1982). These as-yet-undated megacliffs equally mark the end of an important interglacial transgression of probable Middle Pleistocene age (pers. observations).

Poxhole Cliff seems to correspond in age to the only other "megacliff' from the Barbados Pleistocene, which is known as "First High Cliff" and was equally submerged during the Sangamon transgression (pers. observation; Radtke 1989). However, due to higher uplift rates of Barbados, the "First High Cliff' lies mostly inland today, whereas Poxhole Cliff at San Andrés forms the modern coastal cliffline (except where truncated by the Holocene transgression or submerged). The present southeastern coastline of the Dominican Republic is formed by a comparable, partly submerged high cliff, which rises vertically from the fore-reef terrace (Geister 1982).

c) The Sangamon "Younger Low Terrace" ("+8m Terrace")

Poxhole Cliff and most of the landward Middle Pleistocene reef platform were submerged during the Sangamon transgression and became overlain by the Sangamon reef complex ("Younger Low Terrace Limestone"), which was dated by Richards (1966). By contrast to the Middle Pleistocene Limestone of the Older Low Terrace, the transgressive Sangamon reef complex ("Younger Low Terrace Limestone") crops out widely on the surface of the present terrestrial terrace which surounds the Miocene "Hill" (fig. 21). It rests on truncated Miocene and older Pleistocene limestones (mainly "Older Low Terrace Limestone"). The unconformity between both units is marked by a paleosol at Schooner Bight cave. The terrace rocks were deposited up to about 8m above present sea level, and at "May Cliff' up to 9 m. At May Cliff, an intertidal notch at the +9 m level marks the terminal Sangamon sea-level highstand (fig. 20). This notch is cut into the Middle Pleistocene limestone ("Older Low Terrace Limestone").

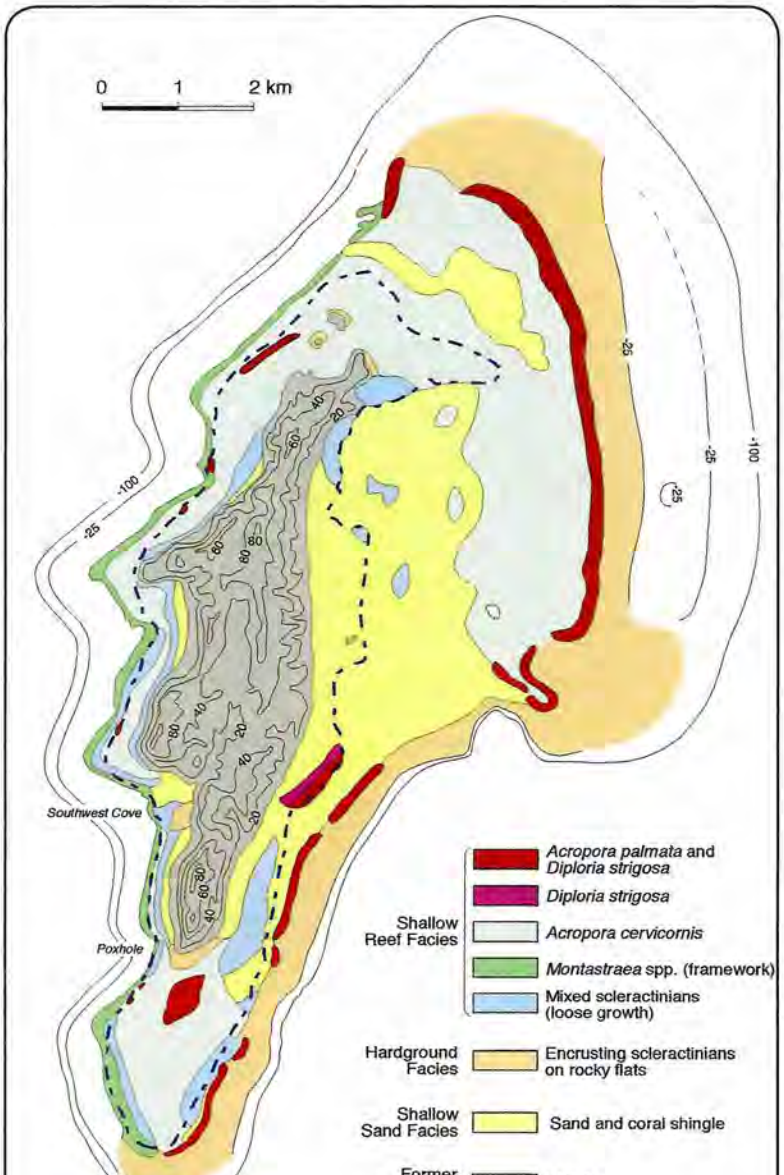


Figure 21. Distribution of facies and benthic communities across the Late Pleistocene (Sangamon) shelf of San Andrés. Former island area is in dark gray. Land topography is conjectural. Outside the present shoreline, facies interpretation is uncertain (not accessible for observation, covered by Holocene sediments, or eroded). Corrected and modified from Geister (1975).

Since the formation of the Sangamon cliff some 120,000 years ago, rainwater solution has lowered the general level of the Sangamonian terrace for about l m, as can be seen at the slight drop-off just outside the notch.

The Sangamon notch is partly filled by an apparent storm deposit of cemented coral shingle and some large *Strombus gigas* shells. Heavy encrustations by melobesioid red algae are notable at much of the Sangamon cliff face. The encrustations also cover the infill of shingle. In addition, many nearby in situ corals of the Sangamon reef complex are covered by massive crusts of red algae several centimeters thick.

As a result of the Sangamon transgression, most of the present island terrace was flooded. Two islands emerged above the Sangamon sea level: the central ridge of the Hill and a much smaller island around Little Hill lying to the N of the landing stip (fig. 24). Apparently, due to the mostly

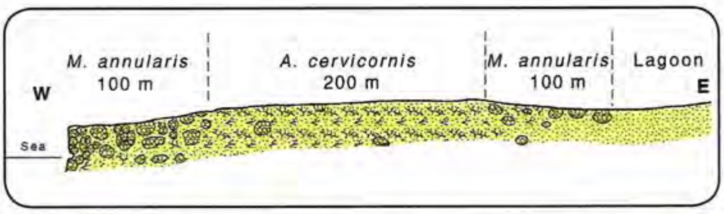


Figure 22. Schematic coral zonation of the leeward fringing reef during Sangamon time. West coast of San Andrés. Along the seaward margin of the reef, there is a diverse coral fauna dominated by the massive star coral Montastraea annularis and associated species. The wide reef crest is colonized by almost monospecific thickets of the staghorn coral Acropora cervicornis. Towards the former boat channel in the E, a discontinuous belt of Montastraea annularis and related species replaces the staghorn corals. Schematic and not to scale. For Pleistocene coral distribution, see also fig. 21.

steep Sangamonian coastline, no major sand beaches were developed. Shallow nearshore areas at Perry (near Little Hill) and at the NW side of North Cliff were paved with encrusting scleractinians (*Diploria clivosa*) similar to those found today in front of the modern cliffline along the west coast. The Sangamonian coastline below the eastern slopes of the Hill is covered by younger slope debris and thus remains inaccessible for examination.

The Sangamon lagoon and barrier reef were essentially in the same position as the modern lagoon barrier reef. The barrier and leeward fringing reefs became established on top of Poxhole Cliff. They were bank-barrier and bank-fringing reefs (see Geister 1983, table 4) comparable in outline to those of the modern reef complex. The fore-reef terrace of these ancient bank reefs would later become the fore-reef terrace of the modern reef complex (-20 m terrace).

While the Sangamon rocks rise several meters above present sea level along the west

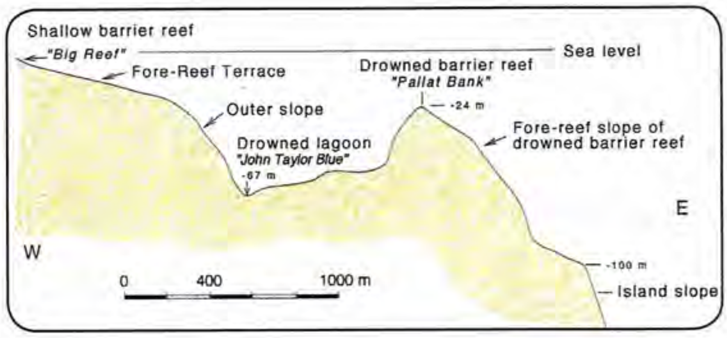


Figura 23. Section across the drowned barrier reef of Pallat Bank at San Andrés with corresponding lagoon (John Taylor Blue). The reef crest is situated at a minimum depth of -24m and lies 43m above the bottom of John Taylor Blue. The drowned reef and lagoon are located seaward of the outer slope of Big Reef. Section constructed from a fathometer profile run from Big Reef to Pallat Bank in 1970. Vertical exaggeration approximately 10x. Adapted from Geister (1983).

coast, the Sangamon reef complex today lies notably lower in the E than in the W as a result of tilting. In the E, the Sangamon reef complex is widely submerged and overgrown by the modern reefs or covered by the Holocene beach deposits. Hansa Point, Cotton Cay, and Haine Cay represent Sangamon lagoonal patch reefs emerging above modern sea level. Only limited surface outcrops of the Sangamon rocks are in lagoonal deposits. They are seen along the central east coast and at Rocky Cay. Sangamon reef and lagoon rocks underlie the Holocene reef complex all around the island.

Along the west coast, the Sangamon rocks form an emergent fringing reef tract. Most of the fossil reef flat was colonized by the staghorn coral *Acropora cervicornis* (see also Land Stop A10). The steep seaward margin of the reef was overgrown by an association dominated by the star coral *Montastraea annularis*

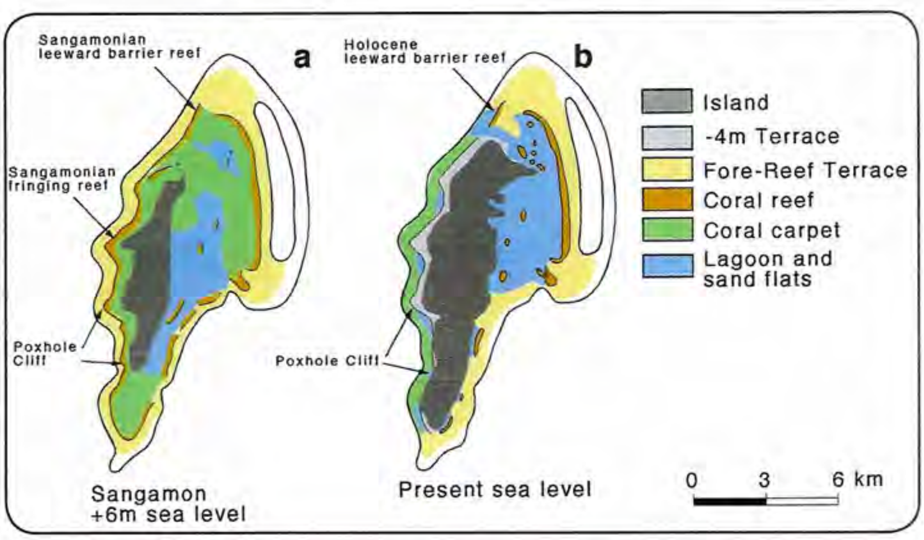


Figure 24. The submerged northern continuation of the Sangamon leeward fringing reef is overgrown by Holocene reef facies forming the modern leeward barrier reef of San Andrés.

Paleogeographic situation (a): Sangamon relative sea-level highstand (+9m). The fringing reef is established on top of the late Yarmouthian (?) Poxhole Cliff which parallels the west coast. Towards N it detaches from the coast and becomes a leeward barrier reef.

Paleogeographic situation (b): Present sea-level stand. Only the low-lying western platform margin and the windward Sangamon barrier reef were re-flooded. They were colonized by corals towards the end of the Holocene transgression. The modern barrier reef becomes established on the antecedent topographic highs of the Sangamon barrier.

and related species. The moosehorn coral *Acropora palmata* is found only in localized patches of the crest, which were under the influence of waves reinforced by refraction above the seaward terrace topography. *Montastraea*-dominated associations are also found in very protected positions along the lagoonward margin of the reef and near the Sangamonian shoreline (fig. 22).

The Sangamon rocks along the SE coast correspond to the lagoonward margin of an oceanic fringing reef (fig. 17). The reef crest here underlies the modern reef formations and boat channel. Thickets of the staghorn coral *Acropora cervicornis* formerly grew on the wide, shallow, flat lagoonal area in the lee of this reef. This is the southern tongue of the present island terrace.

The moose-horn coral *Acropora palmata* formed the crest of the Sangamon windward barrier reef (which is submerged today). This can be verified at Big Reef and at Broken Ground by diving in submarine caves underlying the modern barrier reef framework. Today the windward barrier is dominated by the hydrocoral *Millepora*. Acropora palmata occurs only in more protected settings on the deeper fore-reef slope and in the rear of the crest.

The coastal terrace between Sterthenberg Point and Occasion Call at San Luís is also Sangamonian reef rock. This corresponds to an ancient laggonal fringing reef which parallels the modern shoreline. The reef is best developed in the S at Occasion Call, where an interlocking framework of meter-sized colonies of *Diploria strigosa* is visible with some large *Acropora palmata* colonies between (L and Stop A3). Coral growth becomes discontinuous towards N, where scattered *Diploria* colonies are common and a few pillar corals *Dendrogyra cylindrus* were seen.

Much of the coral fauna in the Sangamon reef complex is not found in a Living position. Most of the staghorn corals Acropora cervicornis along the west coast are fragmented. Around Sterthenberg Point, *Diploria* heads are frequently uprooted and embedded in an upside-down position, and all the *Dendrogyra* colonies had tumbled. Fragmented corals were neither abraded nor piled up, as might be expected from hurricane impact. Earthquake shocks may have caused the destruction. In fact, extension fractures transverse the Sangamon limestone near Sterthenberg Point. The gaps of the cracks are filled with contemporaneous lagoonal sediments. Since emergence of the reef in Wisconsinan time, the lithfied fill material weathered out as low sedimentary dykes. Conspicuous fill components include local concentrations of mollusk shells (see Geister 1973a) and fiagrnented corals (see also Land Stops Al, A2 and A10).

The dominant coral of the entire Sangamon reef platform is *Acropora cervicornis*, a species fairly rare today around the island. By contrast, the hydrocoral *Millepora* was practically absent from the Sangamon reefs, but it became the dominant framebuilder in the modern windward reefs of the island. The reason for this divergent coral distribution in windward and leeward reef settings past and present might be a greater Sangamonian water depth of the reef terrace where the corals grew, as compared to the modern reefs. This might have resulted in divergent wave exposure patterns (Geister 1975). A greater-than-present water depth above the former barrier reef was also inferred from the distribution of the mollusk fauna in the reef complex (Geister 1973a). The Sangamon coral fauna is given in Geister (1975: table 9).

Rather well-preserved Pleistocene corals (*Montastraea annularis, M cavernosa, Dichocoenia stokesi*) were found attached to Miocene coral rock on Sam Wright Hill at an elevation of +65 m (Geister 1975), indicating a rather late and brief sea-level highstand of unknown age. A Sangamon age of the corals must be excluded based on the currently accepted sea-level curves, though no altemative age for the corals can be suggested at present.

d) Deeper submerged reef terraces

A drowned Pleistocene barrier reef ("Pallat Bank") with adjacent lagoon ("John Taylor Blue") was located by dives and echosounding at the northeastern margin of the insular shelf. At present, its crest reaches up to a minimum depth of 24m (fig. 23). The topographic feature is covered by modern coral and algal growth. Rich stands of scleractinians (*Colpophyllia natans, Diploria sp., Porites porites, Eusmilia fastigiata*), octocorals, and sponges have been noted in 1973 during reconnaissance dives in the reef crest area E of Haine Cay. Carbonate sand and mud seems to covermost of the Bottom of John Taylor Blue. Pallat Bank is a shelf-edge barrier reef of undoubtly Pleistocene age (probably Pre-Sangamonian) which formed during one or more relatively low sea-level stands. Nothing can be said about the internal structure and absolute age of Pallat Bank reef.

A consistent but narrow submarine terrace at the -35m to -40 m level is known from around the island (fig. 16 C) and was also seen at Old Providence. Its occurrence at the same depth levels on both the subsiding eastern and uplifting western shelf margins suggests a rather young - probably Wisconsinan - age of the terrace. The absence of a -40 m level in the very young (probably early Holocene) vertical escarpment of the Bocatora Hole collapse feature excludes a Holocene age of this terrace.

Additional submarine terraces were recorded by echosounding from depths of -56m and -90 to -100 m in front of the subsiding eastern insular shelf (see fig. 16). None of these submarine terrace levels is known from the uplifiing western margin of the insular shelf

6.1.4 Relative and absolute dating of Pleistocene marine terraces, sea cliffs and coral reefs

a) Relationships of truncation/superposition and the rate of tilting
The Older Low Terrace (+ 12 m terrace) was truncated at its seaward margin by the fore-reef terrace (- 20 m terrace) in front of Poxhole Cliff and hence must be older. However, Older Low Terrace Limestone is also partly truncated by the Younger Low Terrace landward of Poxhole Cliff. The formation of the Holocene -4m terrace is visibly going on at the present. Its truncation plane along the modern cliff transects rocks of both Older Low Terrace Limestone and Younger Low Terrace Limestone. From these observations we can conclude that the Older Low Terrace is the oldest geomorphologic feature of those here discussed, followed by the fore-reef terrace (-20 m terrace), the Younger Low Terrace (+9 m terrace) and the -4 m terrace.

Due to the very slow tilting rate of the island (estimated uplift: only a few mmf 100 years at May Cliff- see chapter 6.1.5), the youngest terraces should hardly show a notable difference in elevation between the eastern and western shelf margins. Older terraces would be notably lower in the E and higher in the W. Examining the corresponding levels of the outer terrace margins and of intertidal notches in the E and W, the total tilting since terrace formation will give a valuable clue for the relative age of the terraces:

- The Older Low Terrace, though today 12 m high in the W (May Cliff, North Cliff), is entirely missing in the E of the island, because it is lying under sea level and hidden under more recent deposits.

- The inner margin of the fore-reef terrace (along Poxhole Cliff) lies in about –l0 m at Cat Bay (west coast near South Point). Eastward from South Point, it deepens to 15 m. The submarine relief of the submerged cliff is also lowered to such a degree that it becomes inconspicuous and merges with the surfaces of fore-reef terrace and fore-reef slope. Fore-reef slope and fore-reef terrace are not separable on purely geomorphological grounds in front of the windward barrier reef.

- The outer shelf edge of the fore-reef terrace lies 18 to 20 m deep in front of the west coast and southeast coast. It is between 35 to 25 m deep at Pallat Bank at the easternmost shelf margin, where it is overgrown by reef framework of unknown thickness.

- The Younger Low Terrace Limestone rises up to 7m above the modern sea level in the coastal cliff along the west coast (Morgan Jump, Masily). Along the east coast, this same cliff is low (0.5m) or entirely missing in sectors where the Younger Low Terrace Limestone is submerged and overgrown by a modern fringing reef. It is also simply covered by modern beach sediments in places.

- The- 40 m terrace is equally present at the -35 to 40 m level along much of the eastern and western outer reef slopes. Sediment cover on the terrace surface at the different locations does not permit very precise determination of the original level of the terrace surface. It is remarkable, however, that the outer terrace margin is present around the island at a persistent -35 to 40m level, which indicates a rather short period of tilting since its formation and hence a rather young age of this terrace.

All these observations clearly show the effect of continuous eastward tilting. From both truncation/superposition relationships and tilting effects, we find convincing evidence for the following age ranking of the terraces and related geomorphologic features as well as of the terrace deposits studied. These are, from old to young:

- Older Low Terrace and terminal landward high island escarpments (May Cliff, North Clim with terminal notch and corresponding fossil reef complex.

- Fore-reef terrace and landward Poxhole Cliff with terminal -8 m notch.

- Younger Low Terrace limited with landward cliff line, terminal notch and fossil reef complex. - 40 m terrace.

-4 m terrace and overlying modern reef complex.

b) Evidence from radiometry and vertical rates of rain dissolution in limestone.

Richards (1966) obtained a ionium age of 125,000 +- 10,000 years B.P. from corals of the Younger Low Terrace of San Andrés. This corresponds precisely to "substage 5e" of the standard marine oxygen isotope stratigraphy. Reef deposits of "substage 5e" were formed during the great Sangamon (Eem) transgression. No coral samples from older reef deposits were found that were suitable for radiometric dating. This terrace age is a key date which permits extrapolation of approximate absolute ages of the other transgressions until more radioactive dates are available.

The degree of weathering of the terrace deposits by limestone dissolution indicates that, among the uplifted terraces, the oldest tend to be highest and are most heavily eroded. The youngest terraces are in the topographically lowest position and better preserved. The absolute duration of emergence can be roughly estimated from the amount of terrace lowering by limestone dissolution. Base level for measurement is the lower horizontal face of the terminal intertidal notch, which formed in landward continuation of each terrace in the coastal cliff During the process of terrace lowering, the lower face of the notch is protected from rain and remains at its original level, while the adjacent unprotected terrace surface is lowered by rain dissolution with time. As a result, the cliff face seen above the notch will develop a vertical continuation below the notch, which may be called "dissolution escarpment". Dissolution escarpments of Pleistocene terraces may be from several decimeters to meters high. The height of the dissolution escarpment reflects the relative time of terrace exposure to rain since the retreat of the sea. Dissolution escarpments are especially well developed in the walls of North Cliff (fig. 18) and May Cliff (fig. 20).

The surface of the Sangamon terrace in front of the Sangamon notch at May Cliff has been lowered for about lm in around 100,000 years (fig. 20). This amount corresponds to a mean dissolution rate of 1 mm per 100 years. Assuming a roughly constant rain precipitation rate at a given location since Middle Pleistocene time, the duration of the emergence periods of other reef terraces should be grossly reflected by the amount of terrace lowering. In the same geographical area, the height of the dissolution escarpment should be proportional to the approximate exposure time of the terraces. Gross absolute ages may be derNed from the height of the dissolution escarpments. Using this method, the following two additional dissolution escarpments have been measured and their ages calculated:

1) The maximum height of the dissolution scarp below the terminal notches of the Older Low Terrace reef complex is at least 3 m at North Cliff and 4 to 5 m at May Cliff. The attributed duration of the exposure of the Older Low Terrace reef complex would be on the order of 300,000 to 500,000 years. These ages will be minimum values only, since Sangamon limestone deposits have covered the terrace margin in front of the cliff. The dissolution of this limestone might have delayed the lowering of the terrace for 100,000 years or more.

2) A 1.5 m-high dissolution scarp in Poxhole Cliff can be observed in the Cat Bay area below the terminal -8 m notch of the -20 m terrace (or fore-reef terrace). Duration of terrace lowering would be 150,000 years. As this terrace was reflooded during the Sangamon transgression for about 50,000 years, the age of the fore-reef terrace could be on the order of 200,000 years. If Sangamon sediments were deposited in front of the cliff, the lowering of the original terrace would have been further delayed.

c) Evidence from known positions of eustatic paleo sea-levels and succession of climatic cycles.

Recent evidence stemming from Bahamanian slope sediments (Robinson et al. 2002) and submerged stalagmite from Italy (Bard et al. 2002) point to repeated and prolonged sea-level stands with a general tendency for transgression at the -20 to -8m level during isotope stage 7 (Yarmouthian /Holsteinian interglacial, 240,000 to 180,000 years BP). It is thought that these worldwide transgressions might be at the origin of the truncation of the fore-reef terrace.

The next major warm period before the Yarmouthian/ Holsteinian interglacial was the Cromerian complex in the Middle Pleistocene, between 500,000 and 800,000 years B.P. It corresponds in part to the Aftonian interglacial of the North American timescale. It is conceivable that the 300,000-year duration of the Cromerian Complex might have been sufficient for the truncation of much of the rising Miocene island and for the planation of the Older Low Terrace. This might have occurred during several successive transgressions of Middle Pleistocene age. A terminal notch from a final sea-level rise is found at the +13m level in May Cliff and North Cliff

6.1.5 Pleistocene tectonics: absolute tilting rates and fracturing

Tilting of the island began by late Miocene time (around 10 Ma). Since that time, the May Cliff area has been uplifted about 500m (see fig. 18). This would correspond to a mean uplift rate on the order of 5mm per 100 years. The Quaternary uplift at May Cliff is indicated by the terminal Sangamon notch, which is situated today at the +9 m level. In tectonically stable areas elsewhere, the maximum of the Sangamon transgression reached +6 m above modern sea level. The difference between this +6m level and the +9 m level at May Cliff points to an uplift of about 3m during the last 125,000 years. This would correspond to a mean uplift rate of about 2.5 mm in 100 years. It cannot be determined from the available data whether this tilting was gradual or periodic. Althoug these estimates are rather inaccurate, they nevertheless clearly indicate that the tilting movement of the island continues into modern times with the same order of magnitude as in the late Miocene.

The uplift movement might be useful to estimate the original level of the terminal "Cromerian + 13 m intertidal notch" at May Cliff and North Cliff If these are really Cromerian, a minimum age of 500,000 years will have to be used in the calculation. Using the Pleistocene uplift rate of 2.5 mm/100 years, the total uplift since the formation of the notch would amount to at least 12m. If this holds true, the terminal Cromerian sea-level stand would have been near modern datum or a few meters below. As a consequence, no Cromerian high cliff can be found on nearby Old Providence Island, where no uplift occurs.

Additional evidence for persisting tectonic movements comes from a number of extension fractures dissecting the Miocene and Pleistocene reef rocks of the island. No lateral or vertical displacement of the blocks on either side of the fracture was observed, just an opening of clefts generally less than l0 cm wide. The most numerous fractures are found in Miocene rocks, indicating that faulting was also common in pre-Sangamon time, as documented by a more comprehensive cumulative record in the oldest rocks. Some of the clefts of these fractures in the Miocene rocks are more than 0.5m wide. They do not continue laterally into the Sangamon rocks. NNE/SSW- and NW/SE-trending strike directions of the cracks prevail. Some fractures change from one direction to the other. The strike directions thus follow the regional tectonic pattern. (see fig. 25)

Some of the cracks near Sterthenberg Point formed during Sangamon time, when the terrace was flooded. Loose marine sediments filled them. Mollusk shells in-particular became locally concentrated in the freshly opened space (Geister 1973b). However, most fracturing visible in the "Younger Low Terrace" limestone occurred after emergence of the Sangamon reef in Wisconsin time. These cracks were subsequently filled by spany calcite (speleothem). They weather out similar to resistant "calcitic dykes" where the reef rock is exposed to dissolution in the salt spray zone at the sea shore or to humic acids of soils on the terrestrial platform.

Along the SE coast near Bocatora Hole, even younger "dykes" occur. These are only imperfectly filled by calcite or are still open today. Very young fracturing along the SE coast, perhaps of early Holocene age, seems to have triggered the collapse of the platform margin in front of Rocky Point, resulting in a huge vertical submarine scarp at the edge of the southwestern insular shelf ("Bocatora Hole"). In addition, completely open cracks were found on the fore-reef terrace SW of Elsie Bar Channel at around 10 m water depth and deeper.

Most spectacular are the open clefts exposed under water at the cliff edge of Bocatora Hole (Sea Stop C1). These fractures must be Holocene in age and seem to be linked to those of the adjacent island coast. The formation of the extension gashes of San Andrés may be related to continuing rift movements of the NNE trending graben structures located W and E of the islands.

Karst features on the island are clearly fracture-controlled. Numerous NNE-trending fractures in the central Hill resulted in the formation of a series of collapse dolines lined up in a NNE direction. These were subsequently filled by clay and gave rise to the chain of ponds found in Duppy Gully today (fig. 15). Sinkholes without clay fillings were seen in the northern prolongation of this pond chain. It appears that the whole of Duppy Gully was formed by karstic erosion which was controlled by a series of fractures. There is no stream connecting the different ponds, which could be responsible for the erosion of the valley.

The formation of karstic caves in the Pleistocene San Luis Formation is determined by fractures. The caves are mostly very namw and long and follow tectonic cracks. The walls of May Cliff and North Cliff were also predetermined by fractures. After the undercutting during the Pleistocene transgressions, the outer wall of the cliffs collapsed along the fracture-planes. This collapse was robably tiggered by earthquakes.

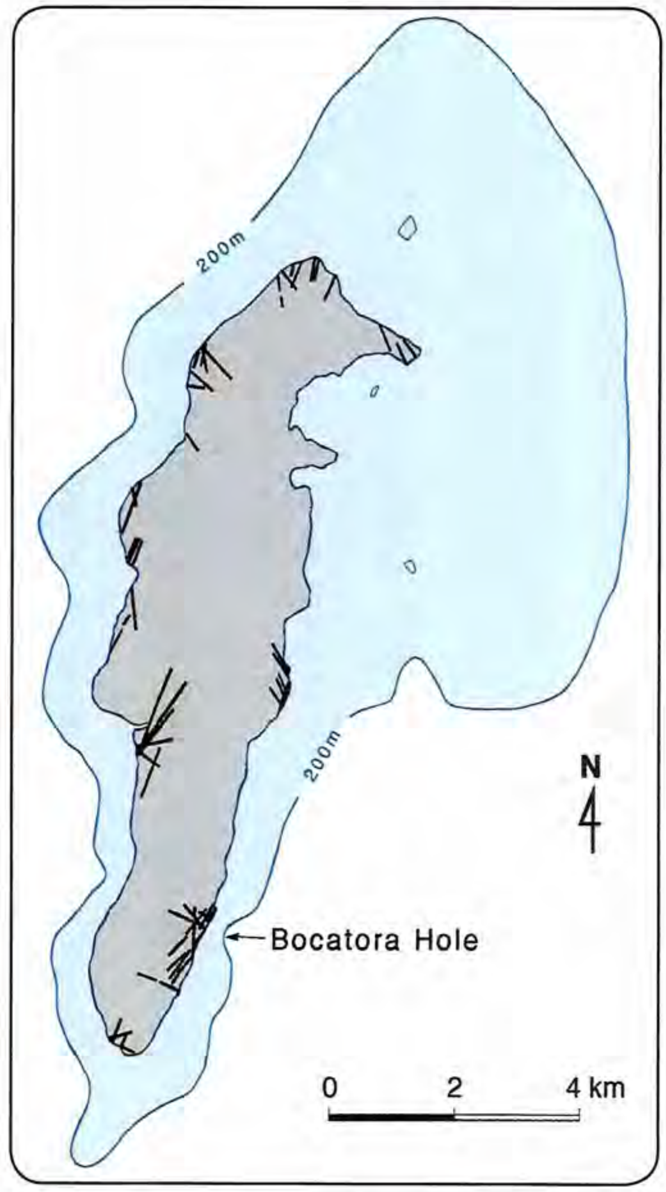


Figure 25. Distribution of major extension fractures cutting across the Sangamon reef terrace along the San Andrés shoreline. Most fractures cannot be followed inland because of dense vegetation or remain hidden under beach deposits. Note the concentration of fractures along the coast in front of Bocatora Hole. Adapted from Geister (1975).

6.1.6 Geologic history of the modern reef complex since the Middle Pleistocene transgression

Much of the geologic history of the modern reef complex since Middle Pleistocene time can be reconstructed. Where submerged today, the Pleistocene limestones of the San Luis Formation form the basement of the modern reefs. As detailed in the preceding chapter, the spatial and temporal relationships of these limestones and their geomorphological features provide valuable keys that help to decipher the changing paleogeography of the island and surrounding reefs.

The shaping of the modern reef complex occurred during at least seven distinct successive transgressive and regressNe phases, as recorded by the submarine and terrestial topog-

raphy. Each interglacial transgression resulted in the partial truncation of the existing limestone body with subsequent deposition of a younger reef complex on the unconformity. Glacial regression lead to emergence of the reef complex resulting in karstification of the emergent reef limestone and the formation of paleosols. See Geister (1983: fig. 57) for a schematic representation of successive sea- level events and their effects on reef geomorphology.
The following sequence of events is suggested by the observations described in chapter 6.1.4 and 6.1.5:

a) The Cromerian (Aftonian?) interglacial transgressions
Truncation of most of the periphery of the uplifted Miocene atoll was followed by deposition of the Older Low Terrace Limetone reef complex on top of the truncation plane in "Middle Pleistocene" time ("Cromerian Complex). More than one transgression was probably involved in this truncation, which was fundamental for the formation of both the modern island shelf and terrestrial terrace. The final coastline of this transgression is marked by the strongly weathered, high inland escarpment of the island, which is best preserved in May Cliff, North Cliff and Little Cliff The age of this cliffline must be on the order of 500,000 years. The peripheral reef of that time was probably a shelf-edge barrier reef situated near the margin of the modern insular shelf.

b) The Kansan (Elsterian) glacial regression
The Aftonian interglacial was followed by the Kansan (Elsterian) interglacial sea-level drop. At present, no geomorphologic features can be related with certainty to this eustatic sea-level low- stand.

c) The Yarmouthian (=Holsteinian) interglacial transgressions
The -20 m terrace is formed by marginal truncation of the Older Low Terrace Reef complex. At the landward side of this terrace, the terminal stage of the transgression is documented by a mostly submerged sea cliff ("Poxhole Cliff ") with a conspicuous intertidal notch in the cliff face at the -8m level. This notch cuts 6-8m horizontally into older limestone. Due to the tilting effect of the island, Poxhole Cliff becomes inconspicuous towards the E and wedges out on much of the eastern insular shelf in about 15m of water depth. This cliffline should be approximately 200,000 years old. Reef limestone deposited during this transgression probably underlies the Sangamon and Holocene reef sediments of the San Andrés fore-reef terrace. It should also be found under younger deposits of the modern upper island slope and would be accessible only by drilling.

d) The Illinoian (=Saalian) glacial regression
The sea level drop following the Yarmouthian interglacial resulted in a prolonged emergence of the entire insular shelf during the Illinoian glaciation. This sea-level lowstand persisted for approximately 60,000 years. A pitted surface and paleosol developed on the surface of the emergent limestone. No further geomorphologic features can be related with certainty to this emergence.

e) The Sangamonian (=Eemian) interglacial transgression
After the Illinoian regression, the old sea cliff and adjacent landward limestone platform were rapidly submerged as a result of the sea-level rise of the great Sangamon transgression. Subsequently, a new reef complex ("Younger Low Terrace Limestone") was laid down on top of the old pre-Sangamon topography marked by the Illinoian paleosol. The new barrier reef itself became established on top of the topographic high of Poxhole Cliff. It was surrounded by the Yarmouthian -20m terrace. This is a Sangamonian bank-barrier reef with the Yarmouthian -20m terrace as a fore-reef terrace. Earthquakes opened extension clefts on the sea floor, which were filled by loose contemporaneous marine sediments which became indurated. The Sangamon limestone deposits crop out at the surface of the modern island terrace where not covered by Holocene beach deposits. The maximum sea level of the Sangamon transgression was reached at about 125,000 years B.P.

f) The Wisconsinan (=Weichselian) glacial regression
Post-Sangamonian regression led to an extreme sea-level lowering during the Wisconsin glaciation, which lasted for about 70,000 years. It was accompanied by emergence and karstification on both the present island and on the surrounding insular shelf.
A minor transgression during an interstadial sea-level highstand of the Wisconsinan glaciation truncated the outer slope in about 35 to 40 m of water depth. As a result, a consistent but narrow -40m terrace was formed both on the leeward and windward slopes of the island. A red soil formed on the Sangamonian limestone exposed on the island. Freshly opened tectonic fracture clefts in the emergent reef, terrace were filled partly or entirely by speleothem calcite.

g) The Holocene postglacial transgression
The Holocene transgression finally re-flooded much of the low-lying periphery of the Sangamon reef complex about 3,000 years ago. The modern reef complex became established on top of the available antecedent topography.

Because of consistent tilting, the subsiding eastern Sangamon reef complex was almost completely inundated by the Holocene transgression. It became the foundation of the modern reef complex. The modern lagoon lies in the same position as the Sangamon lagoon. The windward Sangamon barrier reef crest is completely submerged today to at least 3m and overgrown by the Holocene barrier reef. Only the highest areas of the windward Sangamon reef complex rise above modern sea level. The -20 m terrace surrounds the modern shelf, forming a bank-barrier reef complex with a fore-reef terrace similar to that of Sangamon time. As a result of continuous uplift, the shallow leeward fringing reef of Sangamon age remained emergent along most of the western coastline.

During the final phases of the Holocene transgression (since about 3,000 years ago), the headlands of the old cliffline ("Poxhole Cliff' overgrown by Sangamon corals) were truncated along most of the west coast. As a result, narrow crescentic segments of a Holocene -4m terrace formed in front of these headlands (figs. 21). The subvertical face at the outer margin of the Holocene -4m terrace corresponds to the pre-Sangamon coastline of "Poxhole Cliff". It is densely overgrown today by modern reef framework. Though discontinuous, the Holocene -4m terrace can be followed along the entire west coast (fig. 15). To the NW of German Point, the truncated Sangamon fringing reef detached from the present coast to become the foundation of "Bar," the modern leeward barrier reef of San Andrés (fig. 24). At Top Blowing Rock and Table Rock, the underlying Poxhole Cliff becomes visible again. Also its -8m notch is seen. Though locally interrupted by erosion futher to the NE (Snapper Shoal Channel), Poxhole Cliff seems to connect with the topography of the windward barrier reef.

Due to subsidence of the eastern coastline, Holocene beach accretion covered much of the Sangamon limestone of the coastal lowlands with loose skeletal sand. Johnny Cay and Rose Cay are sandy islets situated on the lagoon terrace. They were formed after Holocene sea level rise by accumulation of coral shingle and sand during storm events.

6.1.7 Main characteristics of the Recent reef complex

The reef complex surrounding San Andrés is about 18km by 10 km, trending NNE (fig. 26). The windward barrier protects the northern and eastern lagoons from oceanic swell. As the crest of the northern barrier (Big Reef) lies at -1 to -2m depth, the breaking waves of the swell pass into the lagoon. As a consequence, the waters are more agitated in the northern than in the eastern lagoon, which has a serni-emergent barrier (East Reef). Along the SE coast, the barrier approaches the shoreline and becomes a fringing reef. Shallow and deep reefs that dot the lagoon are mostly of the knoll reef or platform reef type. Lagoonal fringing reefs exist in front of the north coast ("Little Reef") at Hansa Point, Paradise Point and at Cotton Cay.

The breaking of waves in the deep-lying crest of Big Reef results in swift overflow of waters through surge channels into the lagoon and is thus responsible for the formation of grooves and spurs that are directed from the reef crest toward the lagoon. Grooves and spurs are not developed here on the fore-reef. By contrast, East Reef has a very shallow reef flat, and breaking waves produce a major retune flow by undertow currents to the sea. Here, a well-developed groove-and spur system is found in the fore-reef.

The windward reef wall is dominated by the fue coral *Millepora* spp. and the colonial zoanthid Palythoa sp., with some isolated patches of algal ridge occurring where surf action is strongest. Well-developed algal ridges are very characteristic features along the rim on windward reefs of Indo-Pacific atolls. These are under the steady influence of high oceanic swell. Shallow crests of lagoonal reefs are overgrown either by the moosehorn coral Acropora palmata (where well exposed) or by the finger coral Porites porites (at more protected sites). Deeper reefs in the lagoon are dominated by the star coral Montastraea annularis and associated calm-water species. Water depth of the two lagoon basins is <12 m. The staghorn coral Acropora cervicornis is rather inconspicuous here. Even before the Caribbean-wide bleaching events in 1983/84, most colonies of this species had died. No signs of recovery were observed unti/2001. Living specimens of Acropora cervicornis are still very rare around the island.

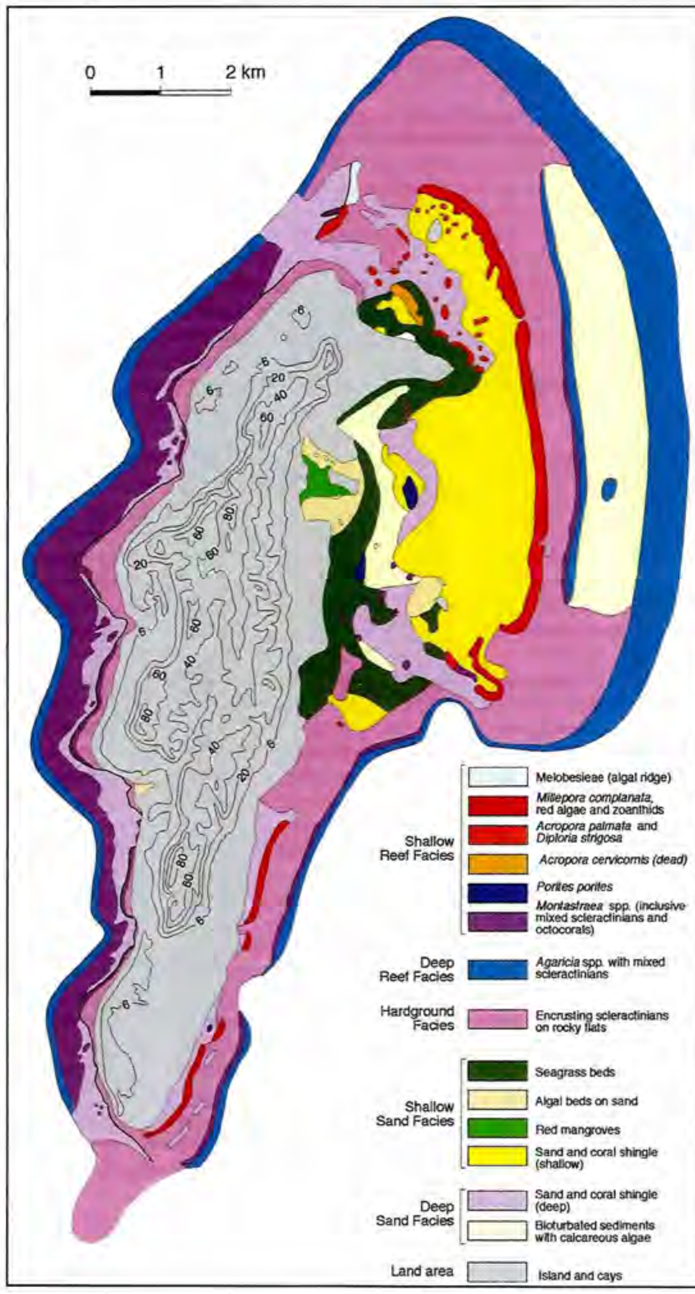


Figure 26. Distribution of bottom facies and benthic communities on the Recent insular shelf and island topography of San Andrés. The facies of the seafloor are classified according to the substrate: reef facies, lagoon facies, and hardground facies. These may be further subdivided according to distribution of benthic communities. Contour lines of island topography in meters. Adapted from Geister (1975).

To the N of the island, there is a short segment of a leeward barrier reef with an Acropora palmata community on the reef crest and with *Montastraea annularis* and associated species covering the fore-slope. No true coral reefs are developed along the west coast of the island. However, the -4m terrace has scattered coral cover that becomes denser near its outer margin. The west coast of the island is subject to interise surf during winter gales that blow from N and NW, causing heavy abrasion to the shallow rocky flats of the - 4 m terrace.

The -20 m terrace (fore-reef terrace) forms the outer rim of the insular shelf It encircles the island completely and has hardly any permanent coral growth in the N, E and S. In the W, it is covered by sediments in areas close to the coastal cliff. At its seaward margin, much of the terrace surface is densely overgrown by a coral carpet of octocorals, large *Montastraea* spp., and a diverse fauna of smaller scleractinians. The distribution of submarine communities on the insular shelf is shown in fig. 26.

The onset of the outer reef slope is marked by a sudden drop-off at the outer margin of the 20 m terrace, which begins between -18 and -25 m. Occasionally, the upper slope may be almost vertical and interrupted by a narrow sediment-covered terrace between -35 and -40 m ("-40 m terrace"). The upper part of the outer slope is densely overgrown by scleractinian corals down to -30 m of water depth. These are mostly massive species that adopt an increasingly plaiy growth habit (*Montastraea* spp., *Colpophyllia natans* etc.) with increasing depth. Sponges and octocorals become more conspicuous than the scleractinian corals by about -25 m. Below -30 m, sponges and octocorals are co-dominant and corals continue to decrease in number. Below -40 m, the green alga Halimeda covers large surfaces and vertical walls. At steep slopes and vertical walls, stony corals become very rare below -50 m. Rocky surfaces are only partly overgrown by sponges and octocorals. The decrease of stony coral cover with water depth is similar on eastern (off Sterthenberg Point) and western slopes of the insular shelf (W of Bar and off Poxhole). It appears to be more rapid on steeper substratum, probably due to reduced illumination. At the vertical wall of Bocatora Hole, notable scleractinian growth is restricted to the upper 30 m. The changes of the benthic communities with water depth are shown in figs. 29 to 30.

Figure 28. San Andrés. Outer reef slope E of Sterthenberg Point at -30m of depth. Note diminished cover of scleractinians and abundant green algae Halimeda sp. March 4, 1999.

Figure 29. San Andrés. Outer reef slope E of Sterthenberg Point at -45 m of water depth. Note sandy slope and predominance of octocorals on rocky substrate. March 4, 1999.

Figure 27. Outer reef slope E of Sterthenberg Point, San Andrés, at -20m of depth. Large platy scleractinians and branching octocorals are common. Note a large brain coral Colpophyllia natans in the center and platy colonies of the star coral Montastraea sp. in the background. March 4, 1999.

Figure 30. San Andrés. Outer reef slope E of Sterthenberg Point at -52m. Steep drop-off to the deep sea. There are hardly any stony corals, just sponges and branching octocorals. March 4, 1999.

6.2 Island geology and reefs of Old Providence and Sta. Catalina

Old Providence Island (or Providencia) extends 7.2 km across in N-S direction and 6.2 km in E-W direction. It covers 2lkm^2 with an additional 1.2 km^2 for nearby Sta. Catalina Island in the N. Both islands are almost entirely volcanic. Rugged peaks rise up to +360 m in the center of Old Providence. Santa Catalina is much lower, with hills less than 130m in height. In the south of Old Providence, there are some intercalations of Miocene reef limestone in the volcanic series and very limited marine Quaternary deposits on land.

The first published information on the petrography of island rocks was by Keeley (193l), who described some volcanic rock samples taken by the Pinchot South Sea Expedition in 1930. Early geological observations in the field are due to Mitchell (1953, 1955), Hubach (1956), Pagnacco & Radelli (1962) and Kerr (1978). Geister (1992) presented a frist synthesis of the geological history of the island. Many new observations were gathered during geological mapping of the island in 2002 in collaboration with Alvaro Nivia (INGEOMINAS, Bogotá), which added greatly to the overall a knowledge of the geological structure of the island. The geological history of Old Providence (with Sta.Catalina), (fig.31) as presently understood, is illustrated and described in fig 32.

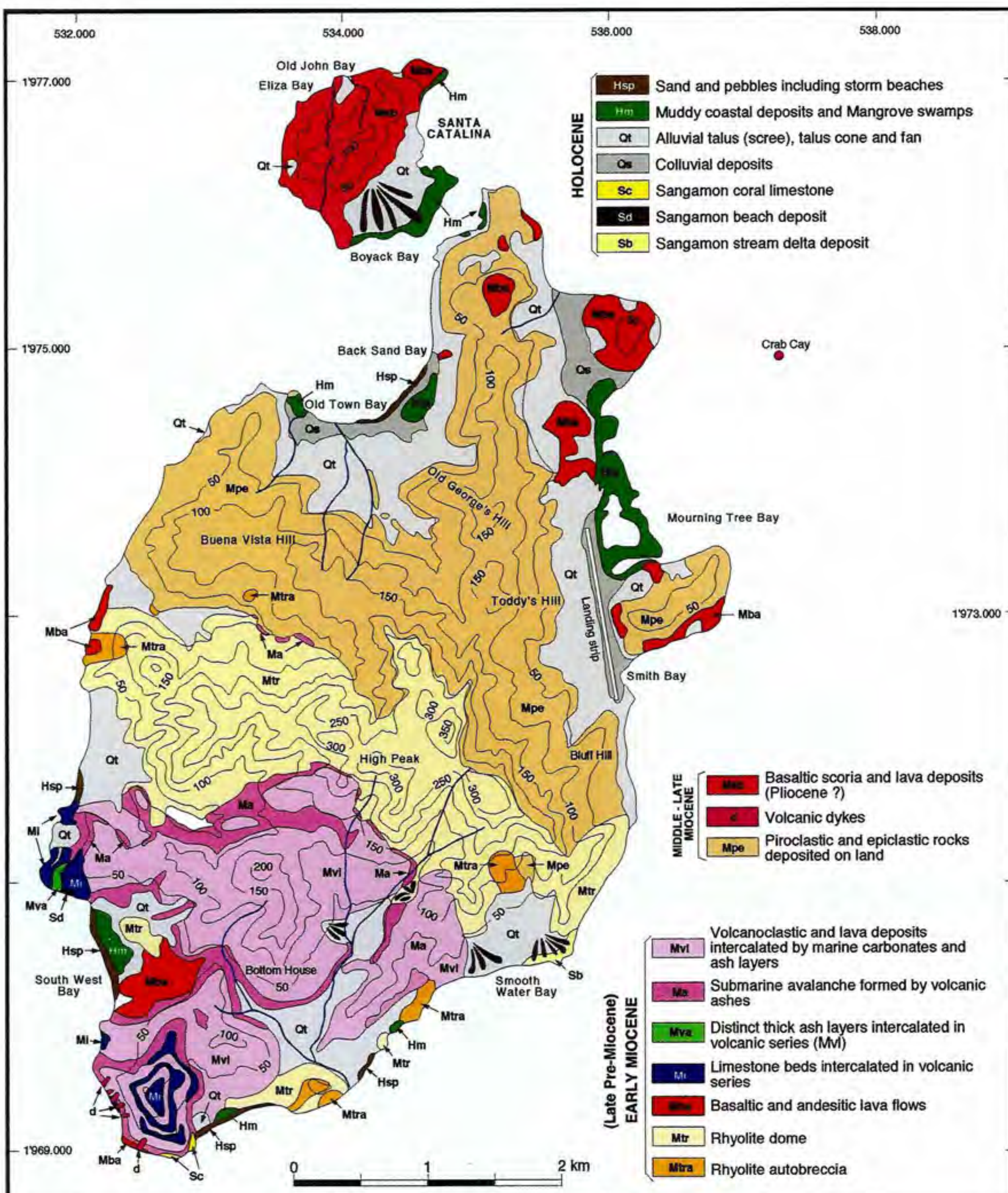


Figure 31. Geological map of Old Providence Island

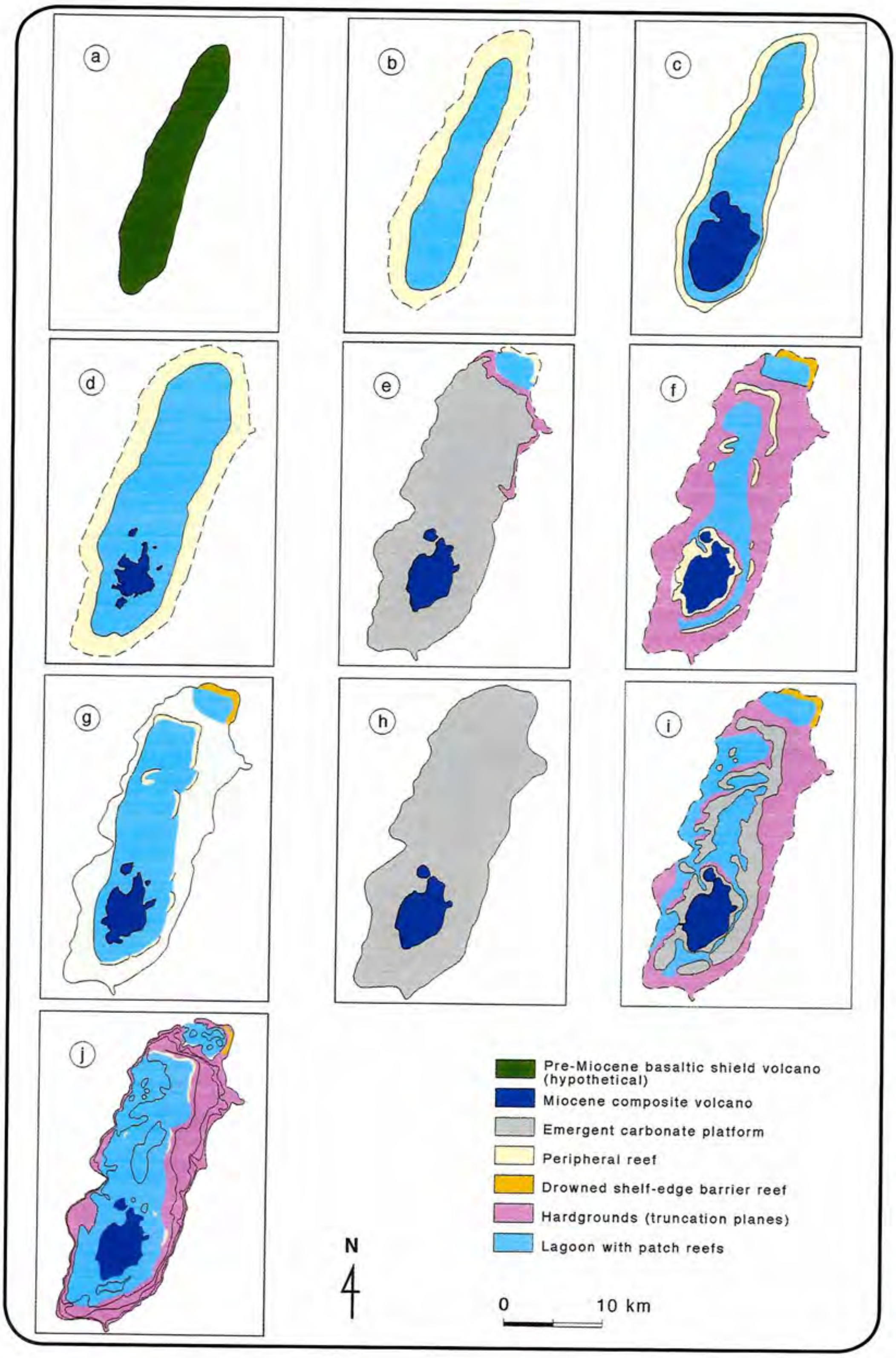


Figure 32. Geological evolution of Old Providence Island reconstructed from field data (relative sea-level stands recorded in insular and submarine rocks and geomorphology) and from the eustatic sea-level curve. Modified and adapted from Geister (1992).

a) Primary volcano stage, probably early in Paleogene time
Fracturing of sea floor was succeeded by the formation of a hypothetical volcanic ridge (presumably of basaltic shield volcano type) which rose above or near to sea level. Subsidence.

b) Atoll stage or coral bank stage, probably in late Paleogene
Continued subsidence of volcano resulted in formation of an elongate carbonate platform on top of the volcanic ridge: primary barrier reef leading to atoll (or coral bank) stage. The exact platform configuration and its facies distribution remain speculative.

c) Secondary volcano stage, Early to Middle Miocene
Extrusion of rhyolitic lavas forming a volcanic dome near the southern end of the early Miocene atoll. Subsequent emission of basaltic to dacitic lavas and pyroclastic material shaped the Miocene composite volcano and thus the volcanic island. Persistence of the carbonate platform.

d) Early or Middle Pleistocene +50-60m sea-level highstand
The highstand is recorded by an erosional terrace above South Point. The configuration of the volcanic island is based mainly on the present island topography. It is not known whether the insular shelf and reef complex also rose to the +60m level at that time. Presence of a shelf-edge barrier reef is highly conjectural.

e) Emergence of most of the late Middle Pleistocene carbonate platform in early Yarmouthian (?) time during a –25m sea-level stand (ca. 220,000 years B.P.)
During this lowstand, the emergent platform margins (with shelf-edge barrier reef) were truncated. Installation of a new shelf-edge barrier reef along the northern margin of the truncation plane. Configuration of emergent platform is based on the modern 25m isobath.

f) End of the Yarmouthian (?) transgression. Relative –10m sea-level highstand (ca. 170,000 years B.P.)
Continued truncation of platform till the end of the Yarmouthian transgressions formed a wide terrace in the periphery of the carbonate platform. This later became the fore-reef terrace of the Sangamonian and Holocene bank-barrier reef complexes. Locally, the Yarmouthian transgression truncated the entire marginal reef area to the ancient lagoon basin. The transgression resulted in renewed flooding of most of the carbonate platform. Remnants of the original carbonate platform rise above the sea level of that time, forming a chain of low-lying elongate limestone islands. Between the islands, the truncation plane forms extended flats between the fore-reef terrace and the ancient lagoon basin, which will later be colonized by patch reefs. The outline of the islands is conjectural and based on the present submarine topography.

g) Sangamon +6m sea-level highstand
125,000 years B.P.
During this transgression, the higher parts of the remaining limestone islands were truncated and the remnants recolonized by reef framework associations. The shelf-edge reef in the N was drowned. There was probably no major reef growth at the outer margin of the fore-reef terrace. A bank-barrier reef formed along the Yarmouthian cliff-line and on top of the submerged limestone islands. Coral pinnacles had probably already become established on the shallow flats between the barrier reef segments. Towards the end of the transgression, the South Point fringing reef was formed (due to its small size, it is not represented on the map).

h) Late Wisconsinan -120m sea-level lowstand
20,000 years B.P.
World-wide lowering of sea level led to emergence of the whole insular shelf. Heavy karstification deepened the old lagoon basins of this time. The whole Sangamon reef complex rose as a huge table mountain to a maximum height of 120m above the ancient sea level. There were neither reefs nor lagoons, only carbonate slope deposits. Outline of the raised carbonate platform is based mainly on the modern bathymetry of the subvertical island slope.

i) Late Holocene –10m sea-level stand
6000 years B.P.
During the rapid sea-level rise in the early part of the Holocene transgression, the antecedent limestone topography was only flooded and not truncated. After sea-level rise slowed down around 6000 years ago, some of the emergent limestone highs were bevelled during a more gradual submersion of the remaining insular shelf. During subsequent slow sea-level rise, topographic highs of the old reef were flooded and recolonized by framework-building reef coral associations. The outlines of islands and reefs are depicted as suggested by the modern submarine topography.

j) Latest Holocene present 0m sea-level stand The last 3,000 years
Sea level became stable at or near present datum. Most of the modification of the insular shelf is by upgrowth of reefs and sediment accumulation. There was also some planation in very shallow water (Holocene –4m terrace) around shoals. At South Point, limestone truncation of sea cliffs continues to present. The pinnacles of the discontinuous reef belt are growing up to sea surface from the –8 to –10m deep shallow ridge between the fore-reef terrace and lagoon basin. They are probably founded on already existent Sangamonian pinnacles.

Old Providence and Sta. Catalina became two separate islands only in historical time. There are no separate volcanic structures on both islands that would suggest a different origin. However, both are parts of the same original composite volcanic cone. Sta. Catalina is an erosional relic of the northernmost and youngest of the heavily eroded deposits of the same Old Providence volcanic complex. During the Wisconsinan lowstand of sea level, the volcanic masses still emerged as a single volcanic body. After the flooding of the island shelf towards the end of the Holocene transgression some 3,000 years ago, both islands still remained loosely interconnected by a low tombolo stricture formed by Holocene sediments.

At the time of discovev and early occupation by Europeans in the 16h and early 17h century, there was only one island named Santa Catalina. In the late 17thcentury, both islands were separated artificially when a channel (today's Aury Channel) was dug between the present islands to serve as an additional defence line for the fortifications built on what is now Santa Catalina. Since then, currents and waves must have considerably widened this artificial channel by erosion (Geister 1992).

Today, the name of Santa Catalina is exclusively used for the smaller northern island, whereas Old Providence is the name for the large island to the south of Aury Channel.

6.2.1 Early island origins

The volcanic rocks of the present islands rest on the southern end of an elongate, almost 33 km long carbonate bank, which should be underlain by an earlier volcanic ridge in agreement with the regional pattern. The elongate shape of this primordial volcano might be the result of progressNe migration of its main conduit for about 30 km along this part of the western Caribbean fracture system. This primordial Providencian volcano, most likely a basaltic shield volcano, would be of pre-Mocene, possibly Paleogene age. None of the deep-seated volcanic rocks of this early island stage are accessible in outcrops today, but they might be represented in the masses of lithic clasts that were ejected during subsequent explosive eruptions in Miocene time.

Extinction of this early volcanism and subsequent subsidence of the volcanic ridge resulted in the formation of an early carbonate platform of the barrier reef type, followed by an atoll stage, by pre- Miocene time. This period of quiescence was abruptly terminated with the recurrence of volcanic activity at the southern end of the Old Providence atoll in pre-Miocene or earliest Miocene time. This new volcanic activity was characterized first by the appearance of a large volcanic dome of rather acidic rocks. This phase of the volcanic dome originally comprised more than the width of the present island. It was followed by more mafic eruptions yielding black lavas, tephra deposits and volcanic dykes, which formed a composite volcanic cone.

6.2.2 Extrusion of rhyolite dome and formation of breccia aprons ("older volcanic series").

The oldest effisNes cropping out on Old Providence Island are thinly banded reddish and gray rhyolites with a microcrystalline to cryptostalline groundmass which locally merges to obsidian. In the core of the dome, the cryptocrystalline groundmass becomes microcrystalline. The overall architecture of this part of the volcanic complex is that of a volcanic dome with an outcrop area extending for 4.5 km across the center of the island, from Kalaloo Point in the E to Lazy Hill in the W.

Concentric fluidal banding or flow-foliation of the lava is well developed, almost ubiquitous, and very conspicuous. This layering is generally flow-folded, with folds ranging from centimetric to metric in dimension. The banding of this lava is vertical in almost the whole outcrop area. At Watson Point, N of Freshwater Bay, it is steeply inclined towards the core of the dome in the center of the island (see Land Stops 11 and 18). At Murray Hill in the extreme S of the island, dip of layering is approximately horizontal. Here fluidal banding is not only folded, but is also frequently contorted and cut by ramp- like shear planes.

Locally (S of Lazy Hill, at Mwray Hill, and to the N of Kalaloo Point), talus aprons of brecciated rhyolite lava are developed. These were probably formed by gravitational collapse of an advancing steep flow front of viscous rhyolite lava. In a small quarry outcrop at Watson Point, this autobreccia overlies a red paleosol. At Watson Point, outcrops of in-situ rhyolite lava show Intensive and irregular vertical jointing which merges towards the N into a wide breccia apron. Along the shoreline at Kitty Wharf, it can be shown that the deposits of the apron are composed of at least three layers of a chaotic breccia. Each layer is several meters thick and corresponds to a distinct collapse event (see Land Stop 19).

The formation of the volcanic dome is as yet undated. However, smaller and larger clasts of banded lavas derived from the dome were frequently found incorporated in overlying volcanoclastic deposits and must therefore be older than these deposits. Elsewhere, the lavas of the dome are visibly overlain by a younger series of thick volcanoclastics and lavas, which form the principal rockmass cropping out on the island today. Pebbles of banded lava are also common as clasts incorporated in the lowermost fossiliferous limestone at South Point, which is definitely of Early to Middle Miocene age. Thus, a pre- Miocene or earliest Miocene age may be suggested for the formation of the rhyolite dome.

Characteristic erosional land/orms of the dome are steepsided conical and pyramidal peaks similar in shape to the famous "pitons" of the Lesser Antilles. They currently comprise some of the highest peaks in the center of Old Providence

Island. These are especially conspicuous in the area E of Freshwater Bay.

6.2.3 Formation of a composite volcanic cone ("younger volcanic series").

Eruptions of the younger volcanic series were centered in the vicinity of the rhyolite dome near the southern end of the Neogene carbonate platform. They produced lavas and pyroclastic and epiclastic material, mainly of basaltic and dacitic composition. The youngest materials are scoria deposits, with the best outcrops on Sta. Catalina Island. All these rocks form a composite volcanic cone that was subsequently subjected to heavy erosion.

Characteristic land/orms of the younger volcanic series include seven high volcanic ridges composed mainly of volcanic breccias and conglomerates, which radiate from the center of the island towards the coast (see Geister 1992: fig. 4). The stratified deposits and lava flows within these ridges show a characteristic seaward dip. The total height of the composite volcanic cone must have reached about 1000m above modern sea-level datum towards the end of the eruptive phase. This can be roughly estimated from the seaward dip of the rocks and from the maximum diameter of the outcrop area observed.

a) Basaltic lava flows

Black, often vesicular basalts with rather smooth, roughly horizontal surfaces form the foothills to the E of the central northward-pointing mountain ridge with Split Hill and Marshall HIll. The best outcrop areas of these rocks are between Ironwood Hill and Jones Point. Some of these lavas seem to partly underlie the thick volcanoclastic series of the central ridge. They probably originated from rather fluid, fast moving lavas of the pahoehoe type. At the eastern shoreline of Jones Point in the N, the lavas developed columnar jointing by cooling. At Lena Point in the S, black lava of olivine basaltic composition forms pillows overlain by thick pyroclastic deposits (see Land Stop J3).

Within the enormous volcanoclastic series of the major mountain ridges, additional basaltic flows several meters thick are intercalated (see Land Stops 11 and 13). These flows are notable for their brecciated top and basal surfaces. The brecciated top grades downward into massive lava, and from there it grades into a brecciated basal layer. Fragmented surfaces with clinker top and a breccia base indicate that the flow advanced over an autobrecciated base of fragmented lava. Flow fragmentation in basalts, as described above, is indicative of the aa lava type. It is frequently found intercalated in pyroclastic deposits. A good example of this can be observed in the coastal cliff outcrop at South Point, where such a flow advanced over a thick bed of volcanic ashes (see Geister 1992: plate 1718). Here, the massive lava layer developed columnar jointing as a result of gradual cooling. Spectacularly developed columns of heavily altered lava form the isolated islets of Palm Cay and Basalt Cay to the N of Sta. Catalina (see Geister 1992: plate 1714).

Radiometric dating of an olivine basalt from Lena Point (near South Point) yielded an age of 14.5 +-1.1 million years (Gobel 1985). This Middle Miocene age is confirmed by fossil-bearing intercalations of carbonates in the overlying beds of Manchioneal Hill. All the volcanic rock masses covering the dome at Old Providence are probably younger than this date. An alkali- olivine basalt from Jones Point in the N gave 7.4 +- 0.4 million years (Wadge & Wooden 1982). These rocks must be older than the overlying epiclastic deposits of Jones Point and probably even older than the volcanic rocks of Sta. Catalina, which dip in continuation of those from Jones Point.

b) Explosive volcanism and pyroclastic deposits

Evidence for explosive volcanism comes from thick pyroclastic deposits such as volcanic ashes and volcanic breccias with blocky to boulder-sized clasts. The ashes are commonly found in the southern half of the island. There is an "early explosive event" with ash deposits found mostly at the foot of the hills around Bottom House and Freshwater Bay, and a "late explosive event" best documented in ash outcrops of Lena Hill and around Manchioneal Hill. Most tephra show mantle bedding formed by draping the preceding topography (see Land Stops 15 and 16).

A dark coarse volcanic conglomerate layer and lava flow, at least 10 to 20m thick with some admixture of ash, becomes locally conspicuous between the ash beds. The latter is best recognizable in the escarpment of Tami Hill just above Southwest Bay. At the foot of this escarpment, the lower ash layer crops out, but the deposit is largely covered by Holocene slop debris. The rather smooth upper surface of the conglomerate bed is overlain by the second ash layer where not uncovered by erosion. The surface plane is visibly dipping towards S (see Geister 1992: plate 12/1). Higher in the section and farther inland, extensive deposits of very coarse volcanic breccias and conglomerates with lava flows are found. They are rarely interbedded with minor ash layers. They form about seven major topographic ridges that radiate seaward, with strata dipping away from the center of the island.

- The "early explosive event" in the S

The early ash deposits form a conspicuous marker bed in the triangle formed by Southwest Bay, Bottom House and Manchioneal Hill. They generally show mantle bedding, and the layers are draped over the low pre-existing topography in this area with thcknesses of 10m and more. Locally, however, the ashes exhibit unidirectional sedimentary bedforms, such as low-angle stratification and dune-forms. Dune-forms are best visible in outcrops along the mountain slope S of the water reservoir near Freshwater Bay. Both presumed stoss and lee-sides lie at angles less than that of repose, which are less than 15'. They are interpreted as antidune forms. Dune-bedding typifies deposits of base-surges. Thus, these ashes may be true pyroclastic base-surge deposits (see Land Stop 21).

The same thick ash deposits also crop out in the low hills to the N of Smoothwater Bay (see Geister 1992: plate 17/1). A questionable volcanic pipe filled with ashes is partly exposed in a quarry at Smoothwater Bay. This is possibly one of the vents that yielded -the thick volcanic ashes deposited in the area. Outcrop size is not sufficiently large to decide whether the vertical contact between basalt and ashes corresponds to the wall of the vent or is just a simple fault (Land Stop I 3). In the latter case, the ashes would have been washed into the depression formed behind the fault. A 10m-wide extension gap at the nearby coastline is equally filled with ashes. At the present state of knowledge, it is not certain that all the ashes in the Smoothwater Bay/Bottom House area are genuine pyroclastic deposits, nor do we know the extent to which epiclastic processes were involved in their formation. Deposits of this same ashfall event formed submarine tephra avalanches on the Miocene island slope which crop out today at Alligator Point (see Land Stops 20 and 21).

- The "late explosive event" in the S

Near South Point and at Lena Point, the coastline is formed by the late ash layer. At South Point, the ashes rise 2 to 3m above the present sea level. They are medium- to coarse-grained sands with local concentrations of lapilli (mainly banded rhyolite). They were deposited in the sea with an admixture of carbonate sand and bear a diverse Miocene fauna. Near Lena Point, to the NW of South Point, the ashes are more than 10m thick in the cliff section and do not show evidence of marine life. Large (up to lm) ballistic blocks left bomb sags in the volcanic ashes. The blocks consist mainly of banded rhyolite similar in appearance to that cropping out at nearby Manchioneal Hill. This tephra bed seems to continue under slope debris and vegetation to the ash outcrops on Manchioneal Hill and on Lena Hill, where it forms the basement of extensive coral- bearing carbonates. The tephra directly overlies the plain surface of the Tami Hill conglomerates.

- The latest explosive volcanism

In the mountain ridge extending from the center of the island northward towards Marshall Hill, coarse volcanic breccias dominate. They consist of polyhedral blocks with plane or slightly curved surfaces and conspicuous dihedral angles. Some of them are more than lm across. A fine matrix is absent (see Land Stop Ll). We believe that the blocks have a pyroclastic origin and were probably ejected by phreatomagmatic explosions. The masses of blocks are deposited in northward dipping strata, in which lava flows are also intercalated. The breccias are best accessible in the Split Hill area. At the present stage of knowledge, it cannot be decided whether all the blocks forming the strata were blown out through the air or whether some of the strata were subject to epiclastic processes. Similar breccias and conglomerates intercalated by dark lavas mantle the erosive surface of the dome further to the S. They were shed to the NW, S and E from the center of the island. From lithostratigraphic relationships, it appears that these coarse breccias are younger than the ashfall events mentioned above.

c) Scoria fall deposits at Sta. Catalina Island

Towards the end of volcanic activity, scoria fall deposits accumulated in the N. These ejecta, which consist largely of vesicular basalt, form the principal rocks of Sta. Catalina today. The most easily accessible scoria deposits are found at the basement of Morgan Fort and along much of the shoreline of Sta. Catalina Island. The giant boulder known as "Morgan Head" is an erosive block of lithified scoria deposits (see Geister 1992: plate 17/3) which forms a conspicuous landmark beside vessels' access route to Sta. Catalina Harbor. All the scoria deposits of Sta. Catalina are coarsely bedded. The dip of beds is similar to that of the northward-dipping lavas and volcanoclastic deposits of Jones Point.

d) Epiclastic rocks

A considerable amount of volcanoclastic debris found on Old Providence Island appears to be of epiclastic origin (weathered and transported by gravitation and water). Without detailed supplementary studies, it is impossible to relate most volcanoclastic deposits either to vent- related processes or to epiclastic transport and fiagmentation. Epiclastic processes with mass transport were active during and after the eruptions in Neogene time. By contrast, mass transport of volcanic material was negligible in Quaternary time.

e) Dykes and extension fractures

Magmatic dykes are mostly mafic in composition and resulted from extension fracturing. They are commonly observed crosscutting the volcanic dome and younger deposits. The strike of the dykes is mainly NNE and NW, following the regional pattern. Width of the dykes ranges between a few decimeters and more than 10m. Some extension clefts are filled with ashes or volcanic breccias. Mitchell (1953:292) mentions that "several thin dykes of quartz-biotite-diorite penetrate the volcanics, especially along the southern shore" without giving further details.

The large gaping cleft in Split Hill in the N of the island is a weathered-out tectonic fracture trending in a NW-SE direction. Additional, less spectacular clefts trending equally NW-SE are seen immediately to the S of Split Hill. These fractures formed after lithification of the rather young (possibly latest Miocene) volcanic breccia and are probably of Quaternary age.

6.2.4 Notes on the petrography and geochemistry of the volcanic rocks by Claudio Scarcia (Bern).

During mapping of the southern half of Old Providence Island in 2000, eleven well-preserved samples were taken from in-situ magmatic rocks. These samples were later analysed geochemically by the XRF method. These data, together with the petrographic descriptions, will be the basis for the chemical classification here employed (Le Maitre 1984). On the TAS diagram, the eleven samples analyzed belong to 3 clusters: 4 trachybasalts, 3 dacites and 3 rhyolites. One sample from a block tuff mass is intermediate between dacite and andesite. All the rhyolite samples came from the volcanic dome. Basaltic and dacitic rocks occur as both dykes and lava flows. In a diploma thesis in preparation at the Institut für Geologie of the University of Bern (Scarcia, in prep.), the data from the analyses will be discussed in more detail and compared with the data obtained by previous authors (Concha- Perdomo 1989; Concha & Macia 1993 and 1995; Kerr 1978).

Coordinates used for the sampling localities were taken from the coordinate scale of topographic map 1:20,000 (Departamento Archipiélago de San Andrés, Providencia y Santa Catalina, 1st edition, 1994, prepared by "Instituto Geográfico Agustin Codazzi" at Bogotá).

Short characterization of some magmatic rocks based on thin sections and geochemistry

Basalts

Sample Nr. CS8
Locality: Black Bay Point, black lava flow.
Coordinates: 532.10/1969.71

Trachybasalt: Matrix is microcrystalline with plagioclase needles oriented in flow direction.
Phenocrysts of olivine and clinopyroxene.

Sample Nr. CS 11A
Locality: Dark, meter-thick vertical dyke at coastline between Lena Point and Black Bay Point.
Lies 3 to 4m N from dyke locality of sample CS11B.
Coordinates: 532.25/1969.40

Trachybasalt: Mass of fine needles of plagioclase with large phenocrysts of plagioclase and
clinopyroxene.

Sample Nr. CS 13
Locality: Black lava flow 100m to the N of Lena Point
Coordinates: 532.31/1969.20

Trachybasalt: Matrix is coarse-grained and predominantly plagioclase with microcrystalline relicts of olivine. Phenocrysts of clinopyroxene form a corona structure around large quartz crystals ("Occelli structures"). Locally, the quartz core has been completely dissolved to form clinopyroxene.

Sample Nr. CSVIII
Locality: 2m thick black dyke from vertical coastal cliff, 220m ESE Lena Point
Coordinates: 532.03/1969.00
Trachybasalt: Trachytic matrix showing thin plagioclase needles. Only hornblende phenocrysts are present. They don't show resorption rims. Microcrystalline pore fillings are common. They indicate foarning due to pressure release.

Dacites-Andesites
Sample Nr. CS33
Locality: Block from block tuff mass. Top of Morris Hill
Coordinates: 533.10/1969.81

Dacite-andesite: Matrix consisting of fine and coarse plagioclase crystals. Pyroxene only found
as coarse grains. High percentage of microcrystalline pore filling.

Dacites
Sample Nr. CS80
Locality: Black horizontal lava flow forming 2m high waterfall in stream valley 100m N of Cashew Hill. 900m to the W from northern end of Southwest Bay beach.
Coordinates: 533.00/1970.85

Dacite: Rock matrix consisting of fine and coarse plagioclase. 5 to 6% of the rock is opaque material.

Sample Nr. CS82
Locality: Vertical dyke oriented NW/SE. 600m E from Southwest Bay beach (northern part) and 250m W of Cashew Hill top.
Coordinates: 532.74/1970.73

Dacite: Matrix is coarse-grained plagioclase. Phenocrysts are biotites that have been slightly altered to clay. Chalcedony blotches are present. A single hornblende crystal was seen. Open voids comprise 3 to 5% of the rock volume, while opaque minerals comprise about 10% of the volume.

Sample Nr. CS 11B
Locality: Clear gray, 2.5m-thick dyke at coastline between Lena Point and Black Bay Point, 3-4m
S of dyke sample Nr. CS11A
Coordinates: 532.25/1969.40

Dacite: Microcrystalline trachytic matrix with oriented lath-like plagioclase crystals. Only a few plagioclase phenocrysts and rare (?) biotite were seen. Hornblende phenocrysts are idiomorphic.

They show resorption rims, which indicate a slowly flowing magma, thus excluding explosions.

Rhyolites
Sample Nr. CS74
Locality: Coastline between Watson Point and Kitty Wharf. Outcrop in volcanic dome.
Coordinates: 532.06/1972.58

Rhyolite: Trachytic matrix showing flow texture with thin plagioclase needles. Phenocrysts are plagioclase, hornblende (one single crystal) and biotite.

Sample Nr. CS67
Locality: N of Kalaloo Point, small roadside quarry. Outcrop in volcanic dome. See also Field e StopI1.
Coordinates: 535.76/1970.79

Rhyolite: Cryptocrystalline matrix with numerous phenocrysts of plagioclase. Crystals are oriented in flow direction. Voids are filled with yellow to green clay minerals which were formed by alteration.

Sample Nr. CS72
Locality: Coastline at Watson Point. Outcrop in volcanic dome.
Coordinates: 532.02/1969.50

Rhyolite: Very hornogeneous matrix, slightly altered to clay. Microcrystals seemingly oriented. Some chalcedony present as orange to brown blotches. Varying degrees of alteration to clay produce macroscopic banding. Phenocrysts are plagioclase and biotite. Parallel orientation of microcrystals suggests extrusion as a volcanic dome rather than by explosion (ignimbrite).

6.2.5 Miocene carbonate environments

In the Manchioneal Hill area, pyroclastic deposits interfinger with Early to Middle Miocene lagoon and reef deposits. There are at least four intercalations of Miocene reef and lagoon rocks within the principal series of lavas and pyroclastic material. Lagoonal carbonates mixed with ashes and rounded volcanic pebbles are well exposed at the seashore of South Point. They contain fossil bivalves, gastropods, and abundant irregular echinoids, as well as solitary scleractinians such as *Trachyphyllia* sp., which are adapted to life on soft substratum. This nearshore lagoon community was suffocated by an ashfall, which at nearby Lena Point overlies older pillow basalts dated 14.5 Ma.

Lena Hill, at the northern foothill of Manchioneal Hill, is formed by an extensive coral carpet of branching scleractinians. These settled on an ash layer several meters thick, which corresponds to the "late ash fall". Locally, small bioherms of massive scleractinians are formed on top of the ashes. The youngest of the limestone intercalations on the very top of Manchioneal Hill is a true framework of massive scleractinians (mainly *Montastraea* sp.).

At Alligator Point, flattened, 0.5m+ Montastraea sp. formed a dense pavement-like framework covering the Miocene island slope. Laterally, avalanche deposits of abundant fragments of branching corals interfinger with the reef framework. A major submarine avalanche of volcanic ashes intermingled with coral fragments was deposited on top of these carbonates at Alligator Point. The ashes of this avalanche seem to correspond to the "early explosive event" which is partly mantling the topography in the area of nearby High Hill (Land Stops I 5 and I 6).

A diverse fauna of shallow-water reef corals of Early to Middle Miocene age is distributed over a vertical distance of 160 m from the modern coastline to the top of Manchioneal Hill. Most common are branching species of Stylophora, *Pocillopora* and poritids in the coral carpets. Massive colonies are mostly species of *Montastraea*, which predominate in bioherms (see Land Stop J2). As reef corals only thrNe in water depths less than 50 m, a relatNe sea level rise of at least 100 m during the deposition of the coral rock will have to be taken into account. This may be attributed partly to the subsidence of the island and partly to the Burdigalian transgression.

6.2.6 Pleistocene carbonate environments, delta deposits and sea-level stands

Pleistocene reef growth can only be studied in very limited Sangamon fringing reef deposits cropping out in a terrace up to 6 m above sea level, all along the coast at South Point. Extensive Sangamon carbonate deposits probably extend under the Recent reef complex. The Sangamon fringing reef of South Point is a good example of the *Porites porites* reef type. The reef flat is composed of dense stands of the finger coral *Porites porites*, with discontinuous patches of a mixed association of mostly massive species in front and in the rear of the reef.

The reef has grown all the way to the shoreline, where coral rock interfingers with Sangamon scree. Coral skeletons of the reef have been radiometrically dated at 118,800+11.0-10.1 ka B.P. This corresponds to stage 5 of the standard marine isotope stratigraphy. Hence , the reef must date from the Sangamon interglacial. A list of corals, mollusks and echinoderms found in this reef.

Pleistocene beach sediments are present as an erosional relic in the modern sea cliff at the southern shoreline of Alligator Point. Here, laminated sediments with *Ophiomorpha* burrows and escape traces probably represent the back-beach area. Layers of rounded cobbles in the sandy groundmass indicate occasional storm layers (see Land Stop I 4).

At Kalaloo Point, stream deposits formed a delta of coarse pebbles and boulders along the sea shore during the Sangamon sea-level highstand. These sediments are partly reworked to a pebble beach of siliciclastic material which was cemented by marine carbonates. Today, these delta deposits emerge for about a meter and more above present sea level but are undercut along the modern coastline. Since the post-Sangamon emergence of the delta, coarse fluviatile deposits of the nearby stream and slope debris have begun to accumulate on top of the older delta deposits (see Land Stop I 2).

Terraces of undoubtedly marine origin at Providencia are only found between -35 and -40 m (northeastern and southern shelf rim, Blue Hole; of Wisconsinan age), between -10 and -30 m (- 20 m terrace or fore-reef terrace forming the outer rim of the insular shelc presumably of Yarmouthian age), between -1 and -4m (coastal cliff at South Point and around certain patch reefs; Holocene age), at +2-4 m (Sangamon interglacial at South Point), and at about +60 m (above Sout Point; presumably Early or Middle Pleistocene sea-level highstand).

The wide fore-reef terrace surrounding the islands is well developed in front of the Recent barrier, with its outer margin lying at water depths of around -25 to -30 m (fig. 32). As at San Andrés, its morphology seems to record a major transgression during a prolonged Pleistocene (presumably Yarmouthian) sea-level stand below present datum. Channel Mouth is a drowned stream valley to the NW of Sta. Catalina in prolongation of Bowden Gully, which enters Sta. Catalina Harbor. It is cut 5 to 8m deep into the surrounding fore-reef terrace in about 15 to 20 m of water depth, reaching an estimated width of 10 to 30 m. It empties into the open sea at Blue Hole, a vertical shelf-edge escarpment further to the W. If the fore-reef terrace proves to be Yarmouthian, then Channel Mouth must be of post-Yarmouthian age and formed mainly during the Wisconsinan sea-level lowstand. A similar but less obvious channel exists in prolongation of Bottom House Gully. It transects the windward barrier reef at Tinkham's Cut but is not conspicuous on the fore-reef terrace.

Vertical escarpments form wide embayments along the outer margin of the fore-reef terrace all around the island. They are interpreted as collapse structures of the outer shelf margin. Best studied is Blue Hole in the NW, with a drop-off at -18 m and a steep slope covered by sediment between -35 and -40 m of water depth. We believe that the steep sediment deposits hide a -40 m terrace, most likely of Wisconsinan age. The age of this particular collapse event must be situated between the truncation of the fore-reef terrace (Yarmouthian?) and the formation of the - 40 m terrace (Wisconsinan).

At the outer edge of the island shelf at Broken Ground, some 500 m SW of Channel Mouth (see map fig. 33), a spectacular submarine extension gash more than lm wide can be followed from 50 up to -20 m of water depth. It transects the Pleistocene carbonates at the outer edge of the fore- reef terrace and is probably part of the fracture system that triggered the collapse of the platform margin at Blue Hole. The trend of the cleft is similar to the Split Hill fault. A Quaternary age - most likely post-Yarmouthian is indicated because the fracture is younger than the fore-reef terrace. However, the presence of a 40 m terrace at the Blue Hole scarp suggests that the gash must be older than this Wisconsinan terrace.

Similar to San Andrés, there is also a drowned Pleistocene barrier reef with an adjacent lagoon basin in extreme N and NE of the insular shelf ("Back of the Elbod' and "Northeast Bank"). The crest of this shelf-edge barrier lies some 25m below present sea level, with an adjacent lagoon floor at the 30 to 35m level (fig. 33 and 34). It represents a sea-level stand during the formation of the fore-reef terrace, possibly in Yarmouthian time. The morphology of this reef might have been modified during Wisconsinan sea-level lowstands.

In contrast to San Andrés, there is no evidence for uplift of Old Providence and Sta. Catalina in Quaternary times. This is indicated by the lack of more extensive emergent Pleistocene reef rock along the coasts and around offshore islets. The submerged outer margin of the fore-reef terrace at -25 to -30 m at Old Providence, and around 18m in front of the San Andrés west coast, equally point to a more stable tectonic position of the volcanic island, if not to slow subsidence.

6.2.7 Holocene terrestrial deposits

The small islets or cays rising from the Old Providence insular shelf are all of volcanic origin, with the notable exception of Low Cay near the extreme NW bend of the barrier. This cay is a modern storm beach or spit of coarse coral blocks consisting entirely of thick branches of the moosehorn coral Acropora palmata.

At Old Providence and Sta. Catalina, Holocene terrestrial deposits are mainly restricted to beaches and swamps, though slope debris is common at the foot of the hills. Most of these deposits are of pure siliciclastic origin, but at Manchioneal Hill (which has outcrops of Miocene limestone), mixed siliciclastic/carbonate slope debris is common. Some of the slope debris is undoubtedly pre Holocene in age, as observed at South Point, where scree interfingers with marine carbonates of the Sangamonian interglacial.

6.2.8 The Recent reef complex (fig. 33-36)

Today, an extensive Holocene barrier reef complex is established on top of a wide submarine platform which surrounds Old Providence and Sta. Catalina. It roughly outlines the underlying Miocene atoll. The whole carbonate platform is 33 by 8km and trends NNE. The 32km-long windward barrier reef is the second largest in the western hemisphere after that of Belize. A few patch-reef segments on the western shelf appear to be remnants of a former leeward barrier reef. A

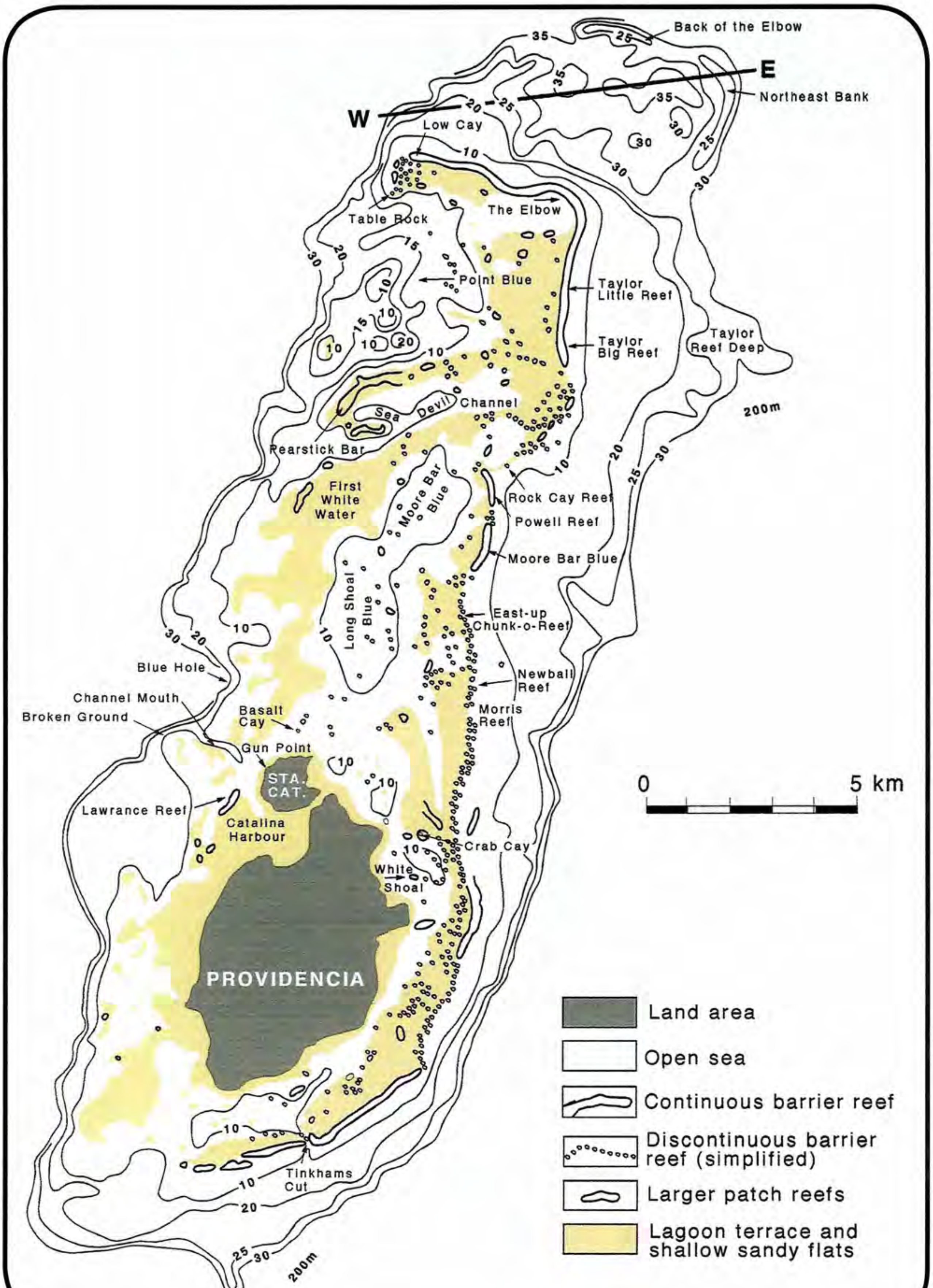


Figure 33. Map showing submarine geomorphology of the Old Providence insular shelf. Local toponyms are indicated. "Back of the Elbow" and "Northeast Bank" are parts of a drowned shelf-edge barrier reef system. Depth contours in meters. Fathometer profile across northern end of bank is depicted in fig. 34. Adapted from Geister (1992).

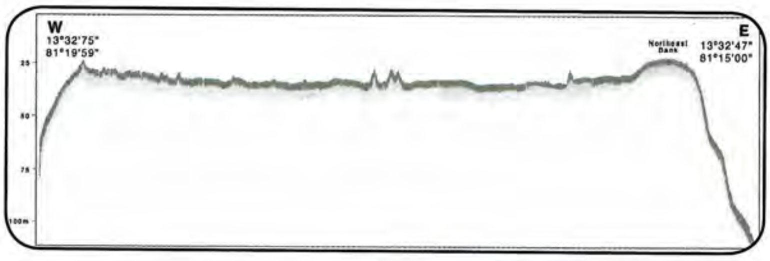


Figure 34 Fathometer profile run across northern rim of the Old Providence insular shelf by research vessel Ancón (INVEMAR). For location of profile, see fig. 33. Water depths in meters.

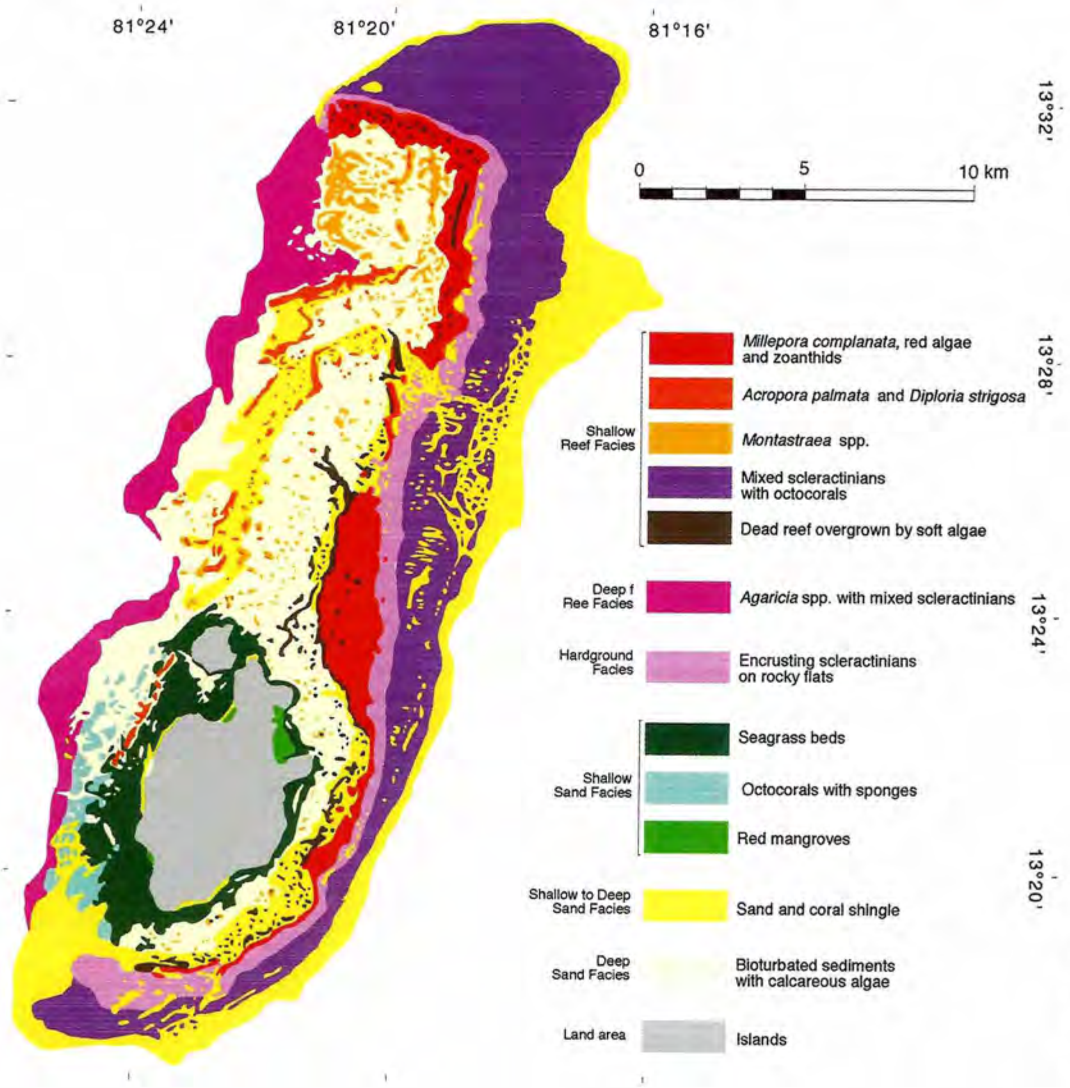


Figure 35 Distribution of bottom facies and benthic communities around Old Providence and Sta. Catalina Islands. Adapted from Díaz et al. (2000).

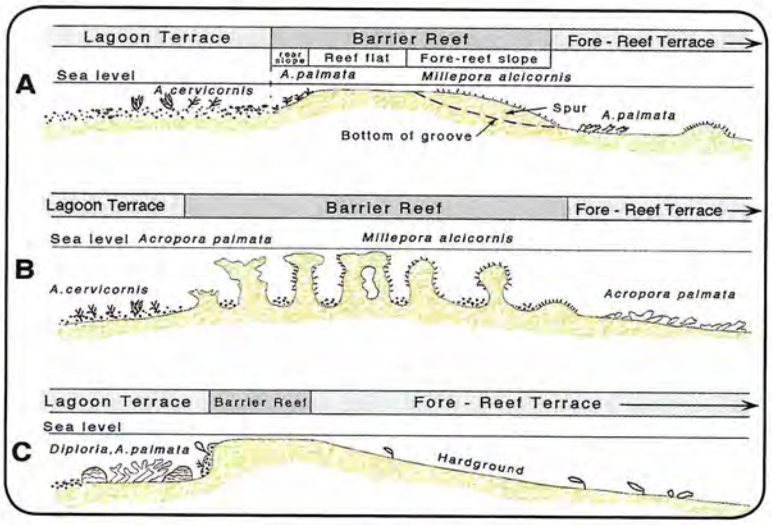


Figure 36. Development of the windward barrier reef of Old Providence Island.

a) Continuous windward barrier reef. Width of barrier is ca. 100m.

b) Discontinuous windward barrier reef. Simplified. The whole pinnacle belt may attain 100 to 1000+m of width, with up to 100 pinnacles per section.

c) Continuous barrier reef. Fore-reef terrace reaches to near low-tide level. There is no framework growth in the fore-reef and on the reef flat. Reef growth is limited to the rear of the reef. This morphologic reef type is characteristic of the NE and SE bends of the barrier.

All three sections are highly schematic and simplified. Strong vertical exaggeration.

From Geister (1992), modified.

detailed description of the reef complex is given in Geister (1992).

The windward lagoon terraces are well developed, with shallow sand cliffs towards the 20 m deep lagoon basins. There are four major lagoon basins protected by the windward barrier. However, the northernmost lagoon basin (Point Blue) is completely open to the W with a steep drop-off to the open sea, probably resulting from the collapse of the western shelf margin in the Pleistocene. The other basins are somewhat protected to the W by a relatively shallow sand-covered submarine sill or by Old Providence Island itself.

The windward barrier reef crest (fig. 36) is overgrown by an association of frame-builders characteristic of high-energy environments. This association is dominated by *Millepora* spp. A local algal ridge is developed near the NW bend of the barrier. Three major segments of the barrier are wide discontinuous belts formed by a broad belt of densely clustered patch reefs (figs. 33 and 36). In deeper water, these patch reefs are true pillar-shaped pinnacles with vertical walls. Their tops often reach low-tide level. In the Crab Cay area, the pinnacles are up to 8m high. Most of them are built by the fire coral Millepora spp., but pinnacles of A. palmata and Mannularis are also common. Most frame-builders on the pinnacles are dead today and overgrown by soft and crustose algae. The tops were still thriving when visited between 1970 and 1979.

Extensive thickets of *Acropora cervicornis* were formerly common on the windward lagoon terraces and in patch reefs, especially on the crests of protected lagoonal ribbon reefs. However, most thickets were broken by Hurricane Joan in 1988 and possibly affected by coral bleaching events. Thickets of *Acropora palmata* characterize crests of shallow leeward patch reefs. There are deeper water patch reefs in the lagoon basins. At Point Blue and in front of Manchioneal Bay, several patch reefs rise to the surface from depths of around 20 m. These calm-water reefs are dominated by *Montastraea* spp. and octocorals.

The Back of the Elbow and Northeast Bank form a drowned shelf-edge barrier reef around the northern margin of the Old Providence carbonate bank. A reconnaissance dive to the crest of Northeast Bank on October 19, 1994 revealed a wide rocky ridge with a crest at about 25 m of water depth. Towards NE, the Bottom descends to a marginal sandy moat at approximately 28 to 30 m before it plunges down the outer slope to greater water depths. The carbonate rock bottom was patchily overgrown by sponges and flattened heads of otherwise massive scleractinians (*Siderastrea siderea*, *Montastraea* spp., *Diploria strigosa*), with some additional branching colonies (*Madracis decactis*).

Sea whips and other branching octocorals were common. Only about 1% of the rocky surface was covered by healthy scleractinians. The rocky bottom was overgrown by dense mats of brown algae (including *Padina* sp. and *Dictyota* sp.). We observed no signs of recent death of scleractinians. The general impression was that no active reef accretion was taking place at present on Northeast Bank.

6.3 Geology and reefs of the atolls and coral banks

6.3.1 Courtown Cays atoll

From shelf rim to shelf rim, the kidney-shaped Courtown Cays atoll (12°24' N 81°28' W) lies about 22 km to the ESE of San Andrés (hence its other name "Eastsoutheast Cays"). It is surrounded by water more than 1000 m deep. The southern half of the atoll structure trends SE- NW, while the northern half shows a clear NNE-SSW trend. Both are tectonic directions characteristic for this part of the Caribbean. Thus, this atoll might be a triple point of two differently trending fault zones underlying the presumed volcanic cone, which appears to form the basement of the atoll.(figs. 37 and 38)

A gently dipping fore-reef terrace characterizes the windward margin of the atoll. It is up to l km or more wide and is formed by a calcareous hardground bored and sparsely overgrown by encrusting organisms and octocorals. From 4 to 8m of water depth, it descends gently towards the platform margin at -24m to -30m. Below 18m and more, hemispherical scleractinians (*Montastraea* spp. And *Colpohyllia natans*) come into sight, as well as coarse sediments that accumulated in shallow depressions of the outer platform. From here, the outer slope descends with an angle of about 40 to 50" to a narrow sandy terrace at about 30 m, which probably corresponds to the 40 m terrace. This terrace seems to be best developed at the northwestern and southeastern margin of the atoll shelf. Below this step, the sea floor plunges subvertically to 400 m of water depth and continues from there at a decreasing angle to depths beyond 1000 m.

Windward reefs are developed on the NE, E and SE sides of the atoll (see Sea Stop M4). The peripheral reefs are well dissected by surge channels and indented in two places. Here the reef crest is interrupted, and the groove-and-spur system is best developed. A prolific assemblage of *Millepora*, Palythoa and encrusting red algae overgrows the spurs. Massive *Diploria*, *Montastraea annularis*, and *Porites astreoides* line the sides of the channels. The finger coral *Porites porites* and the green alga *Halimeda opuntia* are often present. The lagoon terrace lies 1 to 3 m below the surface. Behind the crest of the windward peripheral reef, it extends into the lagoon for 200 to 500 m. From the outer edge of this terrace, a steep sand cliff plunges down into the lagoon basin. Rubble, gravel, and coarse sand cover the terrace surface. The lagoon basin is as much as 12 m deep and is largely covered by white calcareous sediments. An intricate system of deeply submerged anastomosing patch reefs is built predominantly by the Montastraea annularis species complex. It covers about 30% of the NW part of the lagoon floor. Most of these reefs rise about 4m above the bottom, but some are nearly emergent. Patch reefs

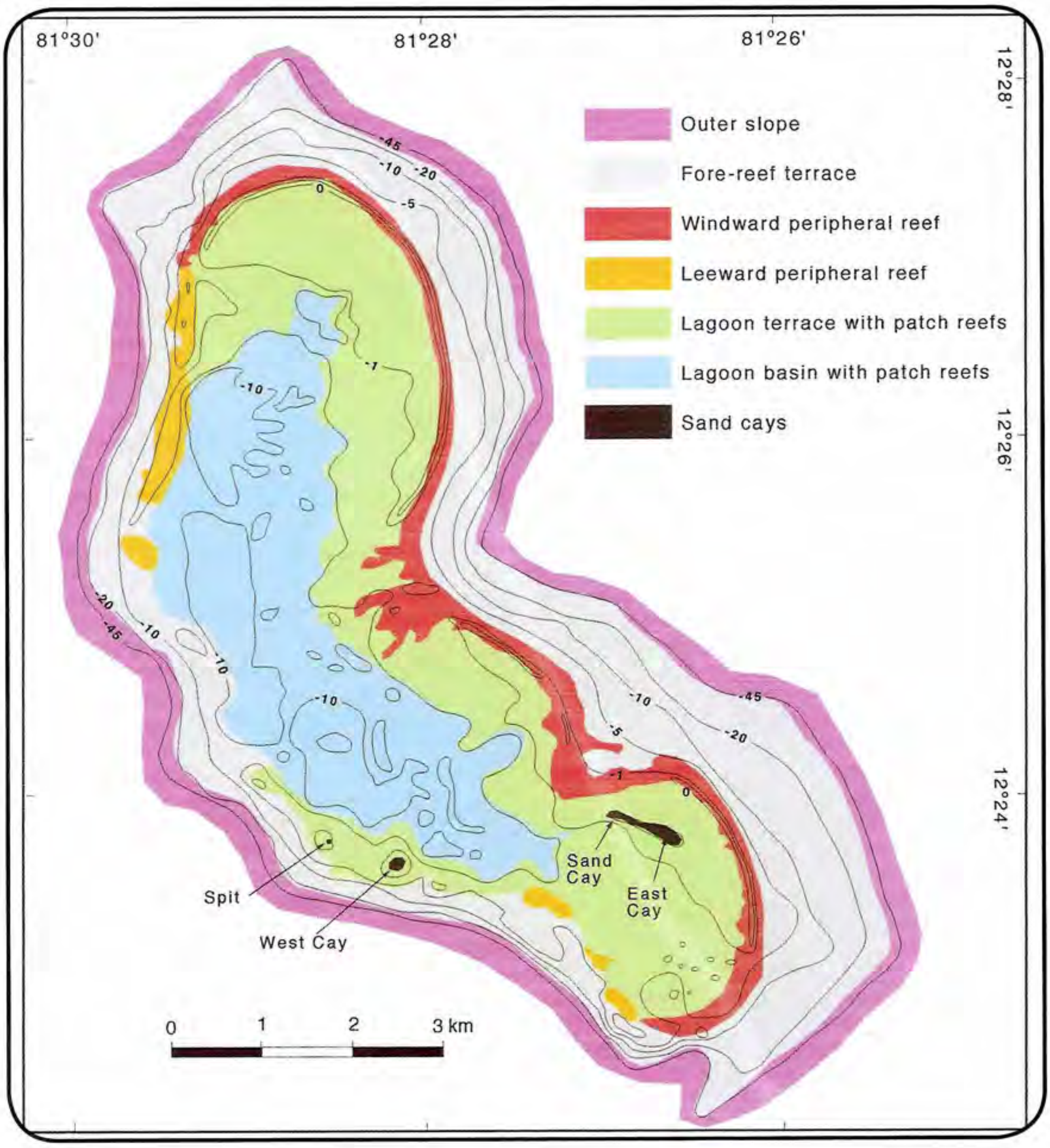


Figure 37. Geomorphology of Courtown Cays atoll. Adapted from Díaz et al. (2000).

in the southern half of the lagoon basin are smaller and more isolated. Some of them also rise within a few meters of the surface. Their reef crests have thickets of *Acropora cervicornis* among the massive colonies of *Montastraea* spp.

The peripheral reef does not encircle the atoll entirely. The lagoon is rather open to the W and SW and lacks a continuous leeward reef tract or a corresponding topographic ridge. Several isolated and poorly developed peripheral reef segments and one sand cay outline the transition of the lagoon basin to the NW and SW margin of the atoll shelf. The crests of these reefs are almost emergent during low tides. They are heavily exposed to surf produced by wave trains arrN-ing from various directions. Instead of corals, coralline algae (*Porolithon pachydermum* and *Titanoderma* sp.) encrust these reefs forming small algal ridges. Numerous boreholes drilled by chitons (*Choneplax lata*) perforate the algal crust. Heavy wave turbulence, swift currents, and an intricate system of caves create a unique and bizarre reef environment (Díaz et al. 1996, Milliman 1969a). The leeward margin of the atoll has no well-defined fore-reef terrace. Instead, the outer slope is either a sudden drop-off formed by a steep sand apron (natural angle of repose), or a vertical cliff with scattered overhanging ledges.

The Courtown Cays themselves currently consist of two small islets, both densely overgrown by coconut trees and bushes, and one tiny sand spit. East Cay and Sand Cay in the SE sector of the atoll have recently coalesced to form a single arrow-shaped island (about 800 m long) lying on the windward lagoon terrace. Middle Cay, one of the originally four emergent cays of the atoll, disappeared more than 20 years ago. The smallest cay, West Cay (= Cayo Bolívar), has a lighthouse and a military post for the Colombian Navy (Díaz

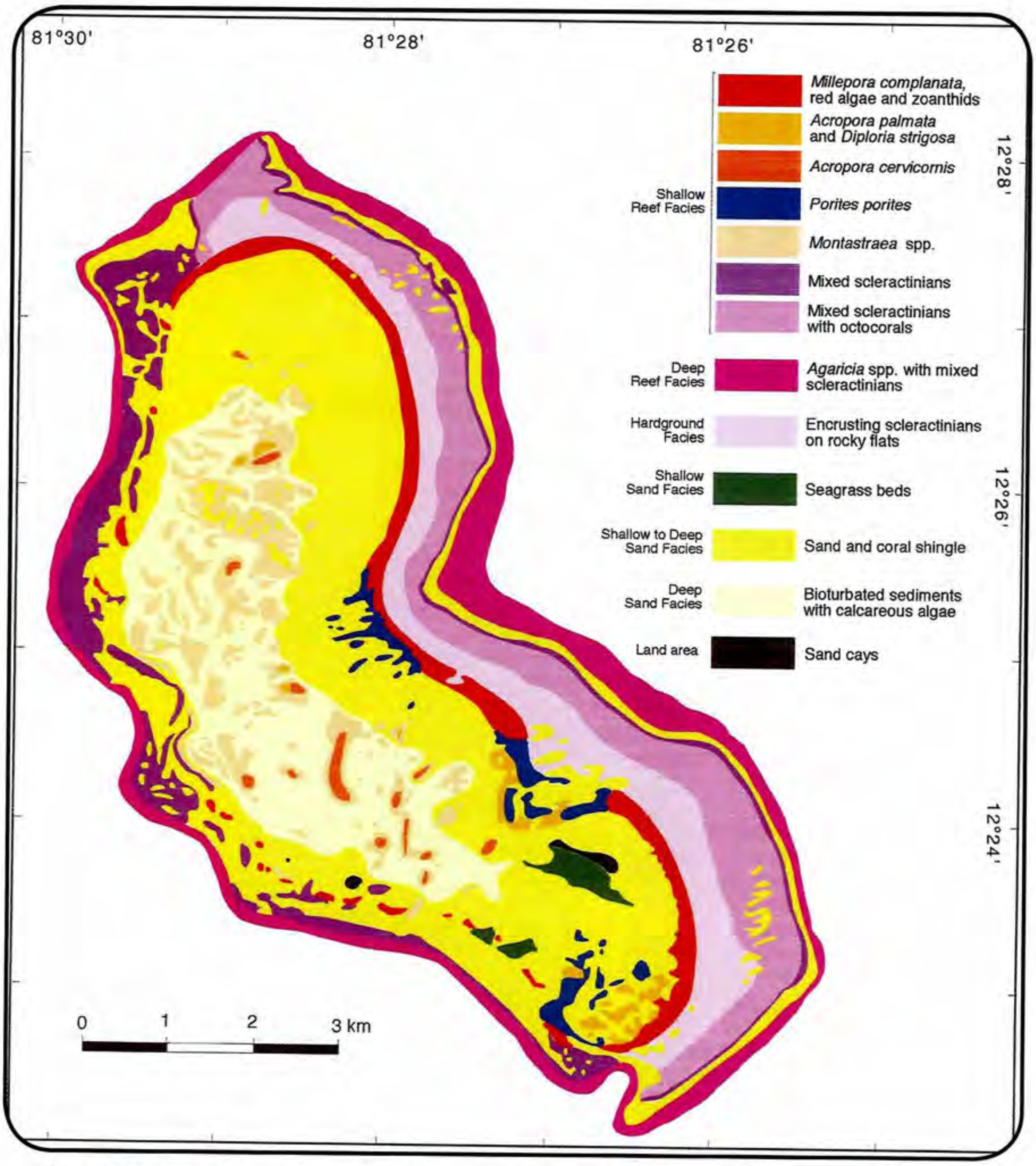


Figure 38. Distribution of bottom facies and benthic communities at Courtown Cays atoll. Adapted from Díaz et al. (2000).

et al. 1996, Milliman 1969a, 1969b; British Admirality chart 1511; chart COL 204).

6.3.2 Albuquerque Cays atoll

Albuquerque Cays atoll (12° 10' N 81° 51' W), lying about 35km SW of San Andrés (hence the other name "Southwest Cays"), is the only atoll among those in the area with a roughly circular outline. Including the fore-reef terrace, the E-W diameter is more than 8km across. The atoll has a volcanic basement, as suggested by paleomagnetic data and a "basaltic pebble" dredged at its northwestern slope from about 700m of water depth (Milliman & Supko 1968). (figs. 39 and 40)

The windward peripheral reef is virtually continuous and attains a length of nearly 6 km. A groove-and-spur system is well developed in the NE sector of the fore-reef. The windward fore-reef terrace is a gently dipping, barely colonized rocky plain descending at low angle from the peripheral reef to about 30m of water depth. Here, a distinct break marks the beginning of the subvertical outer slope. Beyond, there is a narrow terrace at the -35 m level, similar to Courtown. This -40m terrace appears to be best developed in the southwestern corner of the atoll. From there, a precipitous slope continues to greater depths.

As in Courtown Cays atoll, both the morphological and ecological reef zonations are primarily controlled by wave exposure along a windward-leeward gradient. The windward barrier reef shows a well-developed groove-and-spur system. Species composition strongly resembles that of corresponding reefs at Courtown Cays and the islands of San Andrés and Old Providence: a rather high-diversity coral fauna on the higher outer slope just below the fore-reef terrace margin; extensive, almost bare surfaces on the fore-reef terrace itself and exuberant growth of a low-diversity coral fauna dominated by the hydrozoan *Millepora* and the colonial zoanthid *Palythoa* in the reef crest zone.

Two emerging cays (North Cay and South Cay) formed by sand and rubble on the windward lagoon terrace rise to less than 2 m above sea level. The lagoon basin exhibits two distinct depth levels (averaging about -9 and -15 m respectively), easily recognizable from the air by their different blue tones. A narrow, meandering ribbon reef, which fringes the topographic edge for nearly 6 km, separates both levels. Its crest rises to -4 m. Nearly 25 % of the lagoon floor at Albuquerque is covered with patch reefs. Deeper lagoonal reefs, mostly of the anastomosing type, are dominated by the star corals *Montastraea* spp. Shallow lagoonal reefs rising to the surface are characterized by dense stands of the moosehorn coral *Acropora palmata* and the brain coral *Diploria strigosa*. Some of them are of the ribbon-reef type. Somewhat deeper patch reefs are dominated by the staghorn coral *Acropora cervicornis* (Milliman 1969a, Díaz et al. 1996). A series of small, shallow peripheral reefs partly enclose the lagoon basin on its lee along a wide semicircle. They are mainly formed by large thickets of the moosehorn coral Acropora palmata (fig. 39 and 40).

The leeward fore-reef terrace extends for nearly 1.5km to depths greater than 30 m, where it ends at the steep outer edge of the atoll. This extensive and gently dipping platform descends at an angle of 4-7o to about 15m. The profile then steepens gradually to about 40m, from where the outer slope forms a steep drop-off or even a local subvertical escarpment, densely covered by platy scleractinians. In its shallower parts, the terrace is mostly covered by sand and rubble, but the abundance and diversity of stony corals, branching octocorals, and algae increase rapidly with depth (Díaz et al. 1996, Díaz-Pulido & Bula-Meyer 1998, Milliman 1969a and b; British Admiralty Chart 1511; chart COL 203).

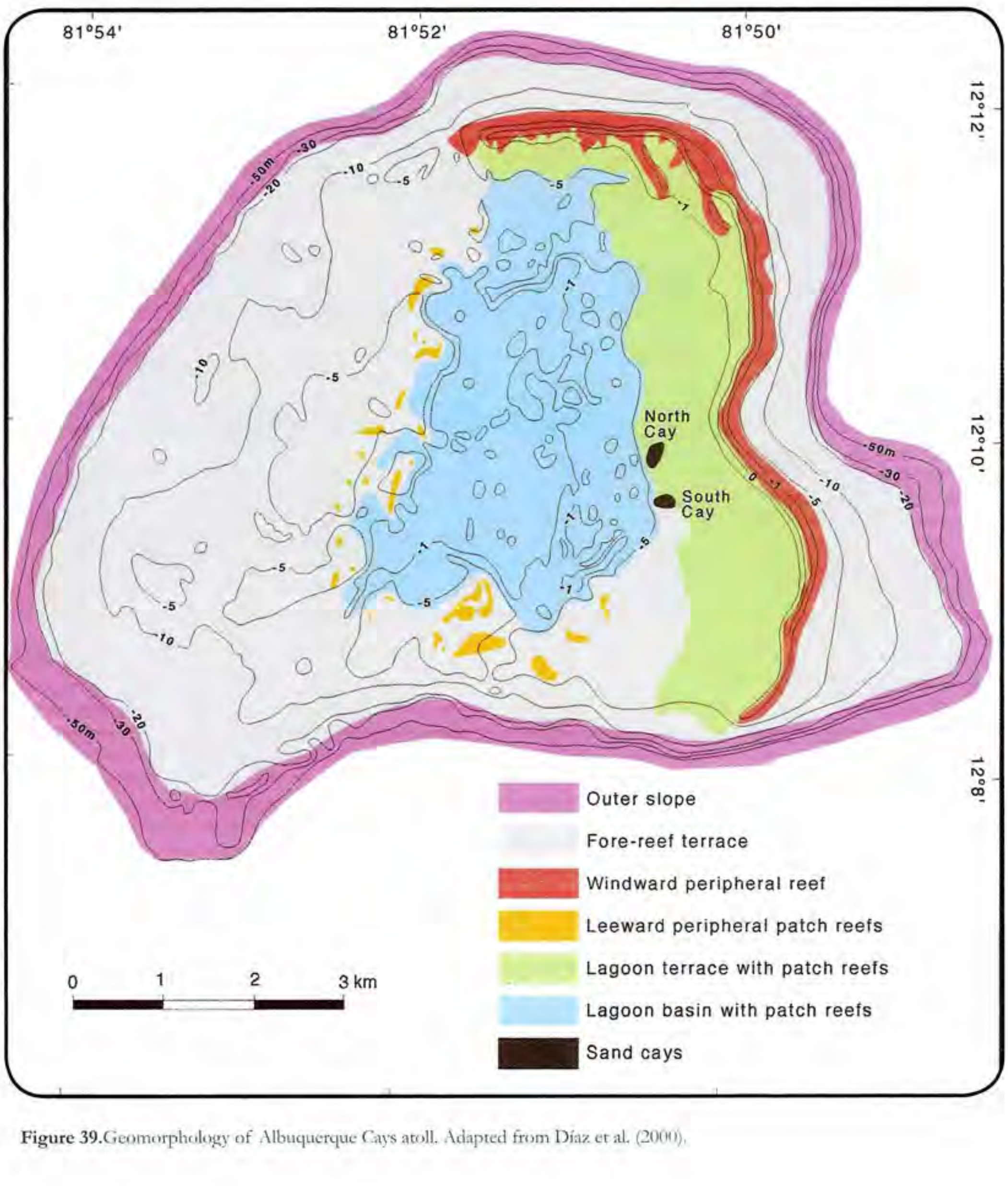


Figure 39. Geomorphology of Albuquerque Cays atoll. Adapted from Díaz et al. (2000).

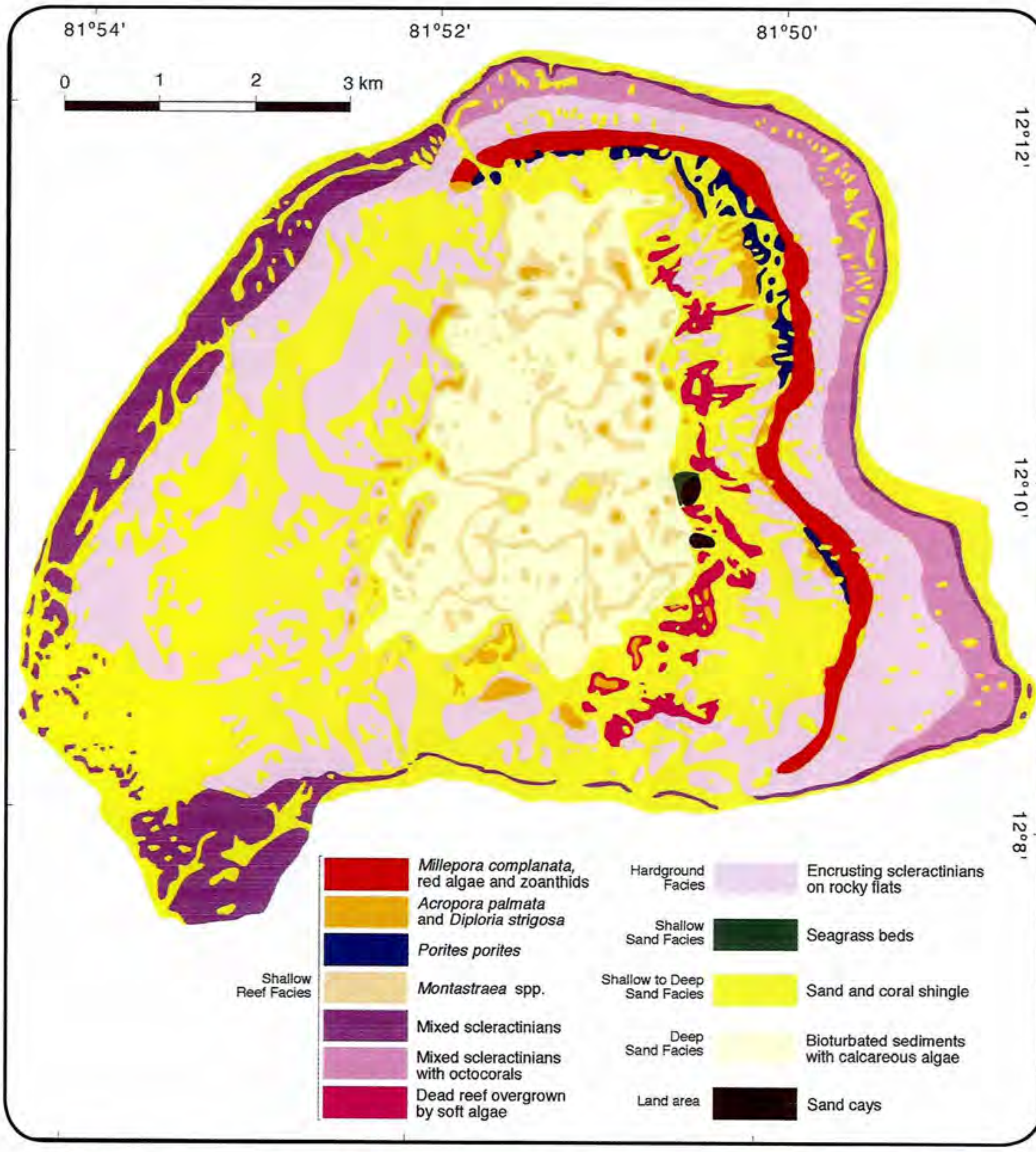


Figure 40. Distribution of bottom facies and benthic communities at Albuquerque Cays atoll. Adapted from Díaz et al. (2000).

6.3.3 Roncador Bank atoll

Roncador Bank (13°34' N 80°04'W) is situated about 135 km ENE of Old Providence Island and about 210 km NE of San Andrés. This atoll is about 13 km long and attains a maximum width of almost 6 km, with an overall trend NW-SE. Roncador Bank lies immediately E of a very young and active rifl graben. The windward reef has a fishhook shape, with Roncador Cay, a sparsely vegetated islet, at its northwestern end. The cay was formed by accumulation of coarse coral debris. It serves as a military post for the Colombian Navy. In addition, there are two minute sand spits in the middle and southernmost sector of the lagoon terrace. (figs. 41).

The windward fore-reef terrace of this atoll is somewhat narrower and deepens more rapidly than that of any of the other atolls. The peripheral reef is virtually continuous only on the windward side. It emerges at low tide at many places during calm weather. Large emergent limestone boulders line extensive portions of the outer reef flat, especially near Roncador Cay. They must have been thrown up onto the reef flat by events of extremely high energy, such as extraordinary hurricane waves or tsunamis. The lagoon terrace of Roncador is considerably shallower than that of the other atolls in the area. It emerges locally during low tide. Water depths within the lagoon basin reach 18 m but average about 12 m.

The hermatypic associations of the windward reef crest correspond largely to those of the two atolls described before. The southern half of the lagoon bears dense concentrations of anastomosing patch reefs, formed mainly by *Montastraea* spp. Some of these patch reefs rise almost to the surface with their summits overgrown luxuriantly by thickets of *Acropora cervicornis*. Patch reefs cover nearly 70 % of the surface of the lagoon floor in this sector.

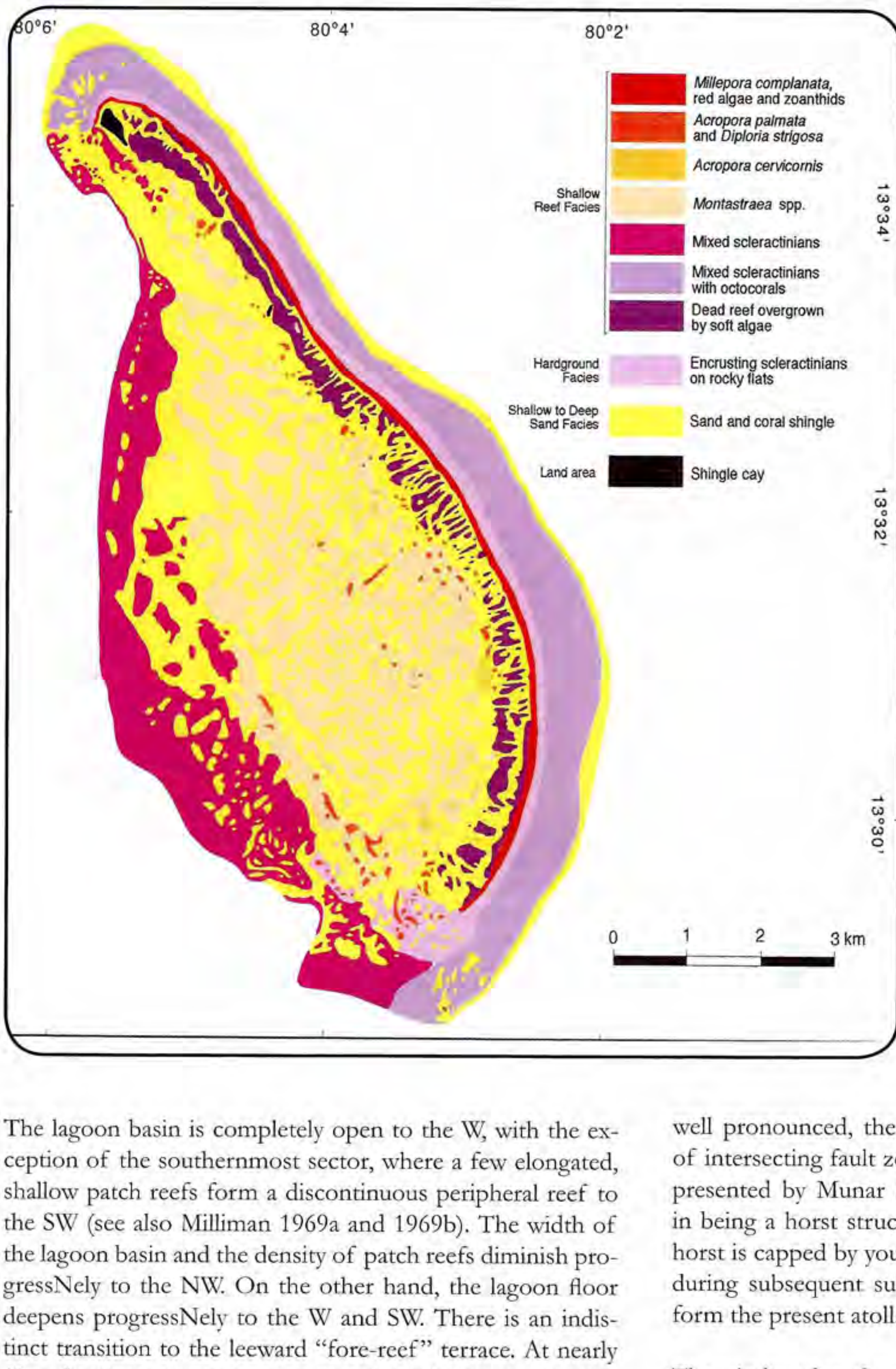


Figure 41. Distribution of bottom facies and benthic communities at Roncador Bank atoll. Adapted from Díaz et al. (2000).

The lagoon basin is completely open to the W, with the exception of the southernmost sector, where a few elongated, shallow patch reefs form a discontinuous peripheral reef to the SW (see also Milliman 1969a and 1969b). The width of the lagoon basin and the density of patch reefs diminish progressNely to the NW. On the other hand, the lagoon floor deepens progressNely to the W and SW. There is an indistinct transition to the leeward "fore-reef" terrace. At nearly 18 m depth, an almost continuous subvertical to overhanging drop-off marks the outer margin of the southwestern atoll shelf. This may indicate a collapsed platform margin facing the active rift graben to the E. If a peripheral reef was ever present along the leeward shelf, it might have been ripped off during this presumed collapse event (US chart 1374).

6.3.4 Serrana Bank atoll

Serrana Bank atoll (14° 34' N 80° 16' W), an extensive reef complex about 36 km by 15 km (from shelf-edge to shelf-edge) with a nearly triangular shape, lies about 150 km NE from Old Providence. Similar to Courtown Cays atoll, the outline of Serrana also trends NE and NW. Though less well pronounced, the shape equally suggests a triple point of intersecting fault zones. According to new seismic results presented by Munar (2000, fig. 6), Serrana bank is unique in being a horst structure showing considerable uplifi. This horst is capped by younger limestones which were deposited during subsequent subsidence of the sea floor, and which form the present atoll. (figs. 42 and 43)

The windward reef wall is well developed on the NE and SE flanks of the atoll. It is interrupted in three places by rather deep passes, one in both the central and eastern segments of the southern reef branch, and one near the northeastern bend of the outer reef wall. *Millepora* sp. and *Palythoa* sp. with some *Acropora palmata* dominate reef crest associations. The reef flat and the lagoon terraces are less distinct at Serrana than at the other atolls.

The sandy lagoon floor is often more than 10 m deep and is mostly covered by extensive patches of soft algae (*Lobophora* sp.). A sandy ridge in an eastern and a western sector naturally divides it. The western part of the lagoon shows wide sandy plains with only a few scattered patch reefs. Elongated secondary "barrier reefs" of *Acropora palmata* semi-enclose the eastern and northernmost parts of the lagoon, creating very calm conditions where deeply submerged anastomosing patch reefs of the star coral *Montastraea* spp. overgrow more than 60% of the lagoon bottom. To the NW, the lagoon basin is completely open. In this sector, the bank ends with a steep drop-off to the open sea. Here, a huge sediment tongue plunges from the lagoon down the western outer slope of the atoll.

The environments of the western lagoon of Senana Bank are notable for being the only site in the whole Archipelago where a major proportion of the sediment grains are formed by modern ooids (Milliman 1969b). Bock & Moore (1971) studied the foraminifers and micromollusks and Diaz- Pulido & Bula-Meyer (1998) the algae from the Serrana lagoon.

There are 6 small reef islets located at Serrana Bank (Ortega-Ricaurte 1944, Milliman 1969a, DHI 1983; U.S. chart 1374; COL 045, COL 046; COL 1625):

1.) East Cay, a small islet covered with coral and mollusk rubble, hardly 1m high.

2.) South Cay, about 150m long and 25m wide, composed of coral rubble and sand with sparse vegetation. Beachrock lines the seaward beach.

3.) Little Cay is less than 100m in diameter and formed by fine sand and rubble lining the seaward beaches. The cay is without vegetation.

4.) Narrow Cay is essentially composed of coral rubble.

5.) Serrana Cay (Southwest Cay) has a lighthouse and is today about 500m by 200m with dunes >10 m high. It is the largest sand cay of the Archipélago. Lying at the extreme SW end of the peripheral reef wall, it is densely covered by bushes and shrubs. Slightly brackish water is found in a well. The islet is populated by numerous nesting sea birds (fig. 45) and was formerly a site of guano exploitation. At present, the Colombian Navy uses it as a military post.

6.) North Cay, on the northern point of the peripheral reef, is low and composed of sand and rubble. According to Ortega-Ricaurte (1944), it is 270m by 135m. Currently, this cay is

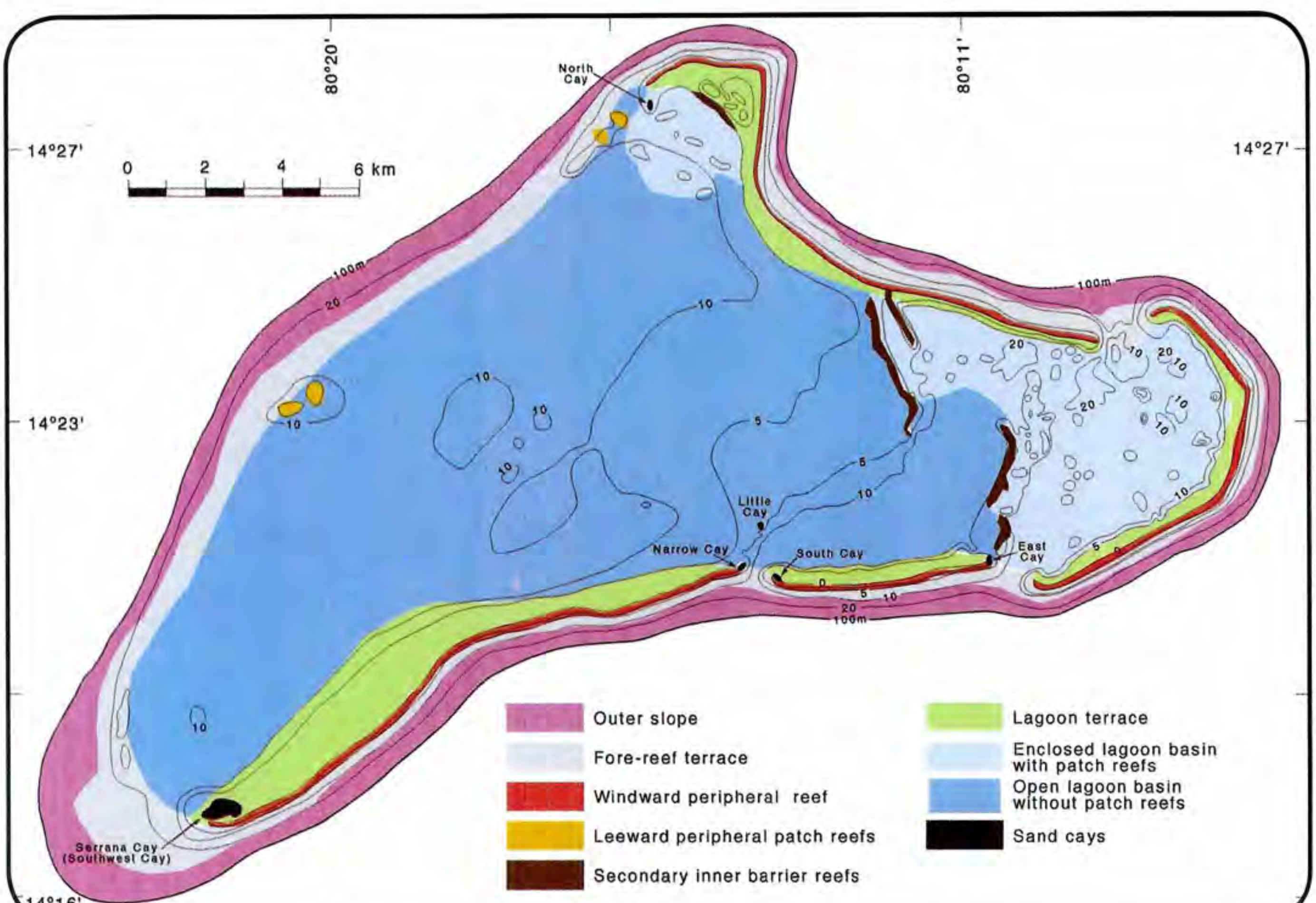


Figure 42. Geomorphology of Serrana Bank atoll. Adapted from Díaz et al. (2000).

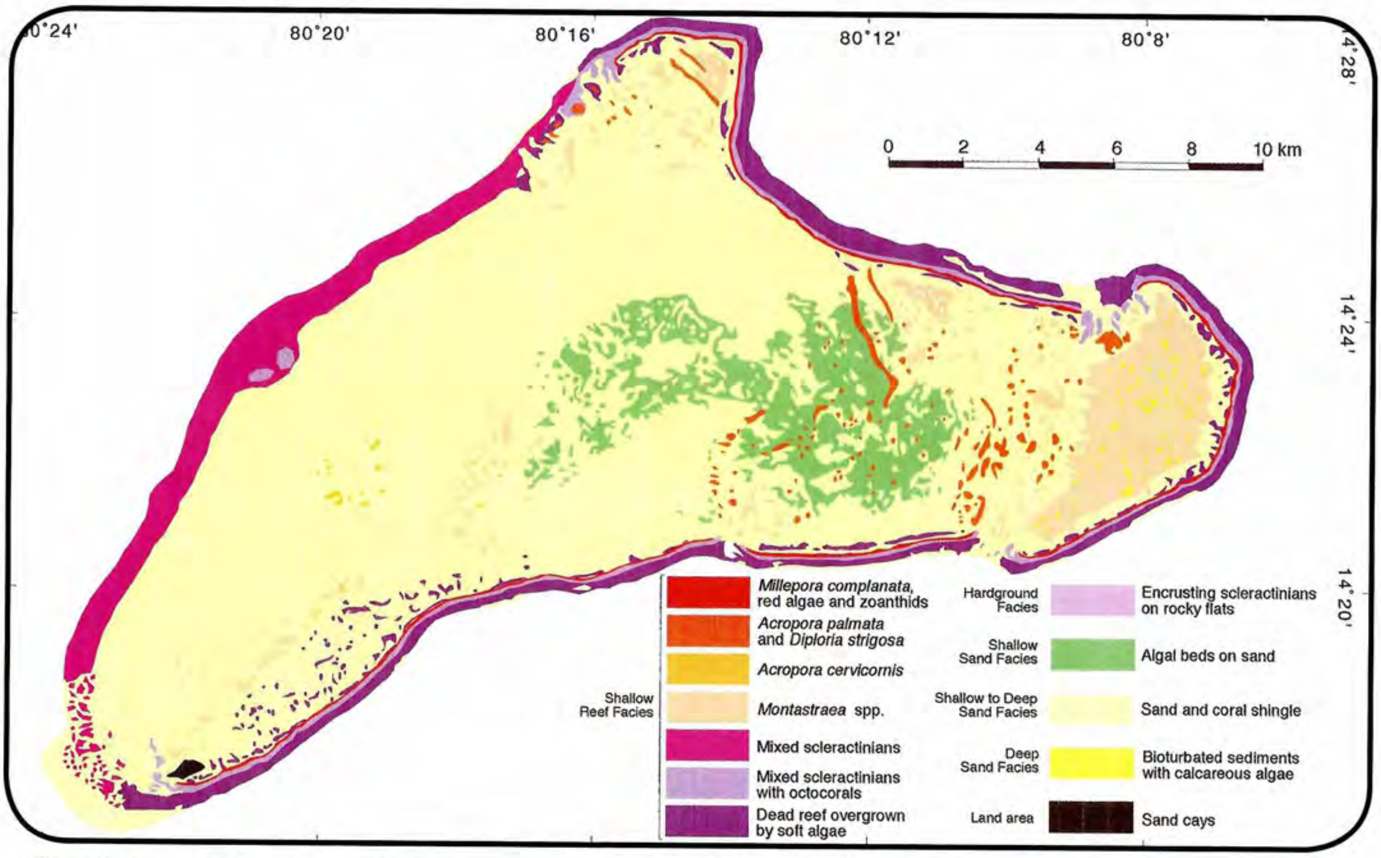


Figure 43 Distribution of bottom facies and benthic communities at Serrana Bank atoll. According to Milliman (1969b), sediment in the eastern lagoon is dominated by Halimeda sands, whereas in the western lagoon it is largely non-skeletal with cryptocrystalline lumps, pelletoids, and ooids. This is not shown on the map. Adapted from Díaz et al. (2000).

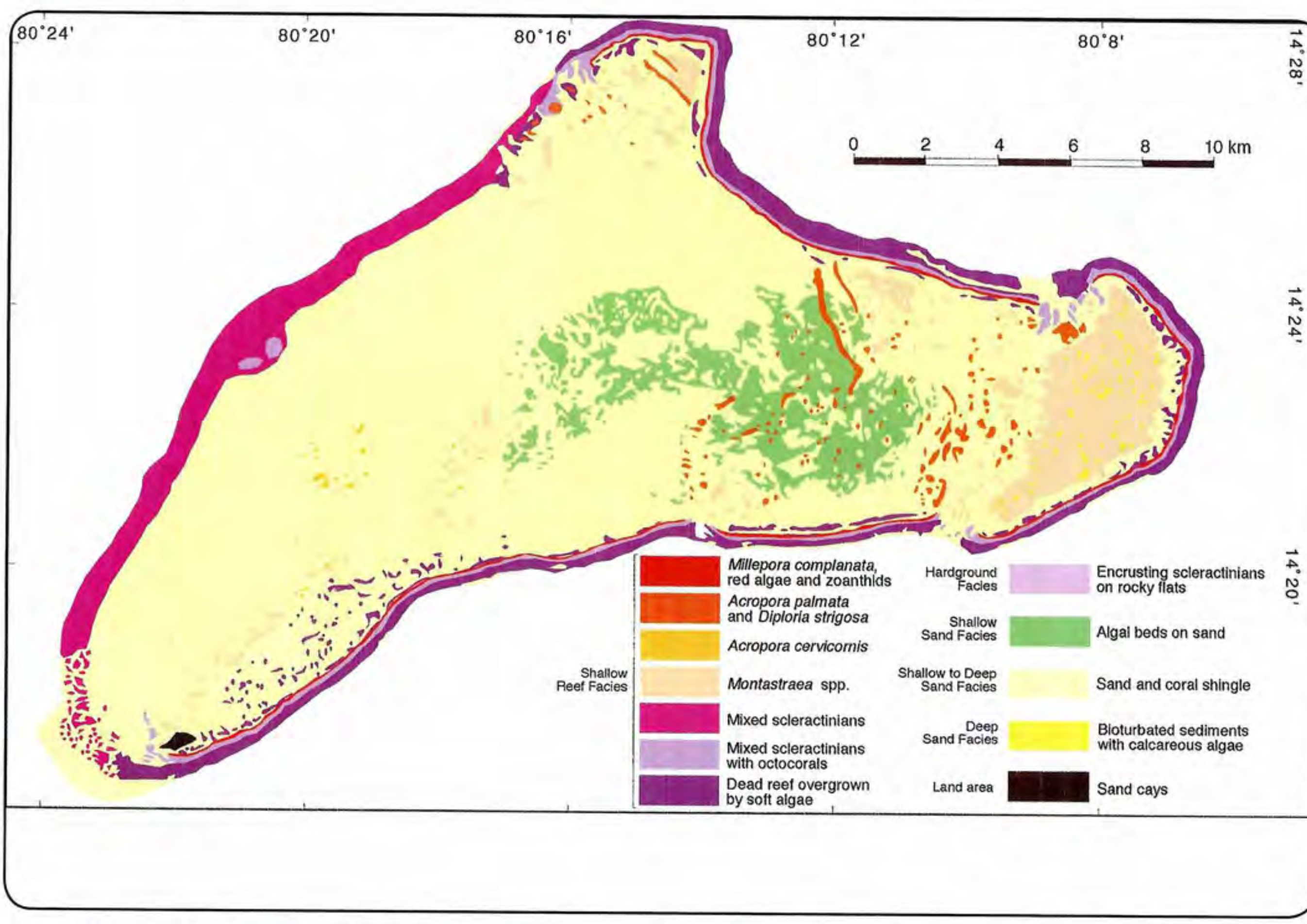


Figure 44 Serrana Bank atoll: North Cay. Note the almost complete absence of major land vegetation. Numerous sea birds (Sulidae, Fregatidae) use this cay for nesting. Photo taken in May 1995 by Sven Zea.

smaller, not more than 150 by 80m (pers. observ. JMD 1995). This cay is a prefered restig place for marine bird (fig.44).

6.3.5 Quitasueño Bank half-atoll

Quitasueño Bank (14° 20' N 81° 10' W) is situated some 80 km to the W of Serrana Bank and some 70 km NNE of Old Providence. It is about 65 km long and 24 km wide and trends NNE, with steep slopes at its outer platform margins. It is by far the largest atoll-like structure of the area. A rather continuous, very shallow barrier-like reef dissected by two conspicuous reef passes extends over more than 40 km along its eastern margin. Although part of this reef wall emerges during low tide, islets are completely absent from Quitasueño Bank (Ortega-Ricaurte 1944, DHI 1983). Near the northern point of the reef, a lighthouse has been built in shallow water. Two major shipwrecks were conspicuous in this reef in 1998. During storms, the northern and southern ends of the reef are subject to heaviest surf, as testified by abrasional topography of the fore-reef terrace. The fore-reef exhibits distinct grooves and spurs which are best developed in the central westward bulge of the windward reef tract. There are no peripheral reefs along the northern, southern and western margins of Quitasueño Bank. The overall geomorphology of the bank is noteworthy: it is an extremely wide fore-reef terrace extending locally more than 15km and lacking peripheral reefs in the N, S and W. The absence of any distinct lagoonal depression in the center might be due to slow westward tilting during the truncation of the fore-reef terrace. (figs. 45 and 46)

The surface of the fore-reef terrace is rather bare where shallower than –l0 m to -15 m, with hardly any discernible reef accretion. Surge channels with coral cobbles and polished rock surfaces at depths shallower than 15 m point to an environment subject to heavy abrasion during storms. The deeper fore-reef. Terrace is mostly overgrown by the mixed corals association, which is characterized by mostly massive scleractinians in rather quiet water. The breaker zone of the reef is formed by dense grow. This of the *Palythoa-Millepora* association with some *Acropora palmata*, as in other windward reefs of this part of the Caribbean.

Leeward of this reef, a "lagoon Terrace" is well developed. It accomodates the sediments shed from the reef Active accretion of this terrace is shown by the partial and complete burial of Living reefs at the prograding sedimentary front of the sand cliff. Beyond this terrace there is a "lagoonal depression" some 4 to 6 m deep that gradually deepens towards the W. Here, patch reefs of very irregular shape are common. Some reach the surface, but the crests of most reefs are submerged to a depth of several meters. The size and shape of these structures can be best appreciated from air. Most notable are ribbon-shaped reefs, more than 1 km long, which roughly parallel the barrier at some distante. The reef flat of at least one of these reefs is densely covered by potato-sized rhodoliths. They are formed by a multiple cover of red algae encrusting a small coral-fragment nucleus. They are very similar in size and shape to rhodoliths described from Belize reefs by Gischler & Pisera (1999). The crest of these ribbon reefs lies in water depths of 2 to 3 m.

Most spectacular are extensive anastomosing patch reefs in the deeper "lagoon". They consist of narrow submerged reef ridges that fused to regular polygonal meshes of reef framework. Each mesh is several tens of meters across and rises a few meters above the surrounding sandy sea floor. The meshes are interconnected and cover the bottom for many hectares in water depths down to around 10 m. This characteristic honeycomb pattern of the lagoon floor is clearly visible from the air. Each of the meshes encloses a distinct micro-lagoon, which forms an effective sediment trap. The crests of the meshwork rise steeply from a sandy floor deeper than 6 m, and at connecting points the reefs may even break the surface. Several kilometers to the W from the peripheral reef, the coral patch reefs are more deeply submerged in water depths exceeding 20 m. Here they show less topographic relief and a less regular outline.

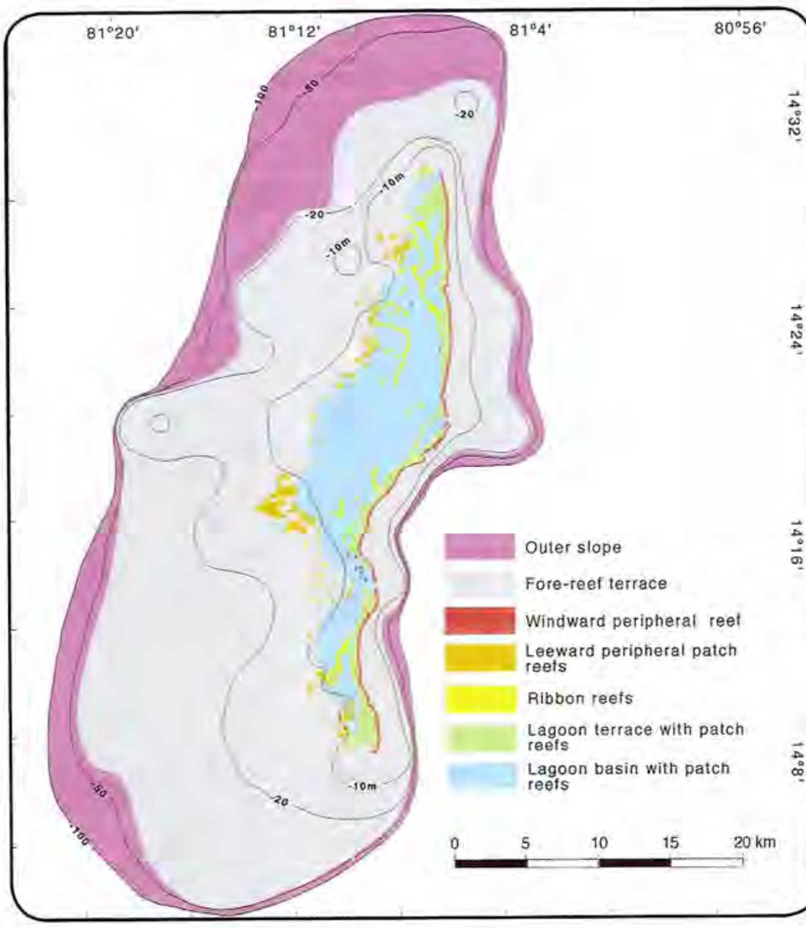


Figure 45 Geomorphology of Quitasueño Bank half-atoll. Adapted from Díaz et al. (2000)

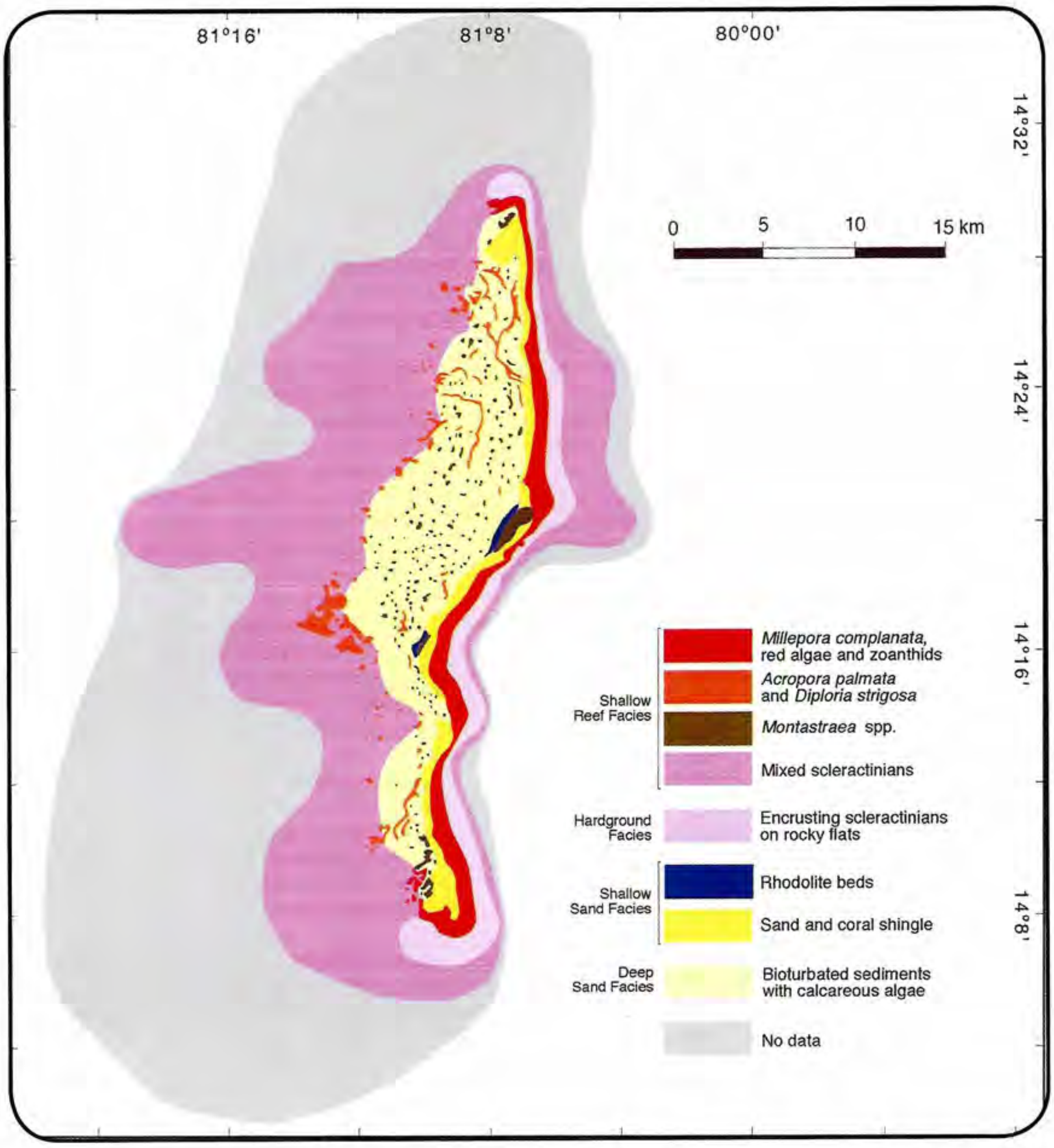


Figure 46. Distribution of bottom facies and benthic communities at Quitasueño Bank half-atoll. Adapted from Díaz et al. (2000)

With its well-developed peripheral reef in the E and its complete lack in the W, Quitasueño Bank may be classified geomorphologically as a half-atoll. The westward-dipping lagoon floor seems to reflect off-reef sediment transport during storms towards the W, but it may also be due to higher rates of carbonate production in the shallow water in the E and to the considerable sediment-trapping capacities of the anastomosing reefs. In addition, Quaternary tilting of the platform to the W cannot be ruled out. This is suggested by the lack of a true lagoon basin, a rather flat westward dipping platform floor, and a fairly continuous peripheral reef developed only in the E. In accordance with the regional pattern, it is suggested that Quitasueño Bank also has a hstory as a Neogene atoll which was truncated by one or several transgressions and overlain by Quaternary reef complexes (charts COL 215, COLA 416, COL630, COL 631, COL 1625).

6.3.6 Serranilla Bank half-atoll

Serranilla Bank (15° 50' N 79 ° 50' W) is situated about 180km NNE of the Old Providence reef platform. The bank is about 46km long in an E-W direction and 38km broad from N to S. It occupies an area of approximately 1,100km^2. Serranilla Bank lies immediately N of the ENE- WS W trending Pedro Fracture Zone (Hine et al. 1992, fig. 1). (fig. 47).

This relatively deep (mostly 10-40m) bank is bordered by steep escarpments. The platform perimeter features scallop-shaped embayments, which are particularly common along the southern margin. Only its eastern and southeastern margins are rimmed by a peripheral topographc reef structure locally emerging during low tides. The overall geomorphology of the feature corresponds to a half-atoll, but an actively accreting coral reef rim is not developed (Triffleman et al. 1992a and b).

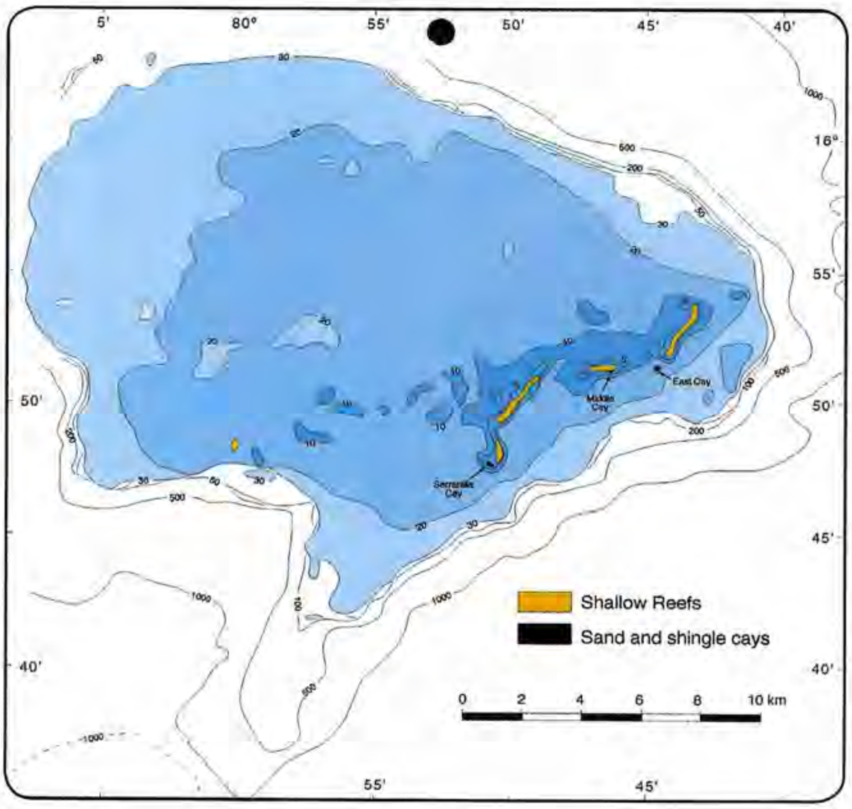


Figura 47. Geomorphology of Serranilla Bank half-atoll. Islets are shown in gray. Depth contours in meters. Adapted from chart COL 634

conjunction with strong currents, promote off-bank sediment transport and active shedding of shallow-water sediment to the deep sea. Muds are probably winnowed from bank-top sediments (Triffleman et al. 1992a).

There are several sand and shingle cays in the southeastern sector which rise up to 2 m above sea level. Beacon Cay, the largest of these cays, is 900 m long and up to 2.4 m high and has a lighthouse (DHI 1983, chart COL 004, COL 208, COL 634, COL 1625, COL 1626; Triffleman et al. 1992a and b).

Beacon Cay is used as a post by the Colombian Navy and Coast Guard. The cay is densely covered by small weeds (*Portula capilosa*). There are also numerous coconut trees. Sea birds are not frequent. The sea is always very agitated around the cay. As a consequence, landing by boat is dificult. Between December and April the boats of the coast guard are camed to San Andrés, because the sea usually gets too rough here (pers. com. Jaime Garzón- Ferreira, INVEMAR).

In the lee of the topographic reef structure, there is a 9 km broad zone with water depths rarely exceeding 5m. This is followed by a sandy Bottom around 19m deep. Hardground overgrown by brown algae and sponges predominates in the shallow southeastern sector. Seagrass as well as *Halimeda* and other calcareous algae flourish on bank-top sands. Sediment cover is thin and coarse-grained. On the western half of the bank, the sediment cover is slightly thicker.

Halimedal/molluscan-dominated sediments are here more common and finer grained. Bedform shapes and location of sediments suggest off-bank transport in resporise to strong easterly trade winds and the northwestward flowing Caribbean Current (Trifleman et al. 1992a and b). The "lagoon basin" is open to the N and to the W and unprotected by a topographic reef rim in this direction. Discorbis rosea-dominated foraminifera assemblages occur on the banktop. They are normally associated with platform-margin environments in other areas of the Caribbean. The preponderance of this robust species is probably the result of the relatively deep banktop depths and dynamic hydrographic conditions found on this platform (Triffleman et al. 1992b).

The bank does not appear to be accretionary under present environmental conditions. According to Hallock et al. (1988), carbonate accumulation on this and neighboring platforms has not kept pace with Holocene sea level rise. Trophic resources in the area apparently exceed levels suitable for coral-reef development and instead favor sponge-algal communities. Terrestrial runoff and topographic upwelling over the Nicaraguan Rise enrich the western Caribbean. Storms, in

6.3.7 Alice Shoal drowned atoll

Alice Shoal, or Banco Alicia (16°05' N 79° 18' W), lies less than 30 km ENE of Seranilla Bank. It forms a circular shoal with a diameter of about 20 km. According to nautical chart COL 004, Alice Shoal has the morphologic characteristics of an atoll, with its marginal windward reefs rising steeply to a minimum water depth of 11m (DHi 1983). The atoll topography is best developed in the eastern sector, where shoals rise for 12m and more above a central lagoon floor 24-30 m deep. The atoll ring is completely open to the NW, as it lacks a marginal reef ridge in this sector. This is in agreement with the regional pattem of atoll geomorphology. At the outer margin of the reef platform, there seems to be a drop-off or very steep slope from about 40m to a depth of several 100 m. The slope becomes gradually less steep down to more than 1000 m (see nautical charts COL 004, COL 206). Nothing is known at present of the benthic life on this atoll. (fig. 48)

Besides Saba Bank in the Lesser Antilles (van der Land 1977), Alice Shoal seems to be the only other drowned atoll known from the Caribbean. The drowning of the isolated bank might result from block faulting prevalent in this area of the Lower Nicaraguan Rise. The Pedro Fracture Zone is situated near the SE margin of this atoll structure (see Hine et al 1992, fig. 1). It is not known when the drowning of the atoll occurred. If the sinking of the platform was rather sudden and happened in the Holocene, available time might have been too short for upgrowth of the reef to the surface, due to the diminished carbonate production described from elsewhere in the area (see Hallock et al. 1988).

6.3.8 Bajo Nuevo coral bank

Bajo Nuevo or New Bank (15°50'N 78°40'W), situated some 60km E of Serranilla Bank and 240 km NE of Serrana Bank, is the easternmost of the coral shoals lying on the Lower Nicaraguan Rise. The elongated bank is trending ENE and attains 9 by 26 km in size. (fig.49)

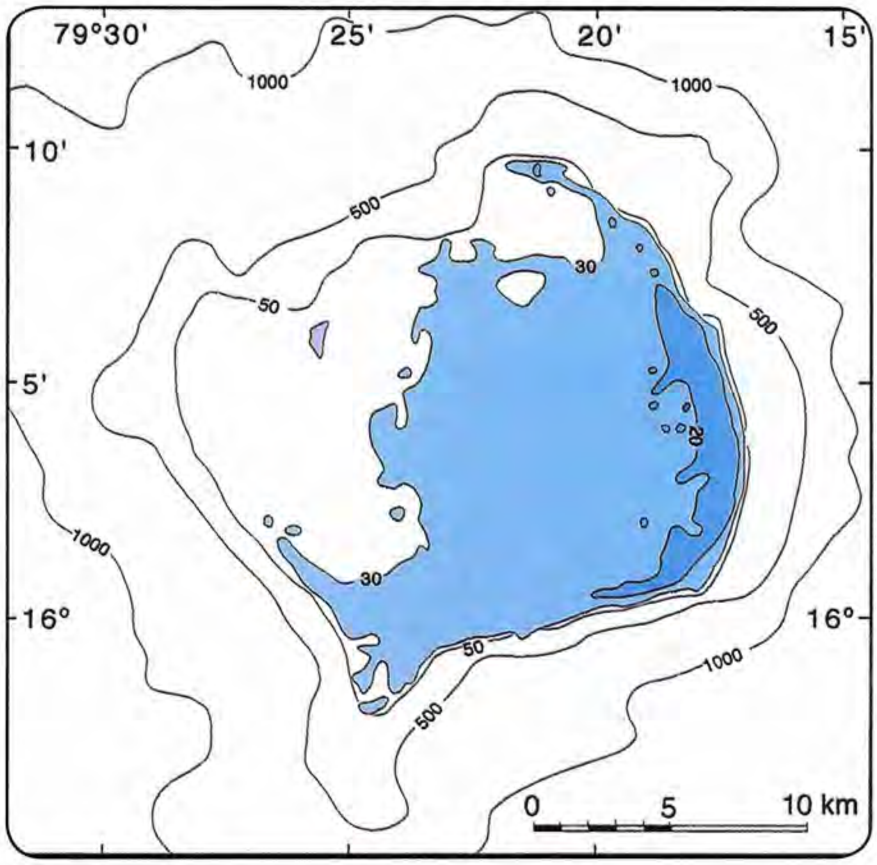


Figura 48. Geomorphology of Alice Shoal (Banco Alicia) drowned atoll. Note that there is no island on this bank. The entire carbonate platform is submerged. Depth contours in meters. Adapted from nautical chart COL 206.

Along its eastern to southern margins, Bajo Nuevo is protected from the swell of the Caribbean by discontinuous windward shallow reefs (East Reef and West Reef). From the hydrographic description, it is not certain if these are Living reefs or purely morphological features. A belt of numerous shoals, possibly of coralline origin, is protected by these reefs. There are no reports concerning the structure and taxonomic composition of these marginal reefs and shoals.

Jaime Garzón-Ferreira (INVEMAR) who spent in May 27,2001 a few hours on Bajo Nuevo reports: 300 m to the E of Low Cay there is a long reef in which the waves break. Along the windward shore of the cay the sea floor is covered by coarse sand with ripple marks and some isolated small patch reefs. The latter are overgrown by numerous algae and octocorals (including Living *Gorgonia ventalina*). In the patch reefs the following scleractinian species were noted: *Porites astreoides*, *P. porites*, *Siderastrea siderea*, *Montastraea annularis*, *M faveolata*, *Diploria labyrinthiformis*, *D. strigosa* and *Agaricia tenuifolia*.

Towards the northern rim of the platform, the sea floor deepens gradually to 20 m or more, followed by a steep drop-off. There is neither a lagoonal depression in the center of the bank nor a marginal reef along its northern rim. Low Cay, a small, unvegetated sand and shingle islet, has a lighthouse. The 100m long and 1.5 m high islet is situated near the northern end of West Reef (DHI 1983, charts COL 004, COL 046, COL 638, COL 1626).

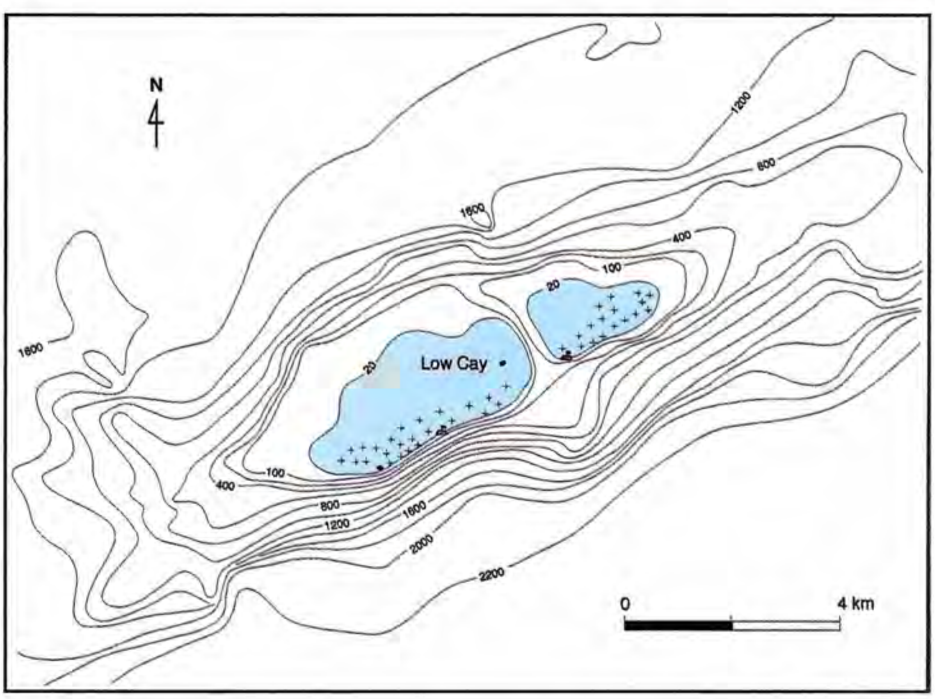


Figura 49. Approximate outline of Bajo Nuevo (New Bank) coral bank. The western limit of bank is uncertain. Islets are shown as dark dots. Crosses mark area where shallow coral rock makes navigation hazardous. The positions of two shipwrecks are indicated. Note that great water depths surround the bank to the N and S. Depth contours in meters. Adapted from nautical charts COL 046 and COL 1626..

In accordance with the rest of the Archipélago, a Neogene atoll structure might underlie a limestone cap of Quaternary coral reefs. The steep marginal escarpment to the N suggests a collapse feature. Bajo Nuevo lies immediately S of the ENE-WSW trending Pedro Bank Escarpment and is aligned in the same direction (Hine et al. 1992: fig. 1). Towards the S, the sea floor plunges to precipitous depths.

7. GEOLOGICAL RISKS IN THE ARCHIPELAGO

In the foregoing pages we learned how the atolls and islands evolved and how geological forces shaped them to become the Archipelago of today. Small oceanic islands are ephemeral structures on a geologic timescale. As soon as they emerge from the sea, they are constantly attacked by waves and subaerial erosion, which they are rarely able to withstand for any extended geological timespan. Since the islands rose above sea level, the destructive forces prevailed on land and along the coastline, while on the submerged foot of the island, limestone accretion continued to form a wide carbonate shelf

The interplay of constructive and destructive geological forces will continue in the future. When harmful to man, these forces will become geological hazards or risks. The study of geological risks on oceanic islands has to focus on the geological forces, which may cause damage to property or endanger the lives of the island population. Some of these factors act intermittently and aperiodically. Their recurrence times often surpass the timescale of human life or even of human history. Lost from the memory of the local population, the same disasters may strike again suddenly and unexpectedly. The magnitude of disaster and the period of recurrence can often be estimated from the geological record. We may therefore expect their re-occurrence in the future. Potentially hazardous geological processes on oceanic islands are volcanism, earthquakes, tsunamis, sea level changes, and hurricanes. Secondary hazards triggered by these may include coastal erosion and mass movements.

7.1 Volcanism

Volcanic activity in the Archipélago ceased with the extinction of the Old Providence volcano, probably in the Pliocene (5 to 2 million years ago). In the wider area, the zone of volcanic activity shifted from the Caribbean side of Nicaragua to western Nicaragua since late Neogene time (fig. 3; McBirney & Williams 1965; Ehrenborg 1996). Volcanic activity has been entirely a restricted to the Pacific margin of Central America since Quaternary times. Though it may re-occur on the islands even after millions of years of quiescence, there seems to be only negligible risk of renewed volcanic activity for the generations to come.

7.2 Earthquakes

Earthquakes result from a slow accumulation of elastic strain which progressively deforms the crustal rocks, producing stored elastic energy until abrupt rupture results in a fault. The sudden release of energy at the point of rupture, known as the hypocenter, produces seismic waves which radiate outwards from the fault.

Shallow-focus earthquakes are the most damaging events. The severity of ground shaking is measured by both horizontal and vertical ground acceleration (depending on the type of seismic wave). The greatest damage to constructions is due to the horizontal movements of the ground. The amplitude and duration of these movements in loose sediments is up to five times greater than in solid rock. Damage is thus generally more severe in constructions founded on unconsolidated material (Smith 2001).

7.2.1 The geological record of earthquakes in the Archipélago

The Archipelago is situated in a tectonic zone that has been highly active in Neogene and Quaternary times. Past and future sources of regional seismicity are extension fracturing on the Lower Nicaraguan Rise and compressional movements in the nearby North Panama Deformed Belt. Geologically recorded earthquakes on the islands are documented by numerous faults on the sea floor surrounding the Archipelago (Christofferson 1983), by extension fracturing of the Pleistocene limestone cap of San Andrés, and by seismic breakage of fossil corals.

More than 70 Sangamonian and post-Sangamonian fractures can be studied in coastal outcrops around San Andrés, and many more are hidden under soil and vegetation. A large majority of these fractures are Wisconsinan, but the youngest seem to be of Holocene age. The fractures document some of the most destructive earthquake events that shook the island in the last 100,000 years.

Major "fossil" earthquakes at San Andrés, as recorded by seismic breakage of corals and by tectonic fractures, may be conveniently grouped according to their age:

a) Late Miocene: Deeper lagoonal environments showing earthquake damage, i.e. many hemispheric corals in a top-down position and slumped coral carpets. Cantera San Andrés and Pepper Hill.

b) Latest Neogene to Middle Pleistocene: Fractures exclusively cross-cutting limestones of Miocene age but not Middle Pleistocene limestone. Exposed in North Cliff, May Cliff and the Duppy Gully area.

c) Middle Pleistocene to latest pre-Sangamon: Fractures that transect the Middle Pleistocene rocks of the Older Low Terrace Limestone without continuing into the adjacent Sangamonian Younger Low Terrace Limestone. Found only at North Cliff and May Cliff.

d) Sangamonian earthquakes: Gaping extension gashes formed during the sea-level highstand of the Sangamon transgression are filled by contemporary marine sediments and seashells. Graded bedding in cleft. Best examples of sediment-filled gashes and nearby earthquake damage (breakage and toppling of corals) are found in Sangamonian near-reef and lagoonal deposits at Bungie Point and Sterthenberg Point.

e) Wisconsinan earthquakes: Clefts of extension fractures, up to 20 cm wide, within the Sangamonian limestone, partially or entirely filled with subaerial limestone deposits (sparry speleothem calcite) since their formation. Differential surface lowering by rain solution resulted in the more resistant massive speleothems weathering out as "calcite dykes" which, today, may rise more than 50 cm above the general terrace level. It seems that "dykes" that stand out highest are older than the lower-relief dykes. Due to the wide surface outcrops in the Sangamonian rocks along the San Andrés coastline, post-Sangamon earthquakes are best recorded. About 70 of the more conspicuous post-Sangamonian fractures were mapped in coastal outcrops. Many more occur inland but are hidden under soil and vegetation.

f) Holocene earthquakes: Almost unweathered open clefts in Sangamon limestone, not yet filled with speleothem. Best examples are found along the coastline between Rocky Point and at South End. Some clefts were filled with red Holocene soil. Open tectonic gashes are equally found on the fore-reef terrace SE of Elsy Bar and at the outer edge of the Bocatora Hole drop-off.

g) Historical earthquakes: There is no devastating earthquake on record in the Archipélago from the last 200 years. The preceding history of human occupation of the islands is only very scantily documented; however, older islanders experienced light earthquakes in about 1940 and 1950. A series of quakes that lasted for several days in mid-February of 1995 caused local concern. The earthquake at 17h 46 m 03s on February 11, 1995 was superficial, with a magnitude of 5.3 on the Richter scale and with the epicenter near San Andrés (latitude 12.49°N, longitude 81.54°W). Several buildings, including the airport, were damaged. The last earthquake on the island (for the time being) was felt in May 1996.

Assuming an even distribution in time of readily visible post-Sangamon cracks, it may be estimated that catastrophic seismic events accompanied by fracturing showed a mean recurrence time of less than one thousand years. Similar periods of quiescence may be expected in the future. This estimation does not include seismicity resulting from fracturing of the deep sea floor in the wider area surrounding the islands.

More detailed paleoseismic studies are necessary to determine the distribution and time-clustering of earthquake events on San Andrés. Future radiometric dating of speleothem fills in Wisconsinan fracture cracks might reveal recurrence periods of seismic activity during the past 80,000 to 10,000 years.

The earthquake record in the volcanic rocks of Old Providence is much less complete and as yet only insufficiently studied. This is due to less favorable outcrop conditions and less convenient means of relatNe dating. The conspicuous gap at Split Hill, Old Providence is a weathered-out fracture plane caused by an earthquake, probably of early Quaternary age. The wide submarine clef at the outer slope at Broken Ground equally testifies for a Quaternary earthquake event.

7.2.2 Earthquake hazards in the Archipelago

The possible hazards of major quakes in the Archipélago are the following:

a) Liquefaction of soils and artificial sand fills

Because of strong shaking, water-saturated granular sediments will temporarily lose their cohesion and begin to flow. Under a building, this will result in loss of bearing strength of the ground, with the possible collapse of the entire building.

At San Andrés between 1966 and 1969, swamps and muddy nearshore areas were filled by sand and mud dredged from the harbor area to gain building land for the expanding capital. These sand fills in town comprise land along the shore in the harbor area, in the former Black Dog Swamp, and between Sprat Bight and North Cliff. Many private houses and commercial buildings, as well as a number of hotels, harbor installations, and part of the airport building, have since been constructed on this unstable Bottom. During the 1995 quake, the buildings in the sand fill areas were more seriously affected than those on the Pleistocene rock. The part of the airport building constructed on sand was damaged, whereas the part resting on hard Pleistocene rock remained unharmed.

Ground shaking can cause natural slopes to fail after liquefaction of sediments soaked with rainwater. This may result in landslides and rock avalanches. A potential, but probably negligible, risk is posed by soft volcanic ashes cropping out in steep slopes above Provision Ground and at Bottom House (Old Providence). Steep marly slopes at Duppy Gully (San Andrés) seem to be relatively stabilized by vegetation, but an earthquake after a period of heavy rains might eventually cause landslides of water-soaked soils from the hill slopes to the valley Bottom. The landslide material might form a natural dam that would break when overflowed by the water retained behind. The sudden flood wave would be potentially disastrous to people and buildings at the valley mouth in the Cove Seaside area.

b) Rock falls and collapse of sea cliffs and karstic caves

Rock falls may be triggered by strong seismic shocks. People who live too close to the vertical walls of the two high cliffs of San Andrés (North Cliff, May Cliw) may be at risk from rock falls, as might people in settlements on the foot of steep slopes below mountain peaks at Old Providence. Areas where large fallen blocks are already accumulated are likely to be affected by rockfalls during future heavy quakes.

Collapse of sea cliffs will cause no major damage to property. The recent cliff along the W coast is lined by large blocks that broke off during pre-historic earthquakes and sank to the foot of the cliff. Recently, several meters of cliff broke away at Lynton Rock, SW coast of San Andrés, during the 1995 earthquake (see Field Stop A8).

Prehistoric collapses of karstic caves are known from Miocene and Quaternary carbonates of San Andrés, where they form "sinkholes" today. There will be only slight risk to buildings that may have been unknowingly built on the roof of such caves.

c) Possible damage to large freshwater reservoir at Old Providence

If the concrete wall of the water reservoir ("Represa") at Providencia should not be earthquake-proof, it might possibly burst as a result of seismic shock. This would cause a major catastrophe for people and buildings established near the mouth of the stream valley at Freshwater Bay. Its estimated maximum content of 180,000m3 of fresh water and mud would suddenly rush down-valley and empty into the sea.

7.3 Tsunamis

Tsunamis are huge impulse-generated ocean waves produced by submarine earthquakes, landslides, rock falls, major turbidity currents, or volcanic eruptions. They have sufficient energy to travel across entire oceans. In the open ocean, they proceed at jet speed with a period between 15 and 60 minutes. The waves have a very small (a few cm to dm) amplitude in the open sea when traveling above oceanic depths, but their amplitude may reach enormous dimensions as soon as the waves enter shallow water.

In shallow water, tsunamis diminish in speed, steepen, and increase considerably in height so that low-lying areas may be inundated. Waves rising to 30 m in front of the coasts have been observed at several occasions in the Indo-Pacific (González 1999). The first recognizable signs of an approaching tsunami are the withdrawal of water from the reefs and from coastline during the approach of the wave trough preceding the first wave. Often, the first three of the tsunami waves show a progressive increase in height.

Tsunami run-up distance and elevation also depend on island size and Bottom topography. Focusing and spreading of tsunami energy and amplitude occur in response to shelf topography and shoreline configuration. In narrow inlets and fjords, the amplitude of the waves may multiply by a funniveling effect. Where narrow shelves surround an island, the run-up heights are likely to be greater than on wider shelves. In the latter case, considerable energy dissipation will occur as a result of shoaling over a wider approach area (Maul et al. 1996).

The highest tsunami waves suggested by geological evidence in the Hawaiian Islands ran up the slopes of the mountains for more than 200 m. These occurred in prehistoric times some 100,000 years or more years ago, when parts of these volcanic islands broke off and slid into the deep sea. The recurrence time for such extreme events in Hawaii is thought to be on the order of 100,000 years (Knight 1999).

7.3.1 Tsunamis in the Caribbean Sea

Though tsunamis and related geological effects were best studied in the Pacific (Bourrouilh-Le Jan & Talandier 1985; Rodríguez 1999), they are also recorded from the Atlantic and the Caribbean Sea. The town of Lisbon was destroyed by a large tsunami following an earthquake in 1755. 2m high waves from this remote transatlantic event were recorded at Antigua and Barbados in the Lesser Antilles, as were "waves high as houses" in Martinique (Mau.1 et al. 1996).

The sudden destruction and submergence of Port Roya1 (Jamaica) during the 1692 earthquake was accompanied by waves in the inner harbor up to 2m high. There is also a report of a 1- to 2 m-high tsunami at the north coast of Jamaica following the 1907 earthquake. There are also several tsunamis on record from the Virgin Island area (Maul et al. 1996). The Caribbean coasts of Panama and Costa Rica repeatedly suffered from tsunamis with wave heights up to 6.1m. The last tsunamis in April 1991 had run-up heights of 2 to 2.5m on the beaches (Camacho 1994). The Panamanian and Costa Rican tsunamis originated from earthquakes in the North Panama Deformed Belt. For a detailed of Quaternary Caribbean palotsunamis see Scheffers (2002).

7.3.2 Tsunami threat in the Archipelago?

There is no record of any tsunami which affected the Archipelago in historical time. However, the biggest limestone blocks washed inland from the coastal cliff along the unprotected west coast of San Andrés might stem from tsunamis rather than hurricane waves. The huge blocks on the reef flat of Roncador were also most likely deposited by tsunami waves.

In the Archipelago, easterly coasts of both islands will be relatively protected from tsunamis by coral reefs. These will serve as natural wave breakers, especially where shallow reef flats are broad and the reefs are separated from shore by a wide lagoon. In these cases, less wave effect may be experienced along the coastline. The low-lying land areas and the land not sufficiently protected by coral reefs would be most affected by tsunamis. These areas might be completely inundated by waves. The most heavy inundation from E-approaching tsunami waves may be expected at San Andrés, specifically in the low-lying land along the SE coast, which barely rises above sea level and is protected only by a narrow nearshore fringing reef and a low beach ridge.

The island capital of North End is protected from approaching waves by the wide windward barrier reef complex, although some flooding might occur in low-lying sectors of the town due to the periodic rise of sea level during the transit of a tsunami.

Tsunami waves reaching from westerly directions would most seriously affect the unprotected west coast of San Andrés Island, where waves could easily wash over the coastal cliff and run inland far beyond the main road. Blocks of Pleistocene rocks might be torn off from the sea cliff and deposited landward on the coastal terrace. Every nearshore building might be seriously damaged by the waves, including the touristic installations of "La Piscinita" at Poxhole. The northern and southern points of the island are equally high-risk areas, since undissipated waves arrNing from westerly directions would be refracted around them and would thus increase considerably in height. This might cause damage or destruction to the small restaurants established around the " Blowing Hole" near South Point and to part of the hospital complex at German Point in the N.

Tsunami risks will be lower at Old Providence due to its mostly steep coastal profile, the protection offered by the wide shallow barrier reef complex in the E and N, and the fact that settlements were built well above the shoreline. There may be some risk to tourist installations along the unprotected beaches of Freshwater Bay and Southwest Bay and in the immediate harbor area of Sta. Isabel. For tsunami waves approaching from westerly directions, funnelling effects resulting in increase of wave heights might be expected in Aury Channel. They might cause damage to settlements at Sta. Catalina and Jones Point.

The damage would not only be on land, but also in the shallow sea around the islands. Tsunamis cause major destruction to reefs, accumulate storm beaches, and erode loose sediments that may be transported to the outer insular shelf and deep sea. Huge reef blocks may be quarried from the forereef and deposited on top of the reefs, as seen at Roncador atoll. Sandy cays may be destroyed or freshly accumulated, or may just shift along the reef flat or lagoon terrace. Major tsunamis are catastrophic events that can fundamentally reshape smaller islands and the surrounding submarine topography (see also Bourrouilh-Le Jan & Talandier 1985).

The tsunami hazard in the Archipelago stems mainly from possible future earthquakes caused by extension movements in the nearby graben structures, and from compression in the Panama Deformed Belt. Tsunamis disastrous for the Archipelago might also originate from collapsing western Caribbean platform margins or, eventually, from explosive submarine volcanism in the volcanic arc of the Lesser Antilles, almost 2000 km to the E (Maul et al. 1996). Damage to life and property will be due to flooding, to the impact of breaking waves, and to the currents associated with the drawdown. As a general precaution from tsunamis, houses should not be built near unprotected shorelines and or in very low-lying coastal sectors.

7.4 Tilting and sea-level fluctuations at San Andrés

7.4.1 Effects of tilting

Tilting rates of the basement of San Andrés are very low. In the past, uplift rates along the west coast were on the order of a few millimeters per 100 years as indicated by the notches at May Cliff (chapter 6.1.5). Subsidence along the east coast due to tilting seems to be much more rapid, but cannot be quantified because of the lack of corresponding notches. The axis of tilting has a NNE trend similar to the graben structures to the E and W. As mean tilting rates have remained essentially stable since the end of Neogene time, comparable values will have to be taken into account in the near geological future. The resultant relatNe sea-level rise along the east coast will continue to be very low as compared to the present and future eustatic rises caused by the effect of global warming. It is still easily offset by reef growth and beach accretion. This sea-level rise alone will not be a problem for the coming generations.

7.4.2 Holocene sea-level history and short-term prospects

The history of deglaciation of the northern hemisphere is fairly well documented for the Holocene. It is characterized by a period of rather gradual sea-level increase punctuated by three events of catastrophic sea-level rise. Catastrophic sea-level rises in Holocene time were caused by the collapse of the North American and Antarctic ice sheets and the release of huge volumes of subglacial and proglacial meltwater. These massive inputs of ice and meltwater into the ocean drowned reefs and destabilized other ice sheets. The following three catastrophic rise events(CREs) have been documented (see Blanchon & Shaw 1995) by the study of drowned reefs:

* CRE 1 at 14.200 years BP with a 13.5m rise
* CRE 2 at 11.500 years BP with a 7.5m rise
* CRE 3 at 7.600 years BP with a 6.5m rise

Evidence for such dramatic sea-level changes during deglaciation has potentially disastrous implications for the future, so long as the stability of the remaining ice sheets in Antarctica and Greenland remains in question (Blanchon & Shaw 1995). According to others (Bindschadler & Bentley 2002), a sudden flooding of the world's coastal lowlands is not imminent, as the process of shrinking of the West Antarctica ice sheet is much slower than originally suspected. However, other recent field observations suggest that a real risk of Antarctic ice sheet collapse, with a sudden increase in world sea level, must be seriously taken into account for the future (de Angelis & Skvarca 2003).

Part of present and future global warming is due to combustion of fossil fuel. This is the reason for gradual and almost inevitable further melting of the Arctic and Antarctic ice shields, resulting in gradual sea-level rise in the near future. Since about 1900, global sea-level rise has been about 10 to 20cm. In the past 20 years alone, the Antarctic ice shield has shrunk about 6%. As a consequence, world sea level continued to rise at a gradual but accelerated rate. According to the UNEP report published in Shanghai in 2001, scientists now expect a much faster (1.4 to 5.6°C), potentially catastrophic warming of the world climate during this century. As a consequence of this warming, the ice shields in Greenland and Antarctica will continue to melt, and world sea level might rise up to 88 cm above present datum by the year 2100.

7.4.3 Possible effects in the Archipelago

A merely hypothetical, though not impossible, catastrophic rise of several meters in the near future would not be felt as a sudden event in the Caribbean, because it would level out over many years to gradual submergence of insular lowlands of the Archipelago. This would affect part of the terrestrial terrace of San Andrés and the sandy cays of the atolls. At San Andrés, the most serious flooding would be felt in the town of North End, which is built on very low ground and barely rises more than 1m above present sea level. Old Providence has a steep and high coastal profile and an almost complete absence of inhabited lowlands, so not even a sea-level rise of several meters would be disastrous to it. There remains a limited risk of flooding of settlements in Sta. Isabel town and on Sta. Catalina Island.

Sea-level rise will not only reduce the land area; salt-water contamination may also affect the groundwater reserves in low-lying ground. Especially at risk are the fresh-water lerises in sandy beach deposits and the karstic aquifers of the terrestrial terrace of San Andrés. On the other hand, a gradual sea-level rise may be beneficial for further upward growth of many shallow reefs that already reached intertidal level. Water circulation and flushing of restricted lagoons might be enhanced. This would improve the Living conditions of patch reef communities and increase their diversity and productivity.

7.5 Hurricanes and tropical storms

Hurricanes and tropical storms form over warm oceans with a sea-surface temperature of at least 26°C. The geological effect of hurricanes (winds of at least 33m/s) and tropical storms (winds of at least 18m/s) is mostly destructNe and caused by waves, temporary rise of sea level, and torrential rains.

7.5.1 Geological effects of hurricanes

Hurricanes produce huge storm waves that may rip off entire reefs and accelerate coastal erosion along cliffy coasts by breaking off entire ledges and by undercutting cliffs by turbulent movements of abrasive coral shingle. Similar to tsunamis, hurricane waves are capable of tearing off large reef blocks from the fore-reef and of depositing them on reef flats and on coastal terraces. The waves accumulate coral debris and sand on storm beaches and may reshape and form sandy cays and sand spits in shallow water.

The flooding by incoming storm waves may be enhanced by a marked general rise of sea level known as the storm surge. This is caused by low atmospheric pressure in the center of the storm. At hurricane centers in the Gulf of Mexico area, storm surge; up to 6m above normal have been measured. Usually, one or two great surges come in with a rather slow rise. The rising water level during the surge increases the effect of the storm waves, which may be another 5m high.

The hurricane waves and storm surge inundate the low-lying coastal areas, causing salt contamination of agricultural land. High storm waves may run inland in unprotected areas (especially low-lying coastal stretches), causing damage to constructions and loss of human life.

7.5.2 Hurricane threats to the Archipelago

In the past, hurricanes haunted the Archipélago at irregular intervals. The last hurricanes which damaged the two main islands are recorded from the years 1932, 1935, 1961, 1971 and 1988. The whole west coast, the southeast coast, and the northern and southern points of San Andrés Island (where waves might increase considerably in height by effects of refraction) are particularly exposed to these waves. One precaution against the hazards of waves and flooding would be to refiain from construction along unprotected shorelines or at the Bottom of valleys.

Hurricanes are accompanied by extreme rates of rainfall that may cause serious flooding and major erosion in valleys. Landslides may be tiggered on steep unstable slopes, which may block the outflow of waters from valleys, creating a natural dam. This, in turn, will burst suddenly when overflowed, causing a catastrophic flood downvalley. Such an event in the Archipelago seems conceivable only in Duppy Gully (San Andrés), where the valley slopes consist in large part of soft clayey material which eventually might slump when excessively soaked with water and not well anchored by vegetation.

7.6 Erosion and accretion of coastline: past and present

Since the end of the Holocene transgression, coastal recession by erosive undercutting and episodic cliff quarrying during hurricanes, tsunamis and earthquakes (fig. 50) has given rise to the formation of the Holocene -4 m terrace along the cliffy west coast of San Andrés. During the past 3,000 years, the cliff receded at rates ranging from less than lmm to about 100mm/year, depending on local conditions. Highest rates can be observed in front of coastal headlands (May Cliff area, Evans Point etc.), where abrasional Holocene terraces are up to 300m wide. Minimum rates of coastal erosion are found in re-entrant positions which have terraces that are just a few meters wide or which entirely lack Holocene terrace formation, as seen at the coastline immediately to the S of Poxhole. By contrast, the eastern subsiding coast at Cocoplum Bay is growing by beach progradation towards its source area, the shallow windward lagoon. Thus, much of the sediment which is freshly produced in the shallow lagoon is accreted to the low beach ridge along the east coast of the island (fig. 51). At Cocoplum Bay, maximum beach accretion in the Holocene was on the order of 300 m during the last 3000 years, corresponding to a mean yearly rate of 100 mm.

At present, the loss of land along the cliffy western coastline is still balanced by land gain along accretionary beaches in -the E. The Holocene coastline of San Andrés has seen considerable changes in the past as the Holocene sea level gradually approached its present position, and there will be further changes at similar rates in the near geological future.

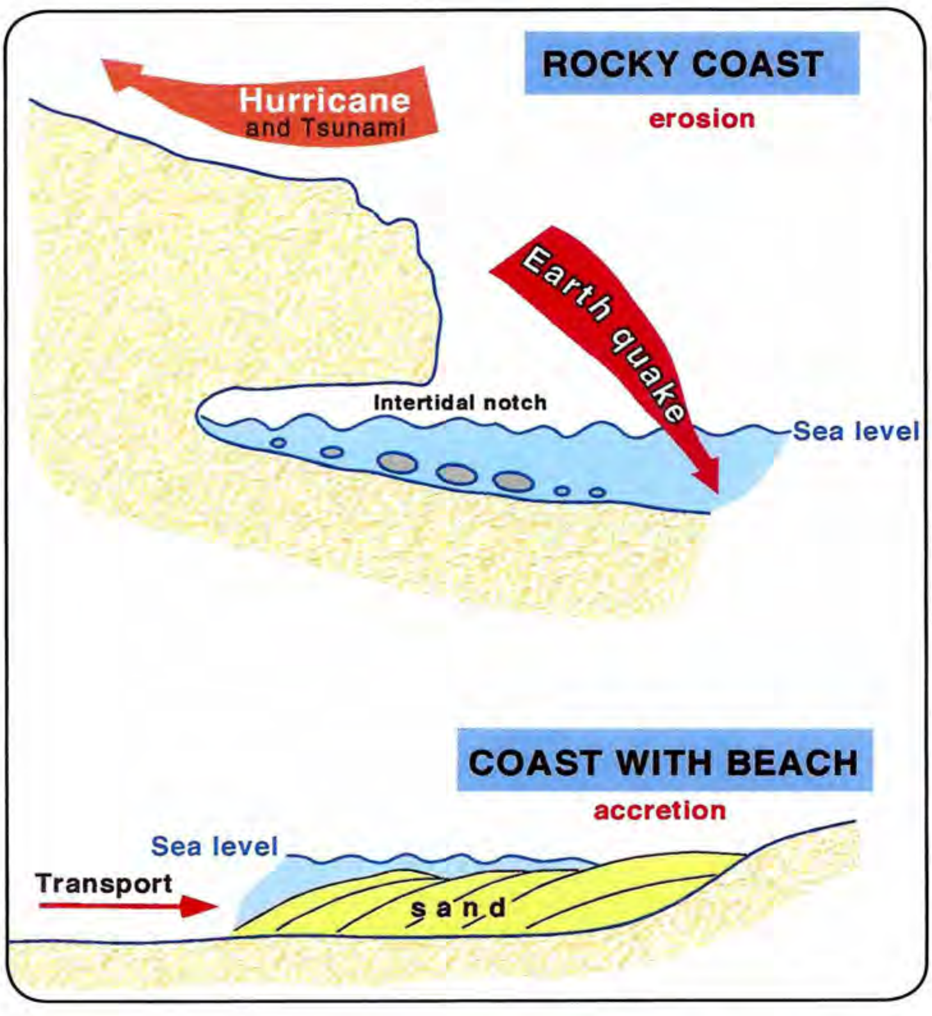


Figura 50. Cliff recession and beach accretion
Above: In the vertical cliff of a limestone coast, bioerosion and abrasion form a deep intertidal notch. The overhanging ledge may be ripped off by hurricane waves or by tsunamis and washed inland. At the unprotected west coast of San Andrés, a number of these blocks, which are several m3 in size, have been found washed inland up to 50m from the cliff edge. During earthquakes, the ledges tend to break off and fall into the deeper water in front of the cliff. Cliff recession rates vary considerably along the same coast line. The coastline at San Andrés has receded up 300m in the last 3,000 years. In these coastal sectors, a wide Holocene -4m terrace was formed.

Below: Since the Holocene transgression, beach accretion has added to the land area. Along the east coast of San Andrés near Cocoplum Bay, land gain was on the order of 300m in the last 3000 years.

8. FIELD TRIPS TO THE ISLANDS AND REEFS

There are more stops described per day than could reasonably be visited with a large group. However, in case of heavy swell due to the strong tradewinds, some of the windward barrier sites cannot be visited without risk. Every field trip participant should protect himself with a broad-rimmed sun hat, a long-sleeved shirt, long trousers, and sunblock. If you don't come with a tropical dive suit, a long- sleeved shirt and trousers should be worn when snorkeling. These clothes will not only protect you against sunburn and scratches by corals, but will also better protect you from hypothermia in the water. Mask, snorkel and flippers are indispensable items for snorkeling. Simple tennis shoes are best for the field trip, especially when wallung in intertidal areas and on sharp Pleistocene reefs. A flashlight may be helpful in caves, and a geological hammer will be useful on, the Miocene and Pleistocene outcrops.

8.1 Visit to San Andrés Island: Holocene, Pleistocene and Miocene reefs and lagoonal environments (Trips A to E)

All the stops on the island are marked in road map fig. 52. Snorkeling sites visited by boat may be easily located by place name using the map of the submarine topography and geology (fig. 15). They are not separately marked on the road map. In addition, it may be helpful to consult the maps reproduced on figs. 21 and 26 for the Pleistocene and recent benthic environments.

Trip A: Bus trip to Quaternary reef/lagoon environments in the S of the island. Synsedimentary extension fracturing: Sangamonian to Holocene (road map fig. 51)

Land Stop AI: Synsedimentary tectonics recorded by Sangamonian lagoon environments at Bungie Point (Fig. 52).

Outcrops in the Sangamon limestone near the seashore show lithified lagoonal mud with queen conch shells and frequent burrows. NW trending fracture clefts are filled with San-

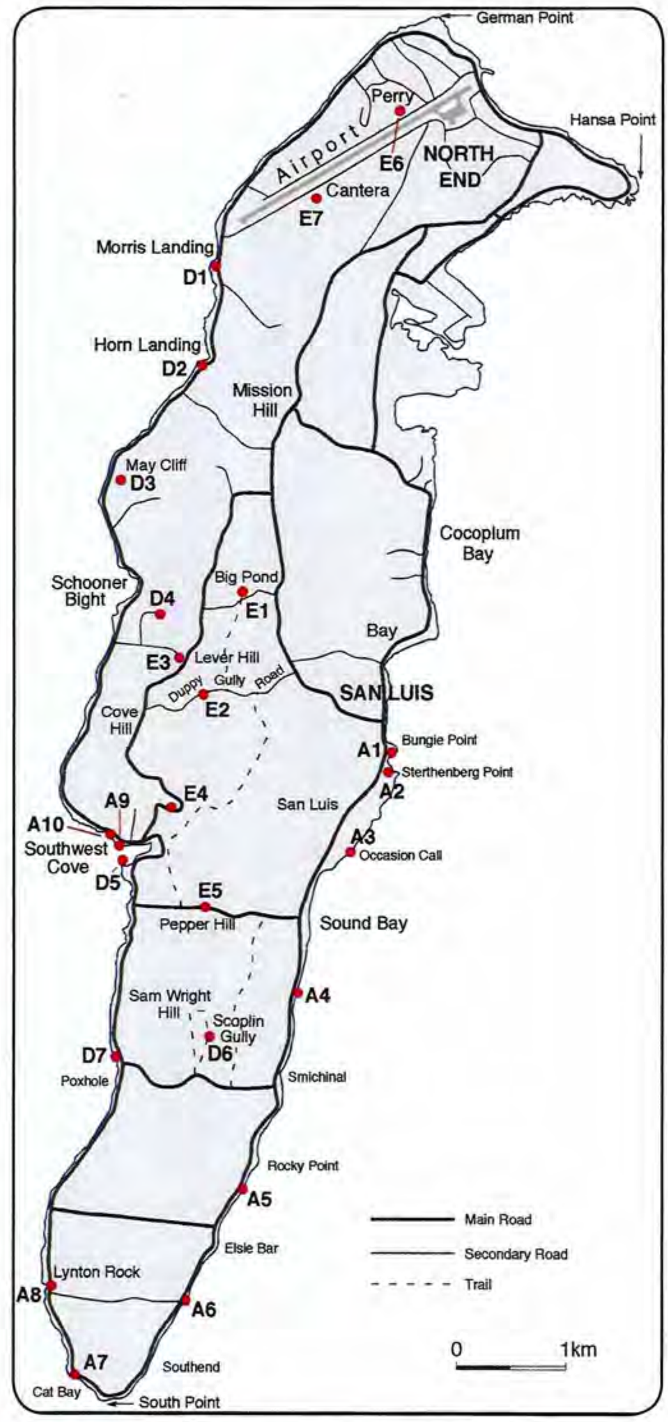


Figure 51. Road map of San Andrés: Letters A to E indicate field trip routes. Numbers mark locations of Land Stops. Sea Stops will be localized on maps figs. 15 and 64 by toponyms.

gamon sediment rich in mollusks. The seashells have fallen in the freshly opened gap during the Sangamon transgression. More than 8 different species of pelecypods and gastropods were encountered in this particular deposit (Geister 1973b). Lithified infill of clefl weathers out as a low ridge.

Figure 52. *Land Stop Al.* Land Stop A1. San Andrés: Bungie Point at San Luís village. Synsedimentary fracture in Sangamon lagoon rocks. Sediment fill of gash bas weathered out as a "sedimentary dyke". Note fragmented corals and Strombus gigas shell. Hammer 32cm. September 11, 2000.

Land Stop A2: Sangamon lagoon and reef environments affected by paleoseisms, between Bungie Point and Sterthenberg Point at San Luis (fig. 53)

Figure 53. *Land Stop A2.* San Andrés: Sangamon reef terrace at Bungie Point at San Luis village. Colony of Diploria strigosa is in an upside-down position. This and other massive coral colonies in that area were probably overturned by seismic shock when the nearby clefts opened. September 5, 2001.

To the N, around Sterthenberg Point, the Sangamonian rocks are mostly lithified lagoonal sediments. The best outcrops are found at or near the seashore. Burrows are locally frequent. The queen conch *Strombus gigas* is common just N of the Yellow Moon restaurant.

Large, isolated, scattered colonies of the brain coral *Diploria strigosa* are common in the lagoonal sediments of the Sangamon terrace. *Acropora palmata* also occurs in this assemblage. Large areas are covered by coral-free sediment. Practically all the hemispherical colonies were embedded in an upside-down position. A large, tumbled pillar coral *Dendrogyra cylindrus* is visible. The corals were probably uprooted by earthquake when the nearby Synsedimentary fractures formed during the Sangamon transgression.

Hemispherical colonies snap off their substratum and are overturned as a result of earthquake shocks (Stoddart 1972). It is unlikely that the corals were transported by storm waves, because in this case skeletons tend to be broken, abraded and piled up.

Land Stop A3: Sangamon fringing reef at the coastline of Occasion Call

Towards the S, at Occasion Call, there is a windward lagoonal fringing reef with an interlocking framework of meter-sized massive brain corals *Diploria strigosa* (fig. 54). The brain corals are associated with the massive star coral *Montastraea* annularis and some branching *Acropora palmata.* Algal crusts up to 10 cm thick coat most corals. Landward, the coral associations become more scattered without forming a framework. Diversity is higher here, and *Acropora palmata* is more common. Many brain corals are found here in a top-down position. Large patches of coral-free sediment are frequent.

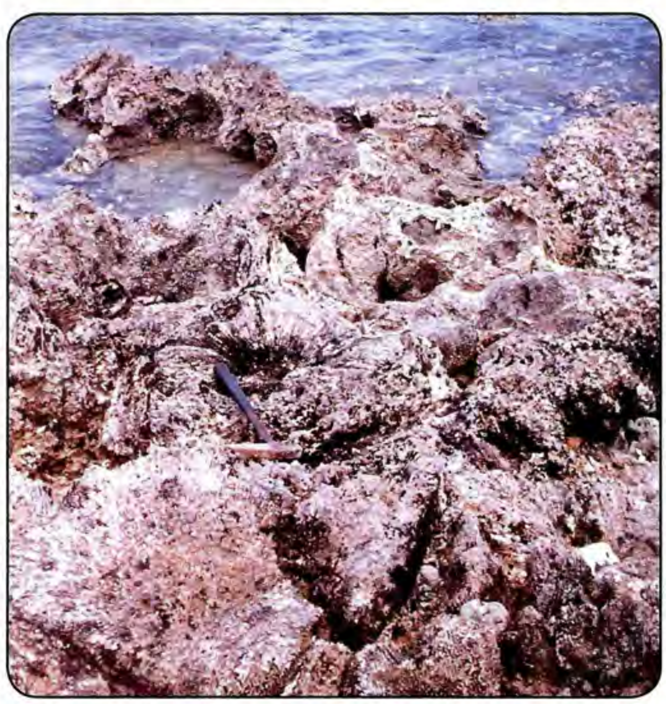


Figure 54. *Land Stop A3.* San Andrés: Dense framework built by massive (up to meter-sized) brain corals (Diploria strigosa) at the coastal cliff near Occasion Call, San Luís. This Sangamon fringing reef was protected by an outer barrier, which is still preserved as the offshore shoal area of Broken Ground. Summer 1969.

Land Stop A4: Recentfringing reef and boat channel between Sound Bay and Smichina

The boat channel of the reef narrows and shallows considerably from Sound Bay to Smichinal. The snorkeling site is to the N of Smichinal. The sandy shore is lined by beachrock. The bottom of the narrow boat channel (1 m deep) is covered by coral fragments or densely overgrown by thickets of *Acropora palmata,* many of which reach lowtide level. The landward rim of the fringing reef itself lies only 0.6m deep.

It is overgrown by a pavement of *Porites astreoides* and *Diploria clivosa*, with a few *Acropora palmata*.

A framework of *Millepora* and large heads of *Diploria strigosa* dominates the surf zone on the reef crest. The seaward margin of the reef crest is hardly colonized by corals. Because of breaking waves on the very shallow reef crest, we cannot swim to the fore-reef. The latter will be visited from boat at another occasion (see Stop C2). A complete section of this reef is described and figured there.

Land Stop A5: Pleistocene reef rock dissected by latest Wisconsinan and Holocene extension fractures, between Rocky Point and Elsie Bar (fig. 55)

Figure 55. *Land Stop A5.* San Andrés: Seashore S of Rocky Point. Holocene fracture is cutting through Sangamon terrace. The cleft is filled with loose sediment, and its upper surface was polished by shingle during storms. No coating by speleothem is observed. This site lies just in front of Bocatora Hole, a collapsed platform margin some 200m seaward from here. Hammer (32cm) for scale. September 13, 2000.

Shoreline outcrops halfway between Rocky Point and Elsie Bar reveal two beautiful tectonic fractures with clefts not filled by speleothem. Immediately to the N of Elsie Bar, there are some gashes partly filled with red soil. The walls of other clefs are coated by thin calcitic crusts. All these extension gashes are part of the early Holocene fracture system that caused the collapse of the shelf margin at nearby Bocatora Hole, just 200 m offshore (see fig. 55). The very young age of the fracturing is inferred from the fresh aspect of the cracks and the absence of both speleothem fill and widening of clefts by freshwater solution.

Land Stop A6: Pleistocene reef rock dissected by Late Wisconsinan fractures (fig. 56)

Four gaping cracks in the Sangamon reef rock crop out along the seashore, just at the branching-off of the small dust road that connects with the west coast at Lynton Rock. There is very incomplete speleothem fill on the faces of the clefts, suggesting a late Wisconsinan age of the fracturing.

Land Stop A7: Sangamonian leeward fringing reef environments at Cat Bay (fig. 57)

Figure 56. *Land Stop A6.* San Andrés: East coast near South End. Cleft of extension fracture, probably of late Wisconsin age, in Sangamon reef terrace. More resistant speleothem encrustations on both sides of cleft stand out after general lowering of limestone surface by rain dissolution. Hammer in cleft 32cm. September 12, 2000.

A beautifully preserved, dense framework of a diverse reef coral fauna dominated by *Montastraea* spp forms the shoreline. This association is characteristic for protected leeward environments. It corresponds to the front annularis zone of the leeward fringing reef.

Looking to the N from this site, we view the characteristic morphology of the San Andrés west coast: a wide emergent Sangamonian reef platform and the high escarpment of May Cliff, which was cut into the Miocene rocks of the Hill by a Middle Pleistocene transgression.

Land Stop A8: Lynton Rock. Collapse of the recent coastal clgSrby seismic shock. Storm blocks and storm beach (figs. 58 and 59)

At the southern shore of the small inlet at Lynton Rock, an overhanging ledge broke off during the May 1996 earthquake. It sank to the inner margin of the -20m terrace at about 6 to 8m of water depth (fig. 59). Numerous large blocks are lining the foot of this cliff along the west coast, testifying to past quakes.

Figure 57. *Land Stop A7.* Land Stop A7. San Andrés: Sangamon reef terrace at Cat Bay. Large colonies of columnar *Montastraea* sp. weathering out on the reef flat. August 29, 2000.

Figure 58. *Land Stop A8.* Land Stop A8. San Andrés: Lynton Rock. The overhanging ledge of this recent coastal cliff broke off as a result of earthquake shock in 1996 and sank to the bottom of the –20m terrace. August 24, 2000.

About 10 to 20 m from shore, a dozen cubic-meter limestone blocks from the same cliff section are dotted on land around the inlet. These were torn off from the cliff by hurricane waves and/or tsunamis and washed inland (fig. 56).

Beyond the road, the storm beach can be seen. It is composed of a mixture of coral shingle and sand deposited during hurricanes. The storm beach can be followed all along the west coast. Mostly, it forms the natural basement of the present coastal road.

Figure 59. *Land Stop A8.* San Andrés: Lynton Rock. Storm blocks torn off from ledge above the notch of the recent sea cliff. Waves washed most of the blocks more than 10m inland on the Sangamon reef terrace. There are 12 blocks more than 1m3 in size dotted around this particular inlet. August 24, 2000.

Land Stop A9: Weathered out speleothem "dyke ", probably of Early Wisconsinan age, at Cove Seaside (250 m W of road junction) (fig. 60)

The conspicuous NW-trending white "dyke" beside the wall of an unfinished building can be easily spotted from the main road. It is just opposite the northern point of the Cove peninsula. The dyke is about 10 m long and 10 cm thick and stands out for about one meter above the general surface of the Sangamon bedrock. This is the weathered-out speleothem fill of an old extension clef in the Sangamon reef rock. The fracturing must have occurred in early Wisconsinan time to allow time for the complete filling of the wide clef by speleothem calcite and the subsequent general lowering of the surrounding platform surface by differential limestone dissolution.

Land Stop A 10: Sangamon leeward fringing reef environments at Morgan 'S Jump, Southwest Cove (450m W of road junction) (figs. 61 and 62)

The outcrop is located on the high, steep sea cliff at this popular bathing site. The Sangamon coral fauna is dominated by the staghorn coral *Acropora cervicornis,* but it includes also brain corals (*Diploria* spp.), *Montastraea annularis,* and organ-pipe *Montastraea* sp. This association characterizes the leeward fringing reef crest of San Andrés (figs. 21 and 22).

It will be noted that all the staghorn corals Acropora cervicornis are broken and out of life position (fig. 62). The reason for the breakdown of corals may be storm impact, earthquake shocks, or just natural breakdown of older colonies in an environment of low sediment accumulation rates. As the fragments are neither abraded nor piled up and don't show a preferred orientation which might be indicative of

Figure 60. *Land Stop A9.* San Andrés: Coastal terrace at Cove Seaside immediately N of harbor entrance. "Speleothem dyke" of early Wisconsinan extension fracture weathered out from Sangamon limestone. It probably formed in early Wisconsin time by tectonic fracturing and was subsequently filled with speleothem encrustations which weathered out when the general land surface was lowered by subaerial limestone dissolution. September 1, 2001.

Figure 61. *Land Stop A 10.* San Andrés: Sea cliff outcrop in Sangamon reef terrace at Morgan Jump, Cove Seaside. Colony fragments of Acropora cervicornis are neither rolled nor oriented. They suggest breakage of thicket by earthquake shock rather than storm impact. Red pocket knife (8cm) for scale. September 1, 2001.

storm waves, it is believed that the breakage is rather due to earthquake shocks.

A conspicuous discontinuity is seen in the outcrop. Some corals from the rocks below the discontinuity continued growth through the discontinuity (fig. 63). This same discontinuity, or a similar one, may be seen in the cliff all along the west

Figure 62. Land Stop A 10. San Andrés: Cliff outcrop at Morgan Jump, Cove Seaside. Disconformity in reef limestone of the Sangamon leeward fringing reef. This same disconformity is visible in the cliff face along much of the west coast. It documents a temporal change or interruption of the sedimentation regime. Note that a few columnar corals (Montastraea sp.) grew across the discontinuity. September 1, 2001.

coast of the island. Its origin is not clear but could be due to a brief change in the sedimentation regime during the Sangamon transgression.

Trip B: Boat trip to the northern sector of the Holocene reef complex (for location, see
maps on figs. 15 and 61)

Sea Stop B1: Windward barrier reef of "Big Reef" near "Johnny Cay" (fig. 64)

The low-lying reef crest and lagoonward grooves (surge channels) in Big Reef permit rapid ovefflow of surging waves into the northern lagoon. The reef framework of barrier and adjacent patch reefs on the lagoon terrace is dominated by *Millepora* spp. The fore-reef terrace and fore-reef slope are devoid of dense coral growth and formed mainly by a carbonate hardground abraded during storms.

Nearby Johnny Cay is a true sand cay without outcrops of any Pleistocene basement. Its beaches to the W, N and E are lined by Holocene beach rock.

Sea Stop B2: Algal ridges at "Top Blowing Rock" and "Table Rocks" (fig 63 and 65)

Heavy surfat Top Blowing Rock results from interference between refracted wave trains that approach from the NE and NW. A rocky shoal causes refraction immediately to the N of Top Blowing Rock. The intertidal reef crest of Top Blowing Rock is a true algal ridge formation built by heavy encrustations of red algae. Well-developed grooves and spurs on the fore-reef slope are directed to the NW. Bottom Blowing Rock to the S is a less well-developed nearby algal ridge. The northern extension of the leeward barrier reef forms the basement of both algal ridges. The two sites are accessible only during very calm seas.
The Table Rocks (Geister, 1983: fig. 15), two isolated pinnacles to the E of Top Blowing Rock, are heavily encrusted by red

algae on their tops. The western pinnacle has a mushroom-like head of algal rock that gives it a table-like appearance. The rocky basements of both the Blowing Rocks and the. Table Rocks appear to be erosional relics of a Pleistocene cliffline underlying both Big Reef and the leeward barrier. This is suggested by a deeply incised drowned notch at the -8m level. The same notch can also be traced all along the west coast.

Note that Top Blowing Rock forms the northernmost prolongation of the old pre-Sangamon cliff that can be followed in front of the west coast of the island and projects to the N from the island (fig. 24). This cliff was overgrown by the Sangamon barrier reef, which forms the basement of the modern algal ridge. Clefts of tectonic fractures are

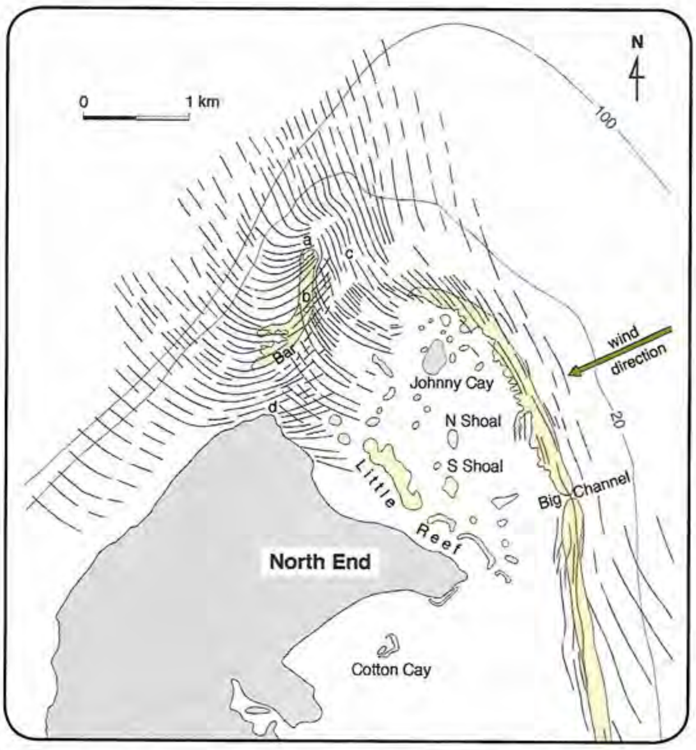


Figure 63. Sketch map of northern part of the San Andrés reef complex showing distribution of reefs in relation to predominant wave direction. (a) Top Blowing Rock, (b) Bottom Blowing Rock in the leeward barrier ("Bar"), (c) Table Rocks, (d) German Point.

Sea Stops **of Trip B** are Big Reef (B1), Top Blowing Rock and Table Rocks (B2), and the leeward barrier of Bar (B3). Adapted from Geister (1983).

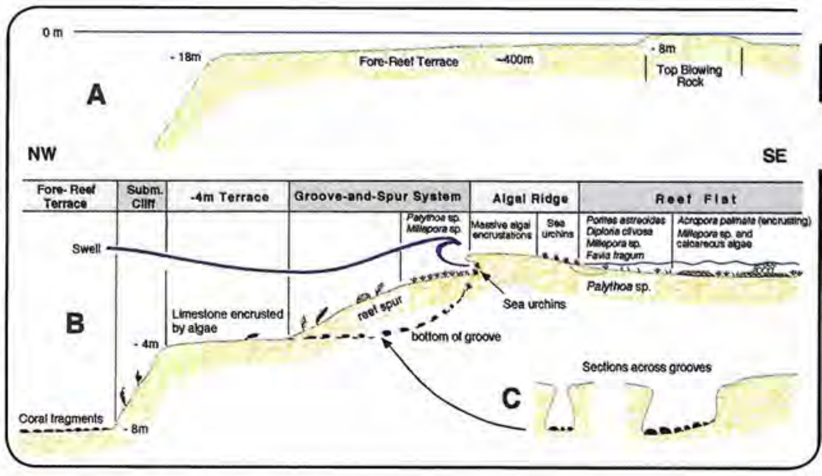


Figure 65. *Sea Stop B2:* San Andrés. Sections across Top Blowing Rock.
A) Topographical section across fore-reef terrace, lagoon terrace, and outer slope. No vertical exaggeration.
B) Geomorphological and ecological features of the reef barrier at Top Blowing Rock: a distinct algal ridge at the outer margin of the reef flat, a -4m terrace in the fore-reef area, groove-and-spur system, fore-reef terrace.
C) Grooves in transverse section. Note cobbles and pebbles at bottom

visible in the whole area. Huge block of Pleistocene bedrock are quarried during storms just to the N of this site, following the tectonic cracks. Around the rock and in the nearby area, the pre-Sangamon -8m terrace level of the inner margin of the -20 m terrace is well represented. The corresponding -8m notch, which is known from all along the west coast, was cut into the basement of the Blowing Rock and the table rocks.

Sea Stop B3: Leeward barrier reef "Bar"

The fore-reef slope is dissected by wide grooves that lead down to the sandy fore-reef terrace in its lee. The reef crest is dominated by Acropora palmata. The fore-reef slope is overgrown by a calm-water community of *Montastraea* spp. The topographic base of the reef is a northern extension of the truncated Pleistocene fringing reef of the west coast (fig. 66).

A strong current leaves the lagoon between German Point and the leeward barrier. During storms, the current carries fine suspended sediment from the lagoon to the fore-reef

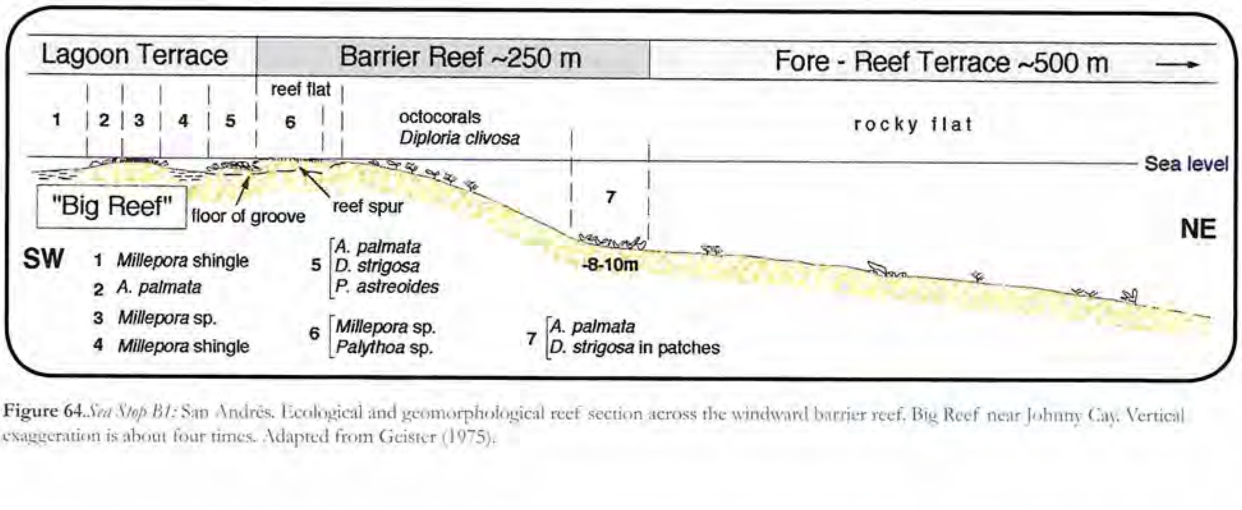


Figure 64. *Sea Stop B1:* San Andrés. Ecological and geomorphological reef section across the windward barrier reef. Big Reef near Johnny Cay. Vertical exaggeration is about four times. Adapted from Geister (1975).

terrace (-20 m terrace) and the adjacent outer slope, where it settles to form a large sediment apron

Sea Stop B4: Shallow lagoonal patch reefs to the S of Johnny Cay

The reef flats of both patch reefs (North Shoal and South Shoal) are about 1-1.5 m below surface and dominated by Acropora palmata thickets that are almost entirely dead today. In the NE corner of South Shoal, a young *A. palmata* thicket, 10m in diameter, was flourishing in 1993-2001. It was vigorously spreading over the surrounding dead reef framework, indicating that the conditions that led to coral death (presumably bleaching) do not persist. At North Shoal, a few isolated colonies of *A. palmata* were alive in 1993 but affected by the White Band Disease. Living *Acropora cervicornis* colonies were extremely rare around the shoals in 1993, though their debris was ubiquitous.

Sea Stop B5: Shallow lagoonal fringing reef at Cotton Cay (fig. 69)

An almost monospecific rigid framework of Porites porites near low-tide level forms a distinct windward reef fringe. The branching melobesioid red alga Goniolithon strictum is quite common in the framework and on the wide intertidal reef flat, where sparse seagrass growth is common. Large Porites astreoides form a discontinuous belt at the outer margin in water about 0.7 m deep. Lush growth of Thalassia testudinum in the lagoon surrounding the reef forms a dense seagrass bed at a depth of 0.7 to 1 m.

The islet of Cotton Cay itself is a Sangamon coral patch that rose above the surrounding contemporaneous lagoon floor. The frame-building species was Acropora cervicornis.

Trip C: Full day boat trip to eastern sector of reef complex (map fig. 15)

Sea Stop C1: Vertical drop-off Bocatora Hole (figs. 69 to 73)

Bocatora Hole is the local name for a submarine rock wall which resulted from collapse of the shelf margin. It may be visited by snorkeling along the outer rim of the insular shelf. The outer edge of the fore-reef. Terrace is very shallow here. It forms a half-circle with a minimum water depth of 5 m at its innermost margin. The seaward drop-off is a sudden vertical precipice down to at least 200 m of water depth (fig. 69). Note the poor coral overgrowth on terrace and cliff wall. The clefts at outer edge (fig. 70) are NNE trending tectonic fractures. Bocatora Hole probably formed during earthquakes when the steep, unstable platform margin collapsed as a result of latest Pleistocene or early Holocene fracturing.

Sea Stop C2: Seaward fringing reef S of Sound Bay (fig. 74)

The windward fringing reef of San Andrés parallels the SW coast of the island. The reef segment to be visited is bordered by two reef passes: Big Channel in the N (off Sound Bay) and Smichinal ("Smith Channel") in the S. The boat channel environments and inner margin of the reef crest have already been described as Land Stop A4.

The fore-reef slope descends from the crest to about 8m of water depth. It shows poor and discontinuous growth by mostly encrusting scleractinians such as *Diploria clivosa*, *Millepora* sp., and *Porites astreoides*, with a few *Acropora palmata*, large heads of *Diploria strigosa*, and octocorals. There is no spur-and-groove system. The fore-reef terrace dips gently from the indistinct base of the fore-reef slope at -8m to the steep drop-off at its outer edge at 18 to 20 m water depth. Coral growth is extremely poor, except at the outer terrace margin, where patches of Porites porites and Montastraea annularis occur. The terrace surface itself shows traces of abrasion, which are well recognizable after storms.

The upper part of the outer slope is mostly a very steep drop-off with rich growth of massive scleractinians and octocorals. It ends at -35 to 40 m in a narrow, clear, sandy terrace which is barely visible from the surface. In some places, the slope is less steep and is covered by fine sediments, which were probably transported and deposited by rip currents during storms.

Sea Stop C3: Windward barrier East Reef (see fig. 75) and visit to the islet of Haine Cay

A beautiful groove-and-spur system occupies the fore-reef area near Haine Cay. The main spur builder is *Millepora* spp., with local *Acropora palmata* patches near the base of the spurs. The continuous shallow reef flat of the barrier emerges during spring low tides. Mitchel Hole, N of Haine Cay, is a narrow pass for small boats across this sector of the barrier. Haine Cay is formed by low-lying Sangamon coral limestone and covered by sandy Holocene storm deposits. The facies of the limestone indicates a shallow lagoonal patch reef environment with *Acropora cervicornis* thickets.

Sea Stop C4: Shallow patch reef of "Dry Shoal"

This coral patch lies in the eastern lagoon basin, well sheltered by the shallow barrier of East Reef. The framework is formed by lush growth of *Porites porite*s at -1.5m water of water depth. In June 1993, several long-spined sea urchins (*Diadema antillarum*) were seen in the framework, including one dense cluster of 6 specimens. Such a concentration has not been observed elsewhere around the island since the dramatic die-off of this species in 1983/84. The reef was equally flourishing in 2000 and 2001, with *Diadema* even more frequent.

Sea Stop C.5: Lagoon terrace and sand cliff near "Rose Cay"

Rose Cay ("El Acuario") is a small sand spit formed on the lagoon terrace by sediment which was carried and depos-

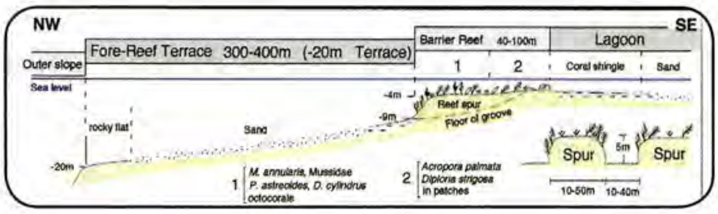


Figure 66. *Sea Stop B3.* San Andrés: Ecological and geomorphological section across the leeward barrier reef NW of the island ("Bar"). Transverse section across grooves and spurs. Vertical exaggeration is approximately 4x. Adapted from Geister (1975).

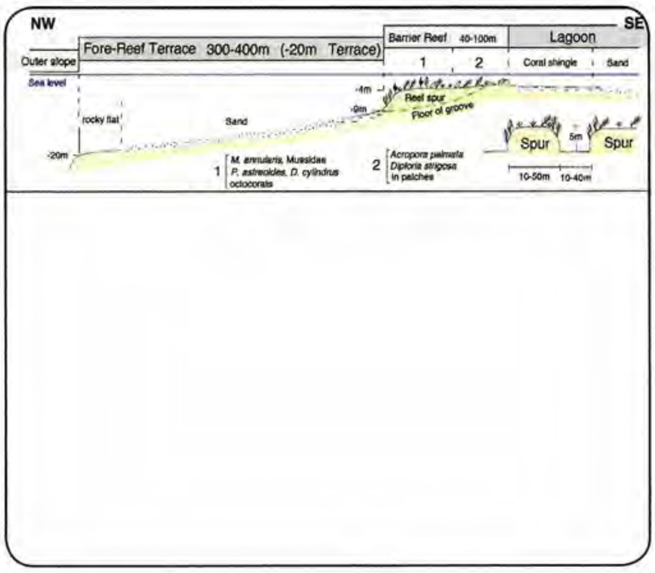


Figure 67. *Sea Stop B3.* San Andrés: Point Channel between Bar and German Point. Fine sediments, stirred up by heavy waves in the lagoon, fall out from currents that transit the shallow lagoon to the island shelf. The fines are deposited in deeper water, mainly on the fore-reef terrace and on the outer slope lying to the NW of German Point. Schematic.

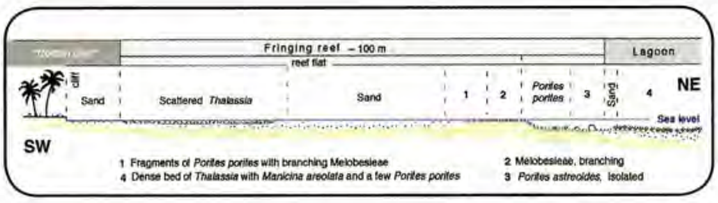


Figure 68. *Sea Stop B5.* San Andrés: Ecological and geomorphological section across the lagoonal fringing reef at Cotton Cay. Vertical exaggeration is two times. Schematic. Adapted from Geister (1975).

ited by converging wave trains refracted around Haine Cay. Beachrock is conspicuous along its shoreline.

During storms, sand and coral debris are washed from the reef onto the adjacent lagoon terrace, where they are deposited as a zone of coral shingle and as sand aprons. Finer sediments are moved by waves towards the drop-off to the lagoon basin, where they are deposited in the natural angle of repose as a sand cliff (fig. 9). See also Geister (1983: fig. 31).

Trip D: Full-day bus trip to see Pleistocene and Holocene leeward reef environments, sea level stands, and Miocene reef environments (maps figs. 15 and 51)

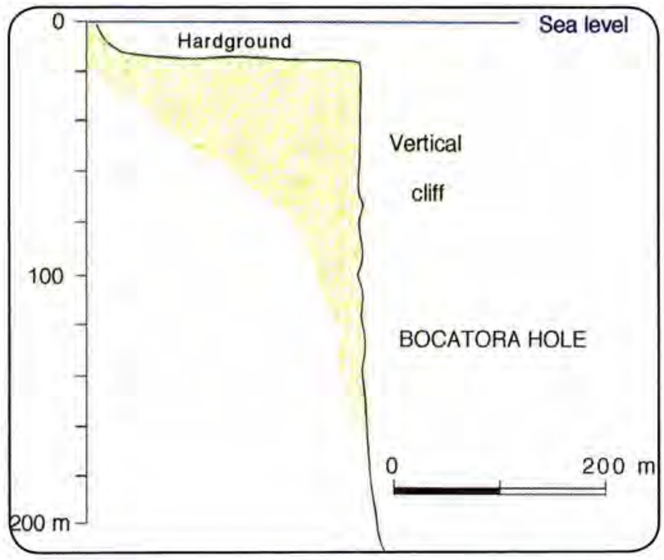


Figure 69. *Sea Stop C1.* San Andrés: Schematic section through the vertical submarine drop-off at Bocatora Hole. It is believed that this extremely high vertical limestone wall formed probably in early Holocene time by gravitational collapse of the unstable margin of the fore-reef terrace.

Land Stop DI: Huge Pleistocene block and leeward Sangamon fringing reef environments, S of Morris landing former trash dumpsite). (fig. 76)

The Pleistocene coastal terrace seen from the main road projects seaward just S of Morris Landing. A huge storm block has been deposited here by waves 12 m inland from the modern coastline and at least 2 m above modern sea level. The block has the shape of a rather regular trapezoid, with side lengths of 4 m, 2 m, 4 m, and 4 m, and a thickness that varies between 50 and 100 cm. The block was torn off from the nearby cliff by a high-energy event (tsunami or hurricane) and deposited in an inverted position on the coastal terrace. Its estimated volume is $9m^3$. The Pleistocene corals, embedded in a Living position, appear upside-down in the block. The present upper surface of the block shows signs of advanced karstic erosion. Limestone solution by rain lowered the general surface of the terrace around the block, leaving the block on a low "pedestal" about 10cm high. Known limestone solution rates in wet tropical climate suggest that the block was placed on this spot several thousand years ago.

A beautiful 20 m-diameter thicket of the moosehorn coral *Acropora palmata* weathered out from the Sangamon limestone about 200 m towards S at the former dumpsite. It is surrounded by a coral facies dominated by the staghorn coral Acropora cervicornis, which is common elsewhere on this leeward reef terrace. The *Acropora palmata* colonies are notable for their unusually thick branches, which are more than 40 cm in diameter. The nearby vertical cliff section at the N side of a small inlet shows a distinct horizontal discontinuity in the coral limestone, similar to that seen at Field Stop A10.

The cliff face and nearshore terrace are beautifully wave-polished at the dumpsite by a shingle of broken glass bottles. Thus, the internal structure of the rock can be studied in great detail. *Acropora cervicornis* is the dominating species in

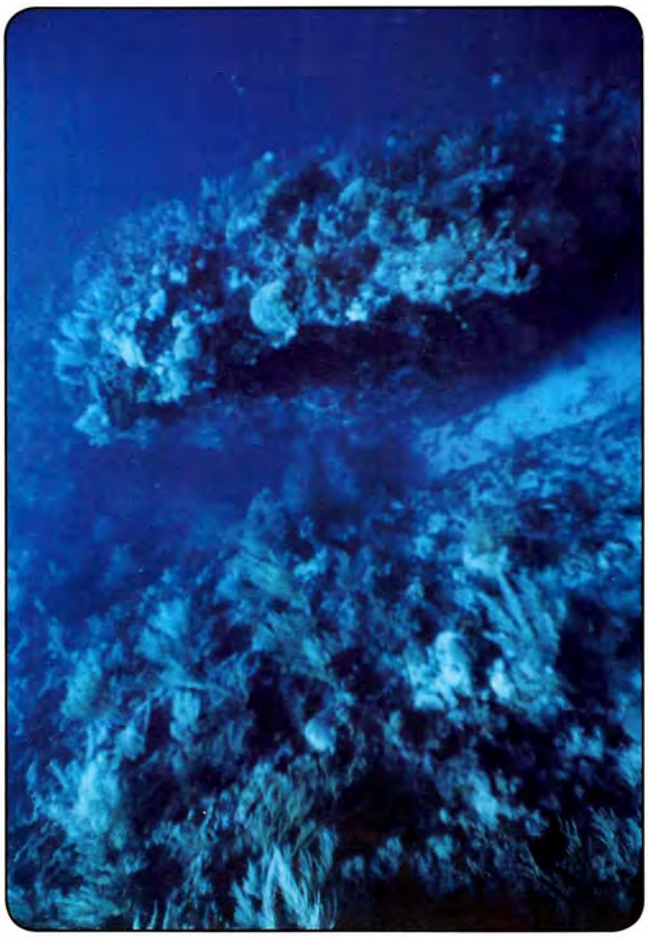


Figure 70. *Sea Stop C1.* **San Andrés: Vertical NNE-trending open cleft at outer shelf edge at Bocatora Hole. Water depth -8m depth. This is one of the extension fractures that resulted in the collapse of this platform margin. June 17, 1996.**

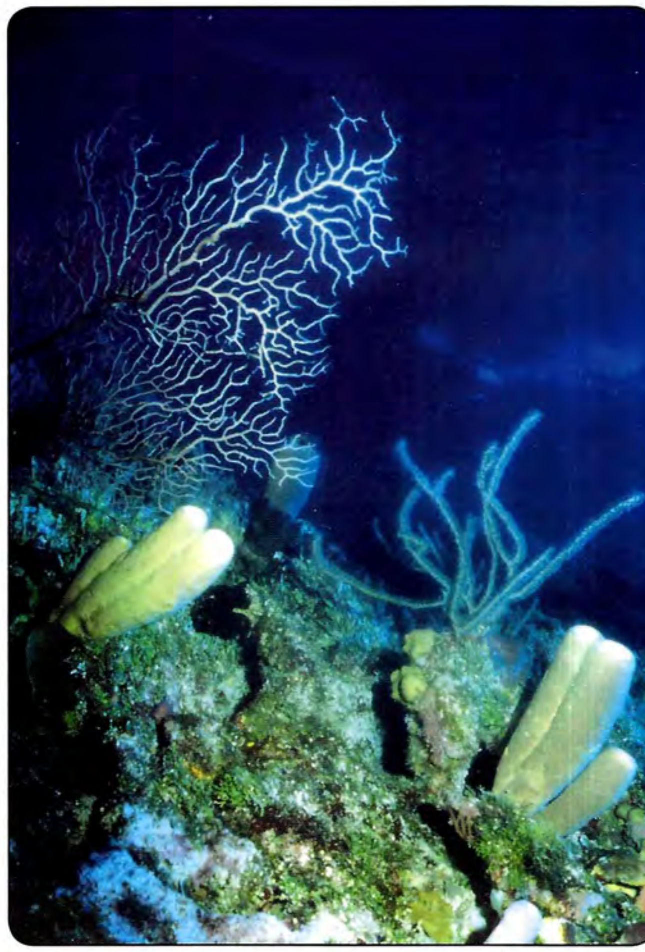


Figure 72. *Sea Stop C1.* San Andrés: Vertical wall of Bocatora Hole at about 40m of water depth. Sponges and branching octocorals are shown with some green algae of the genus Halimeda. August 26, 1998.

Figure 71. *Sea Stop C1.* San Andrés: Vertical wall of Bocatora Hole at 30m of water depth. The star coral *Montastraea* sp. adopted a platy growth habit. Note branching octocorals in background. August 26, 1998.

Figure 73. *Sea Stop C1.* San Andrés: Proliferation of the green alga *Halimeda* sp. on the vertical cliff wall of Bocatora Hole. Sponges at center of picture. About 45 m of water depth. August 26, 1998.

the outcrop. The *cervicornis* colonies are not in Living position but broken. Taphonomic evidence suggests that fragments were not transported and piled up by storm waves. It appears that, similar to Stop A10 (Morgan Jump), earthquake shocks are responsible for the breakage.

Some 200 m to the S of the dumpsite, there is another superb thicket of *Acropora palmata*. The corals have weathered out beautifully in relief on the terrace surface (fig. 77). Both N and S of a nearby embayment, we may examine several large "organ-pipe" *Montastraea* sp., an as yet undescribed

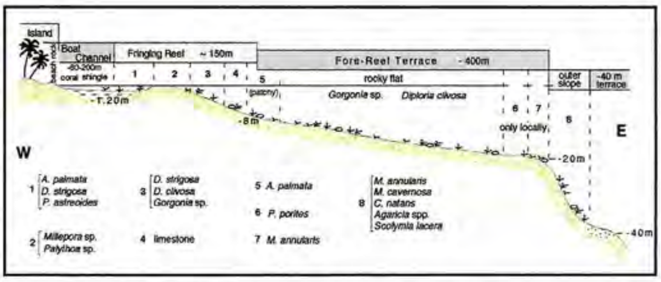


Figure 74. *Sea Stop C2.* San Andrés: Ecological and topographical section across the seaward fringing reef lining the SE coast between Sound Bay and Smichinal. Vertical exaggeration is about 4x. Adapted from Geister (1975).

scleractinian species which is not known from the Holocene (Pandolfi et al. 2001).

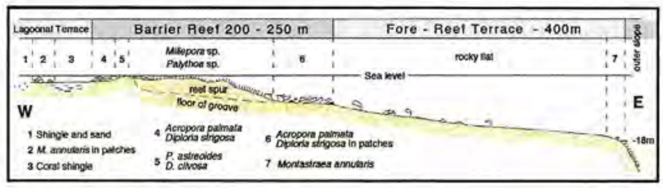
Land Stop D2: Horn Landing. Sangamonian leeward reef facies

Near the northern cliff of the small inlet, a few well-preserved colonies of "organ-pipe" *Montastraea* sp. are seen on the Sangamon terrace. Patches of *Acropora palmata* and organ-pipe *Montastraea* sp. are beautifully exposed along the southern shoreline of the nearby inlet.

Land Stop D3: May Cliff Pleistocene high sea-level stands

This high cliff (fig. 20) consists of Miocene limestone and was shaped by Middle Pleistocene high sea-level stands. It is heavily karstified and encrusted by stalactitic material. The large, gaping intertidal notch at about +13 m is partly filled with broken coral material, sediments, and speleothem deposits. It marks the end of a great Middle Pleistocene transgression (Cromerian age?) which formed the cliff. The cliff wall above the notch is a strongly weathered Miocene lagoonal limestone, yet the wall below the notch is Middle Pleistocene coral limestone (Older Low Terrace Limestone) deposited in and below the large intertidal notch. Rain dissolution has lowered the whole Older Low Terrace surface by at least 4m since emergence. The inconspicuous weathered notches at +18m and +25 m are probably also of Middle Pleistocene age.

Note vertical sections of huge *Diploria strigosa* up to 3m wide in Older Low Terrace Limestone below "Room and Hall Cave" (fig. 78). The skeletons are flattened because the corals lived in the shade of the overhanging lived Large *Acropora*



Figurae 75. *Sea Stop C3.* San Andrés: Ecological and topographical section across the barrier of "East Reef" near Haine Cay. Vertical exaggeration is about 4x. Adapted from Geister (1975).

palmata are seen in this same reef framework in outcrops some 100 m further S.

A horizontal and narrow tunivel, partly obstructed by stalactitic incrustations, leads from the deep Middle Pleistocene intertidal notch into the cliff. It widens to "Room and Hall Cave", a fairly wide karstic cave several meters high which was formed by dissolution along a fracture. Light enters from above along the cleft of the fracture plane. Similar to the modern Blowing Hole at South Point, this cave system probably acted as a blowhole during the +13 m high sea level

Figure 76. *Land Stop D1.* San Andrés: S of Morris Landing. Huge (9m3) limestone block torn off from cliff edge and thrown 15m inland by catastrophic waves and deposited 2m above present sea level. Both tsunami and hurricane waves seem possible agents. Fossil corals indicate that the block is in an upside-down position. Note beginning karstification on upper block surface. Observable lowering of surrounding terrace surface by rain dissolution is 5cm and less. This suggests that the block has been remained in the present position for several thousand years. August 25, 2002.

Figure 77 *Land Stop Dl.* San Andrés: San Andrés: Thickets of Acropora palmata weathering out at surface of Sangamon reef terrace S of Horn Landing. Hammer (32cm) for scale. August 25, 2000.

Figure 78. *Land Stop D3*. San Andrés: May Cliff at Room and Hall Cave. Several flattened *Diploria* colonies up to 2 m in width have grown one on top of the other. "Middle Pleistocene" reef complex. Note +13 m notch at upper margin of picture. Hammer (32cm) for scale. September 13, 2000.

stand, when air and foam were thrown out through the cleft at the terrace above during heavy storms.

Deeper, at about +9 m, the notch of the Sangamon maximum sea-level stand (125,000 years B.P.) is preserved. It is equally filled with lithified coral shingle. The level of the adjacent Sangamonian reef terrace (Younger Low Terrace) has been lowered by about 0.5-1 m by rain dissolution since its final emergence less than 120,000 years ago

A series of vertical fractures dissect the ancient cliff wall. The gaping clefts are similar to those seen at Bocatora Hole (Stop C1). As a result of the fracturing, the cliff is strongly eroded in the fractured zone, which allows ascent to the Lower Middle Terrace (+30 to +40 m). Following this terrace further to the NE, there is a strongly weathered double cliff that forms a distinct step to the Upper Middle Terrace (+55 to +65 m). Both terraces are cut into Miocene limestone. The sediments deposited during their formation are already eroded. The age of both terraces must be early Middle Pleistocene or Early Pleistocene. The Upper and Lower Middle Terraces are considerably older than the notches in the May Cliff wall below.

Land Stop D4 : Schooner Bight Cave. Pleistocene reefji-amework and unconformity

This little-known but good-sized karstic cave near Schooner Bight attained its present shape when the lower part of its roof collapsed and fell into a subterranean lake below the present cave entrance. This unique, freshly exposed outcrop reveals nearly horizontal and vertical sections in the cave ceiling and walls, sill a three-dimensional view of the framework. There are large unweathered in-situ corals of the reef flat that we can examine from below and in vertical sections.

A reddish horizon separates two superposed coral units near the cave entrance. This is a paleosol formed during emergence between successive Pleistocene high stands. The upper coral unit is of Sangamonian age (Younger Low Terrace limestone), while the lower unit is pre-Sangamon (probably Older Low Terrace limestone). Common species in the lower unit are *Montastraea annularis*, *M cavernosa*, *Colpophyllia natans*, *Acropora cervicornis*, and others. To examine the reef rock in this cave in detail, a good flashlight is essential.

Land Stop D5: Thickets of Pleistocene *Pocillopor*a at Southwest Cove

Large colonies of the "Indo-Pacific" reef coral genus Pocillopora are found among coral stands of certain Caribbean affinity, such as *Montastraea annularis*, *Acropora palmata*, *A. cervicornis*, *Diploria strigosa*, *D. labyrinthiformis*, *Colpophyllia natans*, and others. The reef limestone has a Sangamon age (125,000 years B.P.). The best outcrops are along the southern shoreline of the cove and at the northern tip of the small peninsula at the entrance to the harbor.

At present, living *Pocillopora* is only known from the tropical Indo-Pacific. For discussion of the Caribbean-wide occurrence of *Pocillopora* in Sangamonian time, see Geister (1977b, 1984; Pandolfi et al. 2001).

Land Stop D6: Miocene coral communities in Scoplin Gully and on Sam Wright Hill

Coral thickets formed by branching poritids and massive heads of *Montastraea* spp. and *Goniopora* sp., with occasional columnar *Montastraea* sp. (fig. 79), are found on the slopes and the top of Sam Wright Hill. The best section that pennits study of facies relationships is along Scoplin Gully, where numerous heavily altered coral colonies can be seen. A large Strombus sp. the size of the modern Strombus gigas was collected at this location. Patches of large massive scleractinians (*Montastraea, Porites* etc.) are common in poor outcrops on the hilltop. There are no well-developed coral build-ups; rather, there are stratified coral patches that covered the fairly level lagoon floor. This facies, typical for the southern "Hill," corresponds to the shallower marginal part of the lagoon and was rather close to the peripheral reef wall. The strata are visibly dipping E due to the tilting of the ancient atoll. A faunal list of this outcrop is given in Geister (1975: 144).

Figure 79 *Land Stop D6*. San Andrés: Miocene of Scoplin Gully. Large columnar Montastraea sp. The coral has tumbled, but is not broken. July 1970.

Land Stop D 7: Poxhole: Pleistocene reef formation, transgressive reef truncation, and the emplacement of the modern reef complex (figs. 80 and 81)

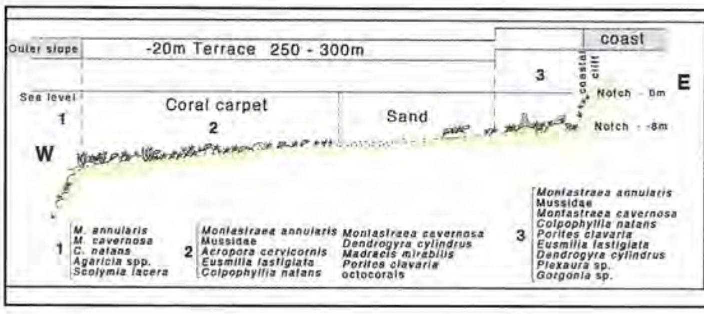


Figure 80. *Land Stop D7.* San Andrés: West coast at Poxhole. Ecological and geomorphological section featuring the -20m terrace and the partly submerged old (pre-Sangamon) cliff wall (Poxhole Cliff) with drowned intertidal notch (at the -8m level). In this particular case, the present coastline is formed by the pre-Sangamon coastal cliff (Poxhole Cliff), which was overgrown by reef framework when submerged during the great Sangamon transgression. Adapted from Geister (1975).

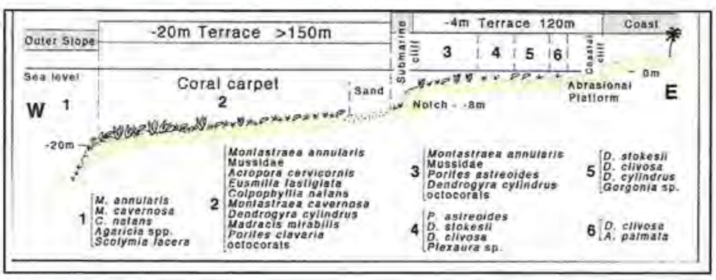


Figure 81. *Land Stop D7.* San Andrés: West coast N of Poxhole. Ecological and geomorphological section featuring the -20m terrace with corresponding drowned intertidal notch (at -8 m). Here the headlands of the pre-Sangamon cliff (Poxhole Cliff) have been truncated since the end of the Holocene transgression, forming the -4m terrace. Due to gradual truncation, the Holocene cliff line moved more than 100m landward from the old escarpment. The latter appears as a drowned coastal cliff. Adapted from Geister (1975).

At Poxhole ("La Piscinita"), the old pre-Sangamon high cliff ("Poxhole Cliff") forms the modern coastal cliff (fig. 80). A recent intertidal notch is evident at present sea-level, and a very conspicuous fossil intertidal notch is found at -8m. It dates from a previous sea-level lowstand. The latter marks the end of the pre-Sangamon (presumably Yarmouthian) trangression which formed the -20 m terrace (fore-reef terrace) by truncation. The now-emerging part of the old cliff face and the adjacent platform margin are heavily overgrown by Sangamonian reef framework, which is dominated by massive and cauliflower-shaped *Montastraea annularis* and organ-pipe *Montastraea* sp. Towards the coastal road, thickets of fossil *Acropora cervicornis* can be seen on the emerged reef platform. They correspond to the reef crest facies of the Sangamonian fringing reef.

Immediately to the N, Poxhole Cliff was truncated by the Holocene transgression, forming a -4 m terrace (fig. 81) by eroding the seaward *Montastraea annularis* reef zone. As a consequence, the modern cliff section and nearby outcrops reveal a Sangamonian reef crest facies dominated by *Acropora cervicornis*.

Snorkeling along the outer margin of the -4 m terrace to the N, we may observe how coral growth increases with distance from the modern cliff due to diminishing abrasional effects. A distinct zonation of scleractinians from the coastline to the extreme outer edge of the -4m terrace reflects decreasing exposure to abrasion by storm waves (fig. 9). At its distal margin, this submarine terrace is heavily overgrown by corals and appears as a true fringing reef *Dendrogyra cylindrus* is very conspicuous here (see Geister, 1972). Where less overgrown by corals, the old intertidal notch at -8m is still visible at the base of this "reef'.

Towards the S from the "Piscinita", Poxhole Cliff has been only slightly eroded since the Holocene flooding. The old cliff with its reef-like overgrowth on Sangamon limestones and its -8 m notch may be followed for about 800 m along the modern coastline.

Swimming seaward.over the -20 m terrace, we cross a -9- to -13 m-deep sandy zone with colonies of garden eels. We then observe a coral carpet until the drop-off into deep water at -20 m. At Poxhole, a wide sediment tongue replaces the coral carpet at the outer terrace margin, from which it plunges over the -20 m drop-off down the upper island slope. It marks the location of a rip current that forms during storms. When the water is clear, the sandy cover of the -40 m terrace may be vaguely recognized from the surface.

The sand zone becomes very narrow where major segments of the -4 m terrace project seaward, but it widens in front of re-entrants between truncated former headlands. This suggests that the rip currents responsible for the seaward sand transport during storms return water to the open sea from the 6 to 8m deep inlets lying between the re-entrants, and not from the shallow -4m terrace segments on which the waves break (see Geister, 1983: fig. 31).

Trip E: Full-day bus trip to Miocene atoll environments (San Andrés Formation)
(road map fig. 50).

Land Stop E1: Big Pond and Duppy Gully

Big Pond and several similar dolines formed by karstification along a series of NNE directed fractures, probably since the beginning of tilting in latest Miocene/Pliocene time. The core of a nearby drillhole (110 m) shows a number of clay beds (altered tephra) in Miocene lagoonal rock which also contain fossil plant material (see also Rojas-Barahona 2001).

From Big Pond, we follow a footpath in a southward direction and pass the freshwater pumping station to reach Duppy Gully Road. Immediately to the W lies Stop E2. This quarry can also be reached by car descending Duppy Gully Road from Cove Hill.

Figure 82. *Land Stop E2.* San Andrés: Large quarry in Duppy Gully. Miocene lagoon sediments with abundant thick-shelled oyster-like pelecypods of the genus Pycnodonte sp. (white blotches in quarry wall). August 23, 1998.

Figure 83. *Land Stop E3.* San Andrés: Section of Schooner Bight road at Lever Hill. Layer of volcanic ashes intercalated in lagoon sediments. The beds are dipping to E. Note that a branching coral outgrew the tephra sedimentation and survived until the carbonate sedimentation was re-established. August 29, 1998.

Land Stop E2: Quarry at Duppy Gully Road (fig. 82)

This big quarry in rocks of the central Miocene lagoon basin reveals sediments deposited on a rather level sea floor. Numerous large, thick-shelled oysters *(Pycnodonte* sp.) that are well-preserved (fig. 83) dominate the low-diversity mollusk fauna. Locally, beds with a more diverse fauna of smaller pelecypods (lucinids, cardiids, venerids etc.) and gastropods (mostly turritellids) also occur in this quarry. With exception of the pectinids, all these shells are preserved as molds only. The presence of Pycnodonte sp. and the absence of corals suggest an environment of the deeper lagoon basin. The dip of the lagoonal strata towards E is well visible in the quarry walls oriented E-W. It corresponds to the tilting of the San Andrés seamount since late Miocene time. A clay layer (probably altered fine volcanic ashes) can be seen in the outcrop wall indicating Miocene volcanic activity in the wider area surrounding the San Andrés atoll.

Land Stop E3: Section of Schooner Bight Road at Lever Hill

The vertical road cut near the crest of the hill shows at least two magnificent layers of volcanic ash embedded in Miocene lagoonal deposits (fig. 83). This bed also indicates a clear eastward dip of the strata within the ancient lagoon basin. Note that one coral outgrew the sedimentation of the tephra bed.

An intricate meshwork of *Thalassinoides* burrows is visible behind the vegetation (fig. 84) on the N side of the road section. Similar burrows are made in recent lagoonal sediments of San Andrés by the crustacean *Callinassa* sp.

Land Stop E4: Miocene lagoonal deposits between Cove Hill and Southwest Cove

The quarry and nearby road cut in Miocene lagoonal sediments show abundant molds of a highly diverse pelecypod and gastropod fauna and rare branches of Acropora sp. Gastropods include *Xenophora, Semicassis, Oliva* and *Bulla.* Frequent pelecypods are pectinids, *Spondylus, Anodontia,* venerids, oysters and *Kuphus.* Only the calcitic shells of oysters and pec-

Figure 84. *Land Stop E3.* San Andrés: North side of road section at Lever Hill (road to Schooner Bight). Intensive burrowing (Thalassinoides sp.) by crustaceans in lagoon sediments of the Miocene San Andrés atoll. August 29, 1998.

tinids are preserved, whilst the aragonite shells of the other mollusk genera are dissolved. Tests of the echinoids *Clypeaster* and *Echinolampas* were also found (faunal list in Geister 1975: 141).

Land Stop E5: Pepper Hill. Carpets of branching corals in Miocene lagoonal environments (fig. 85)

The best outcrops are along Pepper Hill Road and the nearby access road to the hilltop restaurant. The section shows typical thickets of finely branching corals (maidy *Porites* spp.) that formed wide coral carpets on the shallower Miocene lagoon floor (fig. 86). Massive corals (*Montastraea* sp.) are less frequent here. Similar thickets of *Acropora* spp. (staghorn type) and *Stylophora* sp. were frequently encountered in temporary outcrops at Sound Bay and to the N of Pepper Hill. Branching corals are generally broken, but corresponding fragments are found close together. Most colonies appear to have tumbled. The reason for this unusual taphonomic situation may be compaction of the mud, or more likely breakage by earthquake shocks. Branching corals dominate in the outcrops of

Figure 85. *Land Stop E5.* San Andrés: Road cut at Pepper Hill. Broken branching poritid corals in lagoon deposits. Fragments of individual colonies are separated but embedded close together, suggesting that earthquake shocks and not storm action might have caused their destruction. Hammer 32cm. September 12, 2000. .

the central lagoon from the Pepper Hill and Sound Bay area in the S almost to Duppy Gully Road in the N.

Land Stop E6: Intra-Miocene (3 unconformity beside the landing strp at Perry near Little Cliff (fig. 86)
This roadside cut is at the low hill rising N of the landing stip. It is situated some 800 m away from the Fisherman's Place restaurant at Sprat Bight, on the small road that parallels the landing stip in the N. The outcrop reveals 1.8 m of a brownish, heavily recrystallized fossil-free limestone at the base. This is truncated at its top by an unconformity plane ("Perry unconformity"), which shows irregular relief of about 50 cm and is covered by limestone fragments partly corroded by dissolution. There are neither borings nor encrusting organisms on the surface, which dips with an estimated 10°to N.

The unconformity is overlain by at least 2 m of whitish massive limestone. At the base of this limestone, there is some fore-set bedding with beds 20-30 cm thick. No fossils were found in the outcrop. The discontinuity is transected by a microfault, resulting in a vertical displacement of about 30 cm. A Miocene age is corroborated by neighboring fossiliferous outcrops in the airport area (Stop E7), which are definitively Miocene.

Land Stop E7: Miocene lagoon environments and coral build-ups at "Cantera San Andrés " (figs. 87 and 88)

This large quarry is situated just to the S of the landing strip, some 1.5 km from the airport building. It may be reached from the airport by car following the road that parallels the landing strip in the S. Turning W after the entrance to the quarry ("Cantera San Andrés"), we see an easily accessible abandoned quarry wall, some 90 m long and about 10m high. It oflers the best insight into the ecology and structure of the deeper northern Miocene lagoon of the ancient San Andrés atoll. The rocks are very rich in fossils, especially corals and mollusks; however, almost all the aragonitic skeletons are dissolved. Among the mollusks, only the calcitic shells of oysters and pectinids are fully preserved.

Figure 86. *LLand Stop E6.* San Andrés: Intra-Miocene unconformity truncating lagoonal carbonates. The limestone below and above the unconformity is fossil-free. Hammer (32cm) for scale. Road cut at Perry near Little Cliff. August 23, 2000.

Figure 87. *Land Stop E7.* San Andrés: Deposits of the Miocene lagoon in "Cantera San Andrés" at Northend. Note that diagenetically dissolved massive coral colonies appear as cavities in outcrop wall. Large Colpophyllia colony (to the left above person) and other colonies are in a top-down position, suggesting the effect of seismic shock on the lagoon floor. August 28, 2000.

Figure 88. Land Stop E7. San Andrés: Deposits of the Miocene lagoon in "Cantera San Andrés" at Northend. Note massive bioherm to the left of person. It consists of large branching poritid corals, which baffled fine sediment to form a build-up that rose steeply above the adjacent ancient lagoon floor. August 28, 2000.

In the WSW part of the quarry front (left side), we observe a number of caverns up to about Im in diameter. These are the molds left after the dissolution of massive coral skeletons (among others, *Colpophyllia* sp.) that lived on the ancient lagoon floor. All the boring traces of lithophagans and clinoids in the coral skeletons appear in great detail as beautiful calcitic casts in the voids. Many of the massive corals are embedded in an upside-down position on the ancient lagoon floor (fig. 87). As there was no slope on the lagoon floor, the unusual position can most easily be interpreted as a result of earthquake shocks. Most massive corals are not hemispherical but considerably flattened. This points to an environment of deeper water, possibly 20 to 50 m of water depth. A depth range between 20 and 55 m was estimated previously, based on the occurrence of dominant reef corals on this site (Geister 1975: 145).

In the central part of the quarry wall, a coral build-up of branching scleractinians and coral fragments may be examined. It is 6m wide at the base and forms a cupola at least 3 m high (fig. 88). The rocks underlying the build-up are formed by indistinctly bedded limestone. Corals are predominantly *Acropora* sp. (staghorn type) and poritids. The skeletons are preserved partly as molds and partly as calcitic casts of the molds. In the northeastern corner of the quarry wall, there is another small build-up which is formed of massive corals. Some of the colonies attain meter-size.

Due to the eastward dip of the lagoonal strata, the accessible section in this quarry wall totals about 50 m. When following bedding planes along the wall, we see that the large isolated colonies in the WSW part of the quarry wall are stratigraphically lowest. The build-up of branching corals in the middle part of the wall is higher in the section, and the build-up of massive corals to the ENE lies near the top of the sequence.

8.2 Visit to Old Providence Island: Quaternary reefs and island geology (Trips F to L)

Land stops are marked on road map fig. 89. Sea stop sites may be located on the sea chart (fig. 32) by place name.

Trip F: Boat trip to lagoonal fringing reef and leeward reef environments (see map fig. 33)

Sea Stop Fl: Lagoonal fringing reef off Maracaibo Hill (fig. 90)

Between the shore and the reef, there is a 2 m deep seagrass zone. The reef crest is at about 1.5 m. At the outer margin, there is a steep reef slope to the adjacent lagoon Bottom at 3.5 - 5m. Reef crest and lagoonward slope are characterized by a diverse quiet-water coral association dominated by *Montastraea faveolata*. The following species are also frequent: Porites furcata, *Siderastrea siderea*, *Colpophyllia natans*, *Favia fragum*, *Diploria strigosa*, *D. labyrinth formis*, *Dichocoenia stokesii*,

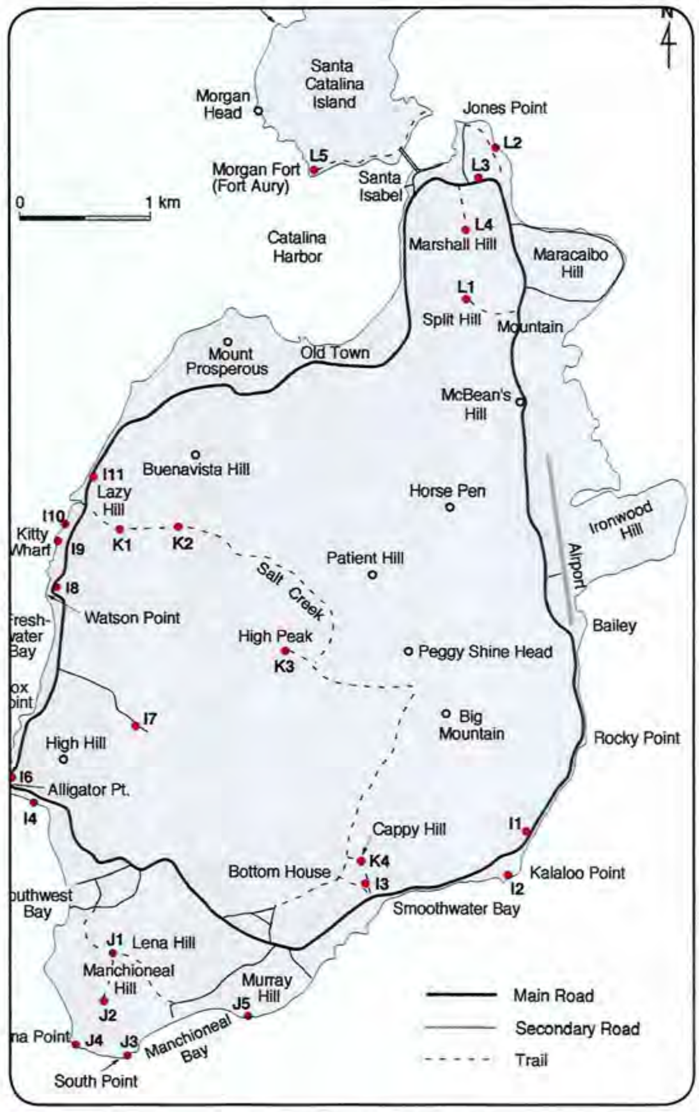


Figure 89. Road map of Old Providence Island. Field trip routes (I-L) and Land Stops (numbers) are marked. Sea Stops will be localized by toponym on map fig. 33.

Agaricia agaricites, and *A. crassa*. Algae, especially *Dictyota* and *Halimeda*, were very abundant and outgrew the corals in 1994. This reef was heavily overgrown by soft algae when revisited in September 2001.

Sea Stop F2: Lawrance Reef in the lee of Sta. Catalina

The shallow patch reef is 700 m long and surrounded by a sandy flat with seagrass 8 m deep. A shallow- water association dominated by *Acropora palmata* and octocorals characterizes the reef flat. Most *A. palmata* were dead in 1996. Living *Acropora cervicornis* is very rare. In 1994, heavy overgrowth competition was observed between Halimeda and the few surviving scleractinians.

Sea Stop F3: Bar reefs in the lee of Old Providence, off Lazy Hill village

Sandy and rocky flats with occasional coral shoals characterize the leeward shelf area of Old Providence. Topographically well defined reefs do not exist. Shoals are characterized by loose associations of large *Montastraea annularis* with *M* *cavernosa, Porites astreoides, Porites porites, Diploria strigosa, D. labyrinthiformis, Agaricia agaricites, Siderastrea siderea,* Isophyllia rigida, and occasional *Acropora cervicornis.* Octocorals, especially sea whips, are numerous. *Dendrogyra* is common and very conspicuous. The shoals rise to 3-5 m water depth and parallel the coast at a distante. Seagrass flats cover the sandy inter-reef areas and the nearshore zone.

Trip G: Boat trip to windward reef environments (see map fig. 32)

Sea Stop G 1: Discontinuous windward barrier reef near Crab Cay

Brown algae and *Halimeda* largely cover the fore-reef terrace at -15 m depth. Some massive encrusting scleractinians (*Dichocoenia stokesi, Diploria clivosa, D. strigosa, Porites astreoides, Colpophyllia natans*) are scattered on the hard substrate. Many corals are dead, and the remaining corals are largely overgrown by algae. Living corals covered about 1% of the surface in 1994. No change was observed in 2001.

The discontinuous barrier itself is formed by high coral pinnacles (local name: "giants"), many of which grew up to the surface from 6-8 m of water depth (fig. 91). *Millepora* forms the framework of the pinnacles at the seaward side, and *Acropora palmata* forms the framework towards the center of the patch reef belt. There are also pinnacles formed by *Montastraea annularis.* Framework growth was still ongoing near the tops of pillars in 1973. The framework of pinnacles is mostly dead and overgrown by soft algae (*Turbinaria* and *Dictyota*) and encrusting red algae. (Corresponds to fig. 36a.)

Sea Stop G2: "Miniature atoll" of White Shoal (fig. 92)

This is a roughly annular lagoonal patch reef forming an almost complete ring with a shallow, sandy mini-lagoon at its center and rich growth of *Acropora cervicornis* at its margins and upper slope. The lower reef slope is overgrown by *Montastraea annularis* and other calm-water scleractinians down to the adjacent lagoon basin at about 5 to 8m of water depth.. Most A. cervicornis was dead in October 1994, and the lagoonward slope was heavily overgrown by the brown algae *Dictyota* and *Turbinaria.* This condition was essentially unchanged in 2001.

Sea Stop G3: Continuous barrier reef E of Iron Wood Hill

The reef flat is densely overgrown by the colonial zoanthid *Palythoa* sp. Seaward spurs and grooves are well developed. Framework of spurs is formed by *Millepora* sp. In 1996, there was almost no soft algal growth on the reef flat and in the groove-and-spur system. Healthy *Acropora palmata* occur seaward. In front of the spurs at -8 m depth, head corals (*M annularis, D. strigosa*) are heavily overgrown by algae. This stop is accessible only during a calm sea. (Corresponds to fig. 90.)

Sea Stop G4 Lagoonal patch reef of Manchioneal Bay (fig. 93)

This patch reef of the knoll-type is situated some 500m off the eastern third of Manchioneal Bay beach (marked in map fig. 31). It rises from a sandy lagoon floor at -6m to water depths of -2 to -3 m. The reef is a 100 by 40m oval with a NE trend. It roughly parallels the barrier reef in this sector. A highly diverse *Montastraea* spp. association at the flanks of the reef dominates the coral framework. The most abundant species are very large cauliflower-like *Montastraea faveolata* associated with *Montastraea annularis, Porites astreoides, Siderastrea siderea, Montastraea cavernosa, Favia Fragum, Diploria labyrinthiformis, Dendrogyra cylindrus* and *Agaricia agaricites.* The sea fan Gorgonia sp. is rare. Sea whips are by far more abundant.

Only the shallowest part of the reef crest, at about 2 to 3 m water depth, is locally overgrown. The coral association here is formed by dense, almost monospecific stands of the finger coral *Porites porites,* with a few *Millepora, Dendrogyra cylindrus, Acropora cervicornis* and other species. In October 1994, much of the coral frarnework was overgrown by soft algae, mainly *Dictyota* that covered locally up to 99% of the reef surface.

Trip H: Pul1 day boat trip to northern sector of reef complex (see map fig. 33)

Sea Stop H1 : Rocky Cay Reef

This is a small, isolated reef segment lying off the windward barrier. Seaward coral zonation is well developed, with *Millepora* framework in the reef crest near low-tide level, *Acropora palmata* on the slope, and *Acropora cervicornis* on the fore-reef terrace at about 7 to 8 m water depth. Most of the *A. palmata* is still in Living position but dead (presumably by bleaching). *A. cervicornis* in about 7 m of water depth is fragmented and dead, probably due to the impact of Hurricane Joan in 1988. *Millepora* in the reef crest zone is still alive but intergrown by soft algae. In 1977 and 1979, the reef was still vigorously flourishing. When revisited in 1993, it was mostly dead. It had not recovered in September 2001.

Sea Stop H2: Drifting in the lee of Taylor Big Reef

Numerous shallow channels interrupt Taylor Big Reef. Swell generated by the trade winds breaks in the crest, producing a swift pulsating current which flows over the shallow lagoon terrace and through the semi-enclosed lagoon basin of Point Blue in the W.

We shall be drift-snorkeling to observe a great array of patch reef types. Patch reefs immediately behind the reef crest are overgrown by *Millepora* and are succeeded by those with extensive thickets of *Acropora palmata* and *A. cervicornis.* Most of the *Acropora* was dead in October 1994. To the W, bizarre knoll reefs (fig 94) and irregular platform reefs (fig. 95) become more conspicuous. Dominant frame-builders here are

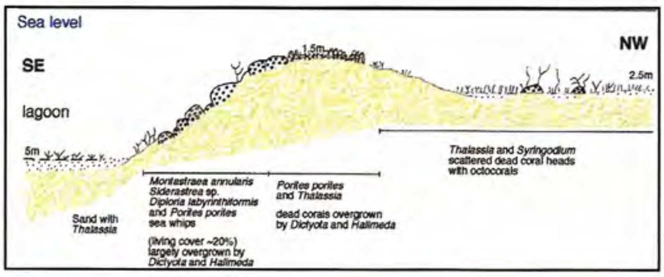


Figure 90. *Sea Stop F1.* Old Providence: Ecological and geomorphological section across the fringing reef off Maracaibo Hill. Schematic.

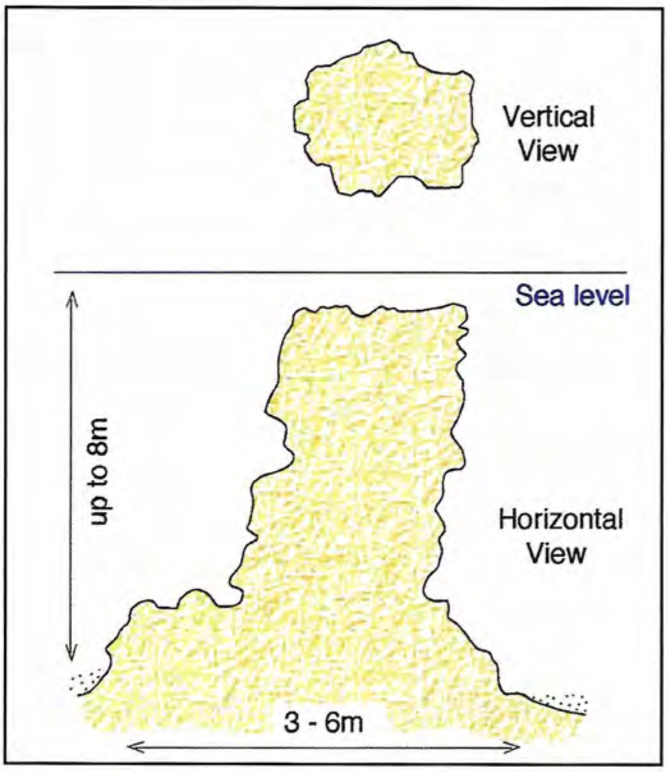


Figura 91. *Sea Stop G1.* Old Providence: Typical view of pinnacle reef from the Crab Cay area.

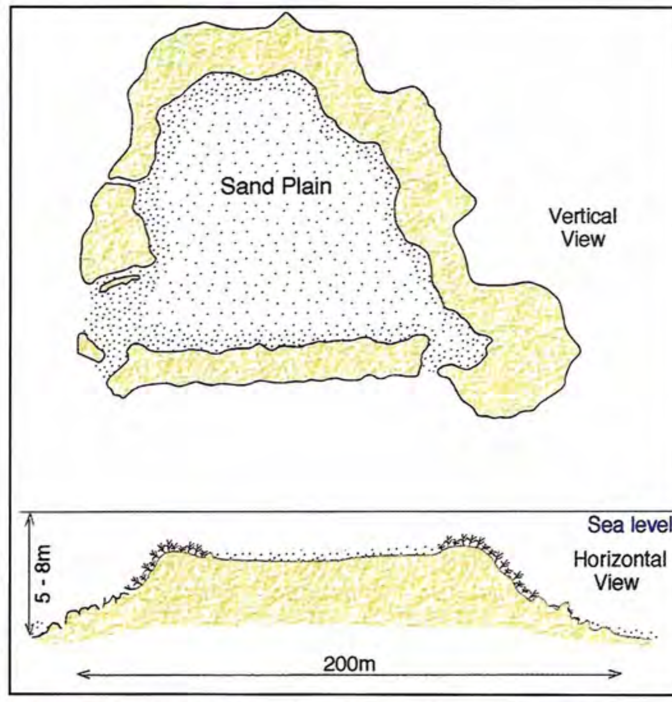


Figure 92. *Sea Stop G2.* Old Providence: Vertical and horizontal view of miniature atoll "White Shoal". Reef builders are *Acropora cervicornis* along the crest and slope and Montastraea annularis at the foot of the slope.

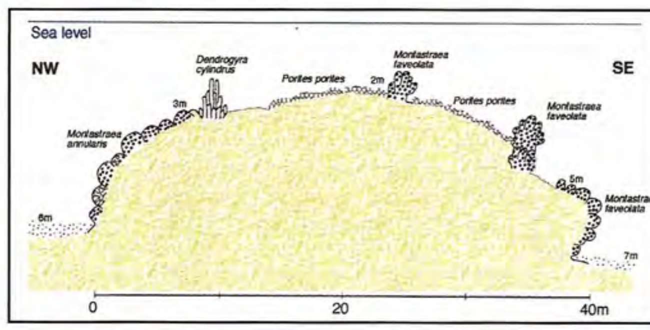


Figure 93. *Sea Stop G4.* Old Providence: Ecological and geomorphological section across a lagoonal reef knoll, 500m off Manchioneal Bay. Schematic. Not to scale.

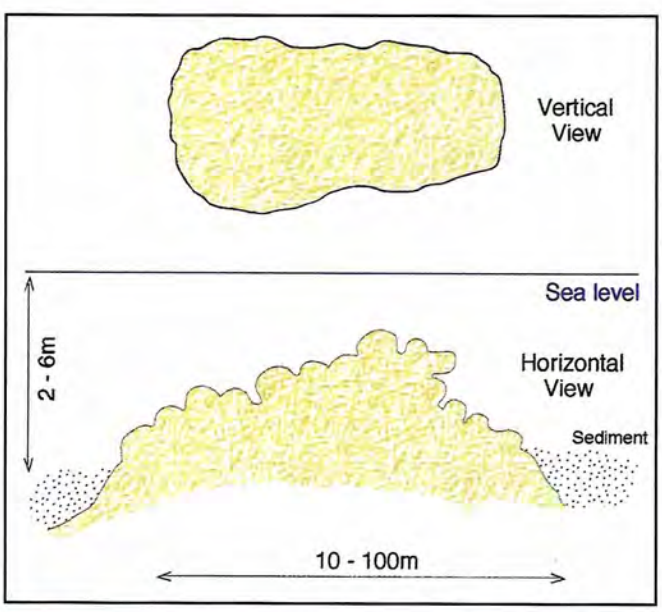


Figure 94. *Sea Stop H2.* Old Providence: Outline of typical knoll reef from the lagoon W of Taylor Big Reef. Reef builders are mainly massive corals.

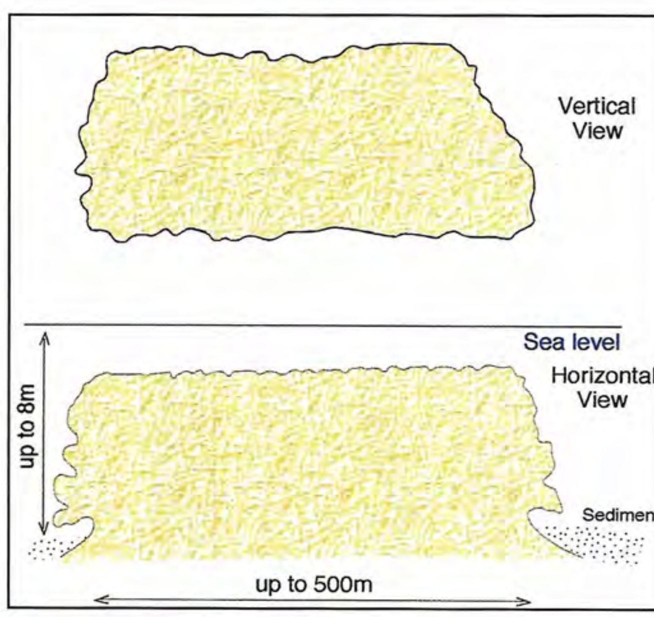


Figure 95. *Sea Stop H2.* Old Providence: Outline of typical platform reef from the lagoon W of Taylor Big Reef. Reef builders are massive and branching corals.

Montastraea annularis and other massive species, most of which are alive. Soft algae were common in these reefs in October 1994, June 1996 and September 2001. Reef flats of platform reefs are generally well below 1.5m water depth.

Sea Stop H3. The Elbow

The fore-reef slope of the barrier in the Elbow area is a rocky flat that slopes gently towards the fore-reef terrace. There is hardly any coral growth, probably due to the abrasive effect of coral fragments moved by breaking storm waves. A few erosional grooves perpendicular to the reef exist. *Millepora* and other frame-builders are abundant only along the lagoonward

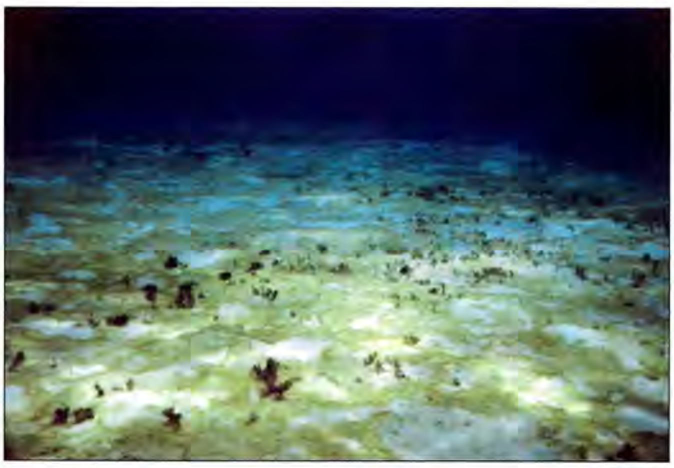


Figure 96. *Sea Stop H3.* Old Providence: Lagoon floor in the lee of The Elbow. Dark seaweeds are stands of the green alga *Halimeda.* Filamentous algae stabilized the surface sediments of the lagoon floor in this area in June 1996

margin of the reef. This fore-reef is accessible only during very calm weather! Reef profile corresponds to fig. 36c.

The lagoon floor in the lee of The Elbow is generally bioturbated. In June 1996, mats of filamentous algae (fig. 96) stabilized much of its surface.

Sea Stop H4: Low Cay (fig. 97)

This is a block ridge with a lighthouse near the NW bend of the windward barrier reef. It rises for about 1m above sea level. The blocks consist exclusively of large broken branches of *Acropora palmata* deposited by storm waves. The shape of the ridge changes during heavy storms. There is no land vegetation.

Sea Stop H5: Pearstick Bar (or Second White Water)

This is a shallow sandy ridge between Point Blue (> 20 m deep) in the N and Sea Devil Channel (- 8 m deep) in the S. Its crest at 2 - 3 m water depth is overgrown by patches of *Acropora palmata* associated with abundant *Porites* astreoides and *Diploria strigosa*, as well as plexawid octocorals. Most *A. palmata* were dead in October 1994-1996. A similar sandy ridge (First White Water) with patches of parily Living *Acropora palmata* lies to the S from here. The general setting of reef environments on both ridges is similar to that of Lawrance Reef (Stop F2).

Sea Stop H6: Basalt Cay

Basalt Cay and nearby Palm Cay are entirely built of columnar lavas which are practically without vegetation. When approached from the sea, they offer a spectacular sight. Minerals within the rock are heavily altered.

Sea Stop H7: Gun Point, Sta. Catalina

Several guns dating from pirate times may be seen in shallow water immediately in front of the point. These are encrusted by corals and coralline algae.

Trip I: Full day trip by pick-up truck around Old Providence to see island geology (road map fig. 89, geological map fig. 31).

Land Stop I 1: Quarry in rhyolites to the N of Kalaloo Point (fig. 98)

Figure 97. *Sea Stop H4.* Old Providence: Low Cay near the northwestern bend of the barrier reef is a mere shingle ridge formed by broken pieces of *Acropora palmata* which were accumulated during storms. Most of the islet barely rises above sea level. Lighthouse in background. Photograph taken on June 20, 1993.

Figure 98. *Land Stop I 1.* Old Providence: Massive rhyolites of the volcanic dome in quarry to the N of Kalaloo Point. Apparent stratification is an effect of exfoliation parallel to land surface. The fine lamination of the rocks (not visible in photograph) is essentially vertical. September 2, 2001.

This is a quarry outcrop with white to light-gray stratified felsitic lavas showing flow-banding. They belong to the rhyolite dome, which crops out in a wide zone between Lazy Hill and Freshwater Bay in the W and Rocky Point and Kalaloo Point in the E. This complex is of uncertain pre-Miocene to earliest Miocene age. Jointing of rock corresponds to the slope dip at this site. The interna1 flow lamination of the rock is almost vertical (not visible on the photograph).

Land Stop 12: Emergent Pleistocene stream delta at Kalaloo Point (fig. 99)

Figure 99. *Land Stop I 2.* Old Providence: Pleistocene pebbly delta deposits cropping out in cliff section near Kalaloo Point. Rocks are cemented and were probably deposited during the high sea-level stand in Sangamon time. September 2, 2001.

The low coastal section shows a conglomerate of pebbles transported seaward by a nearby stream. This was later consolidated by carbonate cementation. Judging from the present elevation above sea level and carbonate cementation, the rock must be of Sangamon age.

Land Stop 13: Quarry in volcanic ashes and basalts at Smoothwater Bay (fig. 100).

Thick Miocene ashes can be exarnined in a quarry just to the N of the main road. The ashes in the quarry may represent the fill of a tuff pipe. A possible vertical pipe wall of dark basalts can be examined near the northern end of the outcrop. The outcrop situation is not sufficient to outline the possible former vent. However, the proximity of a tuff pipe in the area is also suggested by a very thick layer of ashes and blocky tuffs covering the low hills to the N and NW of Smoothwater Bay. As an altemative, the vertical section of the basalt may result from a tectonic fault, in which case the ashes might represent epiclastic material transported laterally into the depression. To the N, higher up, basaltic lavas crop out at the hill slope (fig. 101).

Land Stop I 4: Pleistocene beach deposits in cliff section at Alligator Point (fig. 102)

Pleistocene shallow lagoon and beach deposits are visible in the coastal cliff at the northern end of Southwest Bay beach (see Geister 1992, plate 13/4). There is rippled stratification

Figure.100. *Land Stop I 3.* Old Providence: Vertical section in possible tuff pipe at Smoothwater Bay. Note that basaltic bedrock to the left is crosscut by pipe. September 15, 2001.

Figure 101. *Land Stop I 3.* Old Providence: Basaltic lavas uphill from tuff pipe outcrop. July 1979.

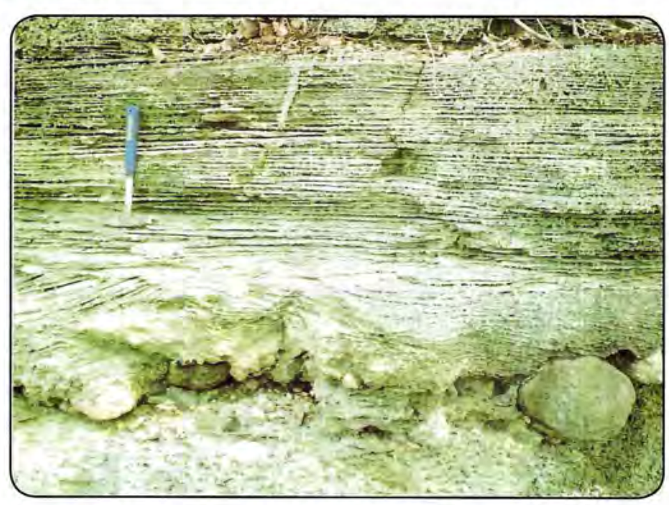


Figure 102. *Land Stop I 4.* Old Providence: Frontal view of cliff section revealing Pleistocene beach sediments at the southern shore of Alligator Point. Note lag deposit of volcanic cobbles near bottom of picture. It is overlain by cross-bedded sands followed by finely laminated beds. The latter are crossed by vertical cylinders interpreted as burrows made by crustaceans (*Ophiomorpha* sp.). Probable age is Sangamon. September 2, 2000.

and laminated bedding, with escape traces weathering out as vertical cylinders which transect the bedding planes. These have been previously interpreted as plant rootlets. Body fossils are rare. Only topshells Cittarium pica and fragments of pelecypods were collected in this outcrop.

Figure 103. *Land Stop 15.* Old Providence: Cliff section at Alligator Point (S side), Old Providence. Exhumed submarine island slope with large, flattened in situ heads of *Montastraea* sp. in growth position. September 2, 2000.

Figure 104. *Land Stop 15.* Old Providence: Exhumed submarine island slope showing avalanche deposit of fragmented branching poritid corals. This carbonate bed was succeeded by an avalanche of gray volcanic tuffs with coral fragments deposited on top of the coral avalanche. Cliff section at Alligator Point (S side). September 2, 2000.

Land Stop 15: Submarine island slope deposits in Miocene cliff section at Alligator Point (figs. 103 and 104)

Close to the preceding outcrop, rich Miocene coral faunas can be collected along the southern cliff of Alligator Point. Submarine slope deposits are well exposed in the modern sea cliff along the southern flank of Alligator Point. The Miocene slope surface here was exhumed by modern coastal erosion. Beds are equally seaward dipping with an estimated slope angle of 15 to 20o. There are coral carpets of branching species (mostly *Stylophora* and *Porites)* associated with massive heads of *Montastraea.* Pavements of hemispherical to platy scleractinians (fig. 100) and thickets of finely branching *Porites* sp. are visible. Nearby avalanche deposits of coral shingle (fig. 101) and volcanic ashes may be examined. They are partly intermingled with coral fragments. Debris flows formed of coral fragments - mostly of branching Porites sp., but including a few massive *Montastraea* sp. - are conserved at the paleo-island slope. They are overlain by slumped volcanic ashes containing numerous colonies of branching *Porites* sp.

Land Stop 16: Road cut above Alligator Point: Miocene coral framework and debris Jlows (fig. 105)

Figure 105. *Land Stop 16.* Old Providence: Close-up view of interlocking framework formed by flattened massive colonies of Montastraea sp. covering Miocene island slope. Road section above Alligator Point. August 31, 2000.

Basaltic volcanics of the younger period of volcanic activity (Early to Middle Miocene) interfinger with Miocene limestones of the paleo-island slope. Large massive scleractinians (*Montastraea* sp.) with a thick-platy growth habit form a true reef frarnework of Miocene age in roadside outcrops at the highest point of the road. One- to two-meter-thick debris flows consisting of volcanic ashes and coral fragments are intercalated.

Land Stop 17: Rhyolites and epiclastic basaltic deposits at water reservoir near Fresh Water Bay.

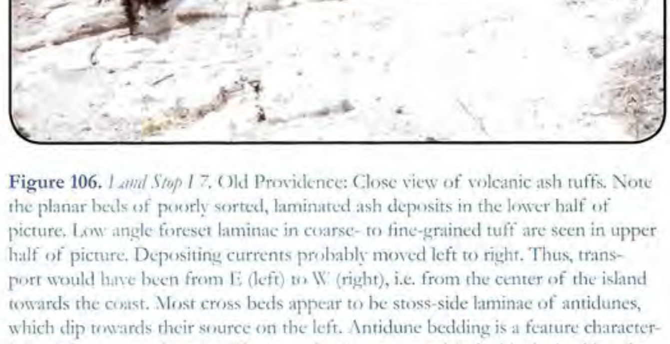


Figure 106. *Land Stop 17.* Old Providence: Close view of volcanic ash tuffs. Note the planar beds of poorly sorted, laminated ash deposits in the lower half of picture. Low angle foreset laminae in coarse- to fine-grained tuff are seen in upper half of picture. Depositing currents probably moved left to right. Thus, transport would have been from E (left) to W (right), i.e. from the center of the island towards the coast. Most cross beds appear to be stoss-side laminae of antidunes, which dip towards their source on the left. Antidune bedding is a feature characteristic of base surge deposits. The cross-laminae are overlain by block-sized bombs near top of picture. An Early to Middle Miocene age of these ashes is suggested by the coral fauna found in the ash avalanches at nearby Alligator Point, which were formed by the same explosive event. Hill slope to the S of concrete dam of freshwater reservoir near Freshwater Bay. September 2, 2001.

A black basaltic dyke is visible behind the water purification plant at the entrance of the valley. It visibly transects the felsic rocks in the quarry wall. Rhyolite lavas are accessible in a large fresh outcrop to the S of the dust road that leads to the dam of the big water reservoir ("Represa") E of Freshwater Bay. The rhyolites are overlain by Miocene dark volcanic conglomerates and white ashes on the slopes and top of the mountain ridge to the S of the dam. The ashes are best exposed on the valley slope facing the water reservoir (fig. 106). They show unidirectional bedforms with low-angle cross-stratification and climbing dune forms and thus might be deposits of pyroclastic surges.

At the N side of the valley leading to the water reservoir, the rhyolite weathers out as steep-sided pyramidal to conical peaks similar to the "pitons" of the Lesser Antilles.

Land Stop 18: Laminated rhyolites at Watson Point between Lazy Hill and Freshwater Bay

Outcrops of older banded rhyolite lavas can be examined in roadside outcrops at this prominent headland between Lazy Hill and Freshwater Bay (fig. 107). The layered rocks here dip landward today. Some of the rock material is fragmented, but the fragments are still more or less in original position.

Towards N, the same rocks become more shattered and form a sort of collapse breccia. From here, there is a gradual transition to the breccia on the way to the large roadside quarry lying to the N (fig.108).

Figure 107. *Land Stop I 8.* Old Providence: Outcrop of banded rhyolite lava forming part of the volcanic dome. Layers dip towards the center of the island. Age: late pre-Miocene or very early Miocene. Road cut at Watson Point, between Lazy Hill village and Freshwater Bay. August 12, 2002.

Figure 108. *Land Stop I 8.* Old Providence: Shattered rhyolite of the volcanic dome in vicinity of the autobreccia deposits of Stop I 9. Road cut to the N of Watson Point. August 12, 2002.

Land Stop 19: Collapse breccia of rhyolites at Kitty Wharf (fig. 109)

The outcrops lie on the coast across the coastal road from the big quarry. The rocks at this popular bathing site are formed by a chaotic, well-cemented mass of fragmented, finely laminated pink rhyolite rocks. The successive thick debris layers cropping out in the sea cliff indicate that the rock masses were deposited in several phases. It appears that the breccia formed from gravity collapse of the oversteepened flank of the rising rhyolite dome. The chaotic, unsorted deposits contain mainly angular blocks and sand-to-dust-sized debris, and they are interpreted as pyroclastic flows. The breccias are covered by Quaternary slope debris.

Land Stop I 10: Columnar basalt at the rocky shoreline S of Lazy Hill village

This outcrop is off the road and forms a low sea cliff and adjacent platform. The rock is a black olivine basalt with columna jointing that has developed as a result of gradual cooling.

Land Stop I 11: Roadside cut N of Las, Hill village (below statue of Christ) (fig. 110)

Basaltic and andesitic(?) conglomerates and ashes representing the Miocene eruptions. Some of the black blocks in the conglomerate reach boulder size.

Figure 109. *Land Stop I 9.* Old Providence: Autobreccia of rhyolites cropping out at coastal cliff of Kitty Wharf. September 2, 2001.

Figure 110. *Land Stop I 9.* Old Providence: Autobreccia of rhyolites cropping out at coastal cliff of Kitty Wharf. September 2, 2001.

Trip J: Full day visit to sedimentary and volcanic outcrops in the Manchioneal Bay area (road map fig. 89; geological map fig. 31)

Manchioneal Hill is the southernmost hill of the island (150 m high), also known as South Hill. On the hike to the top, we shall see outcrops of Miocene fossiliferous limestone. The limestone beds are intercalated in lava flows and volcanoclastic deposits. In addition, the panorama from the hilltop will be very much appreciated.

The most instructive coastal outcrops of the island are between the western end of Manchioneal Bay and Lena Point. Along this relatively short cliff section, we may see a Pleistocene fringing reef, Miocene lava and pyroclastic deposits with a fossiliferous limestone intercalation, and volcanic dykes. Nearby Murray Hill is one of the major outcrop areas of banded rhyolite.

When approaching Manchioneal Bay from bottom House by road, follow the off-branching footpath to Southwest Bay, which leads uphill on the west side of a small ravine. At the junction on the flat top of Lena Hill, one branch of the trail descends to the right to Southwest Bay. Take the left branch, which leads up to Manchioneal Hill. In the ravine, outcrops of basaltic conglomerates and volcanic ashes crosscut by dykes are seen along with huge volcanic boulders of probably epiclastic origin.

Land Stop J1: Volcanic ash layers and Miocene coral carpets at Lena Hill

Before reaching the flat top of Lena Hill, the trail is cut into a 3m thick bed of volcanic ashes, which is overlain by lm of coral limestone. The uppermost ash layer and limestone cap contains a rich fauna of Miocene reef corals. Common genera are branching *Pocillopora, Stylophora, Porites*, and some massive colonies of *Montastraea* which form a coral carpet. Massive *Montastraea* (colony diameter 0.5m) and *Porites* colonies form the interlocking framework of a small patch reef, which will be seen in nearby outcrops along the trail to the top of Manchioneal Hill. Echinoids, oysters, and red algal nodules are common everywhere in these exposures on Lena Hill.

Land Stop J2: Miocene reef framework on top of Manchioneal Hill (fig. 111 and 112)

A pure Miocene reef limestone, several meters thick, caps the hilltop. It consists almost exclusively of large massive and interlocking colonies of *Montastraea* spp. This relic of reef rock was probably preserved from erosion by overlying volcanic material which has since been eroded. It may be the last witness to an ancient major reef tract surrounding Old Providence in Miocene time. In the Manchioneal Hill section, the establishment of a carbonate platform on the younger ash layer of Lena Hill can be observed, with the development of coral carpets of branching corals and small patch reefs of massive corals on top of the ash layer. These beds are overlain by shallowing-up coralliferous beds, which terminate in the framestone facies on top of Manchioneal Hill. The reef rock on the hilltop is considerably younger than the coral pavement of Alligator Point (Land Stops I 5 and I 6), over which avalanches of the older ash layer were shed. Coral faunas in both outcrop areas indicate a Miocene age.

The hilltop affords a great panoramic view over the southern part of the modern barrier reef and lagoon. Return by the same trail to Manchioneal Bay.

Land Stop J3: South Point of Old Providence: Pleistocene fringing reef, Miocene coral limestone and volcanic rocks (fig. 113)

Two isolated segments of a Pleistocene coral reef fringe the W and E sides of South Point, where they form a distinct +3 m terrace. The terrace surface locally rises up to 4 m above present sea-level datum, and marine carbonate relic sediment is found even higher within Pleistocene slope debris above the reef. This reef documents the terminal Sangamon sea-level high-stand corresponding to "Substage 5e" of the standard marine oxygen isotope stratigraphy of the Pleistocene chronology (see Geister 1992:55). Thus, this reef

Figure 111. *Land Stop J2.* Old Providence: Interlocking framework formed exclusively of massive colonies of *Montastraea* sp., Upper Miocene. Hammer 32cm. Very top of Manchioneal Hill. September 16, 2001.

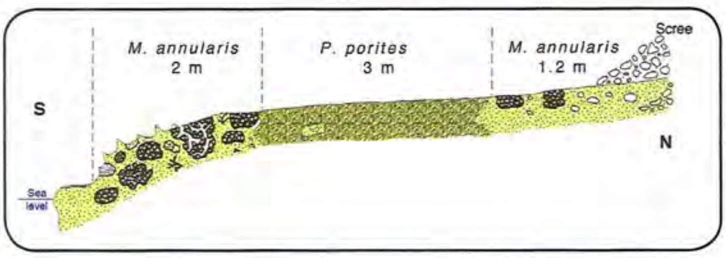


Figure 112. *Land Stop J2.* Old Providence: Section across the Sangamon fringing reef at South Point, showing ecological zonation of predominant coral species. To scale. After Geister (1980).

Figure 113. *Land Stop J3.* Old Providence: White stratified volcanic ashes with ballistic blocks overlying black pillow basalts at Lena Point. The tuffs and blocks are indicative of explosive volcanism. The basalts are the oldest dated effusives (14.5my) of the island. They postdate the formation of the volcanic dome. September 9, 2000.

is contemporaneous with the Younger Low Terrace Limestone of San Andrés.

The adjacent Sangamon sea cliff was cut into lavas and tuffs of the ancient coast line. Along the cliffline, Sangamon reef deposits interfinger with contemporaneous scree material that periodically avalanched downslope into shallow water. Debris of Miocene volcanic rocks and Tertiary corals, the latter baked by hot lava and stained red by oxidation, were incorporated into the Sangamon reef rock, where they became subsequently cemented by marine carbonate mud. Some Pleistocene corals *Siderastrea radians* encrusted volcanic pebbles in the ancient nearshore zone. A large (50cm) baked colony of the Miocene scleractinian *Psammocora trinitatis* became embedded side-by-side along with the Pleistocene reef corals of the eastern reef segment. The large erosive gap between the two reef segments of the fringing reef reveals cross sections of slope debris intercalated in the reef framework.

The narrow (2-5 m) fringing reef itself shows a distinct coral zonation: Dense growths of Porites furcata colonized the reef flat, whereas *Montastraea annularis* and related massive species formed narrow fringes along the fore-reef and near the landward cliff (fig. 110). Altogether, 14 coral species have been recorded from the reef, plus seven species of gastropods and bivalves. Note that most corals are covered by a thick crust of red calcareous algae, similar to that seen in the Sangamonian reef corals at San Andrés and along the corresponding sea cliff.

The gap between the segments of the Sangamon reef terrace also yields access to the substratum of the reef deposits, which in this sector is formed by Miocene nearshore and shallow lagoonal deposits. A thick layer of volcanic ashes covers this nearshore lagoonal environment. In their basal layers these tephra are fossiliferous, bioturbated, and mixed with carbonate sediments. The fossiliferous rocks yielded numerous corals, burrowing echinoids, balanids, and other fossils, indicating an Early or Middle Miocene age. Reworked pebbles of the banded rhyolite from Murray Hill are embedded along with fossils in a Miocene nearshore conglomerate. They prove that the extrusion of the rhyolite dome is older than the basalts overlying the tephra layers. The ash layer, which is several meters thick, can be followed along the shoreline for several 100 m to the W. It disappears below the Pleistocene reef terrace to the E.

This tephra layer itself is overlain by a several-meter-thick dark lava flow which came to rest on its autobrecciated basal layer of fragmented lava. Cooling of the massive lava flow resulted in a distinct columnar jointing. The upper surface of the lava is rough and spinose with clinkery fragments, as is characteristic for aa lavas. The dense gray groundmass is formed mainly of numerous microliths of plagioclase. The stratum is rich in large phenocrysts of plagioclase and contains layered vesicles.

Land Stop J4: Pillow lavas and pyroclastic rocks at Lena Point

K/Ar whole rock dating of olivine basalt pillows at Lena Point yielded ages of 14.5+-1.1 Ma, corresponding to an early Middle Miocene age (Gobel 1985). These lavas are covered by a tephra layer, which appears to be the lateral continuation of the ashes of the previous outcrop. The modern sea cliff at this site exhibits several meters of white ash deposits crosscut by dykes. Large and smaller clastic bombs of banded rhyolite fell onto the bedded ash deposits, where they left bomb sags. This ash layer can be followed further all along the west coast of Manchioneal Hill and probably continues to Lena Hill (*Land Stop J1*).

As the banded rhyolite blocks are already incorporated in this younger volcanic series, we can state again that the formation of the rhyolite dome of the island necessarily predates all the basaltic and carbonate deposits which build up Manchioneal Hill.

Land Stop J5: Banded rhyolites at Murray Hill (eastern end of Manchioneal Bay).

The banded, reddish-gray felsic rocks of pre-Miocene (?) or earliest Miocene age are beautifully exposed along the sea cliff of Murray Hill. Most of the rocks in the outcrops are shattered and out of place. The rocks show beautiful banding in reddish and whitish layers with intricate fluidal folding patterns. The banding is locally contorted and cut by ramp-like shear planes. The ground mass of the rock consists mainly of microliths of feldspar oriented according to flow lamination. In contrast to the other rhyolite localities of the island, the layering of the rocks at Murray Hill is approximately horizontal.

The general lithology is similar to the rocks encountered in the roadside cut at Watson Point between Lazy Hill and Freshwater Bay. To the N of Murray Hill, dark conglomerates of the younger eruptions overlie these rocks.

Trip K: Full-day hiking trip across the island: Salt Creek valley, High Peak to Smoothwater Bay (road map fig. 89, geological map fig. 31).

For this trip, solid shoes and ample dnnking water are essential. Part of the route (between the headwaters of Salt Creek and High Peak) is off-trail, so a machete will be helpful. Those not acquainted with the area should hire a local guide.

The itinerary begins at Lazy Hill (near *Land Stops I 10* or I 11) and follows the bed of Salt Creek upstream until reaching the wide plain that spreads between High Peak, Patient Hill, and Peggy Shine Head. From the headwaters of Salt Creek, it proceeds southward across dense bushland to reach the trail which leads to High Peak. The hike along Salt Creek to the Peak should only be done in the dry season. During the rainy season, the route to High Peak may be followed from Bottom House or Smoothwater Bay directly to Stop K4, and from there to the Peak. Return would be by the same itinerary.

Land Stop K1: Banded rhyolites at the entrance to Salt Creek Valley

Laminated rhyolites cropping out in the gully are part of the volcanic dome that forms the steep hills to the S. The lamination is dipping 45° to E. The itinerary follows the riverbed upstream over large boulders of basalts and banded rhyolites.

Land Stop K2: Basaltic lava flow in riverbed of Salt Creek

Dark lava flows with white plagioclase and black basalt conglomerates with ash layers crop out in the riverbed. These rocks will be repeatedly seen upstream along the itinerary. They form the mountains to the N of Salt Creek valley.

Continuing the itinerary, giant basaltic blocks and cascades have to be circumvented to reach the 300 m-high central plain of the island. The surface of the plain appears to be mainly altered rhyolitic material. There are few outcrops and the vegetation very dense.

Land Stop K3: Rhyolites at High Peak (figs. 114 and 115)

Massive, deeply weathered rhyolites will be seen all along the trail leading to High Peak. The rocks here reveal a vertical lamination. This is the central area of the rhyolite dome. These same rocks form all the smaller peaks to the W of High Peak. They all developed the typical "piton" shape which is so characteristic of the eroded volcanic domes of the Lesser Antilles.

The panoramic view from High Peak over the island and the entire surrounding shallow reef platform is great. On very clear days, even the Hill of San Andrés has been sighted from here. There are not many outcrops, but the vegetation is impressive and observation of the flora and fauna is rewarding. Some of the gullies contain limited outcrops of banded rhyolites and dark volcanic conglomerates containing ashes from the younger basaltic eruptions.

Land Stop K4: Blocky basalt in white ashes at water distribution tank and on nearby hills.

The low hills in the area are all capped by white ashes with blocky basalt: Layers of basaltic conglomerates are common. These may be both pyroclastic and epiclastic rocks. Volcanic ashes with blocky clasts can be best studied near a water dis-

Figure 114. *Land Stop K3.* Old Providence: Rhyolite rocks of the central volcanic dome weathering out along the trail to High Peak. Weathering produces rounded boulders, though close-up examination of rocks shows a distinct vertical banding pattern. September 5, 2000.

Figure 115. Old Providence: Rhyolites cropping out near the trail descending from High Peak towards Bottom House. Exfoliation planes parallel to surface. August 22, 2002.

tribution tank on the ridge between bottom House Gully and Smoothwater Bay.

The itinerary ends at the main road in Smoothwater Bay at *Land Stop I 3.*

Trip L: Volcanic outcrops in the vicinity of Sta. Isabel

Land Stop L 1: Hike to Split Hillfrom the village of Mountain (figs.116 and 117)

The top of Split Hill can easily be reached by foot from the village of Mountain by climbing up over steep grassland. On top, the wide NW trending tectonic clef of the "split" can be examined. This is an extension fracture widened by erosion. Similar but less spectacular parallel clefs can be seen in the mountain ridge to the N of Split Hill. The rocks are very coarse, northward-dipping volcanic conglomerates (mostly basaltic) with hardly rounded clasts. The material in this ridge seems to be pyroclastic in origin and must date from some of the youngest explosive eruptions recorded in the rock sequence of the island. These deposits may have been formed by phreatomagmatic explosions, in which great volumes of lithic debris were blown out from a rigid plug in the conduit near the center of the island. Much of the dark blocky material is embedded in a white ash matrix. The ridge with Split

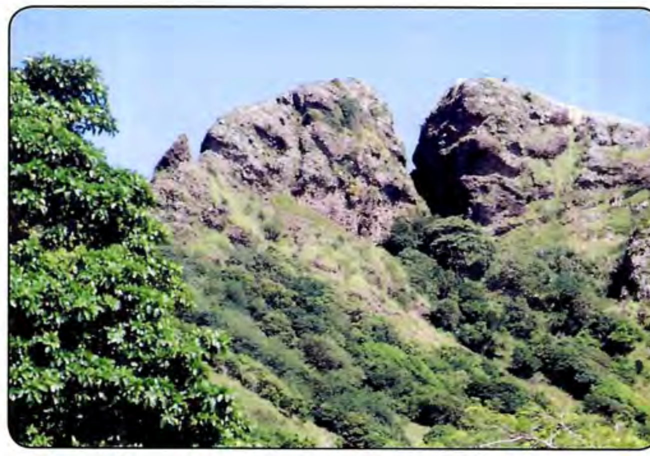


Figure 116. *Land Stop L1.* Old Providence: Eastern flank of Split Hill as viewed from the plane. Two weathered-out extension gashes are clearly visible. Note that bedding planes are inclined towards N (right). September 6, 2000.

Figure 117. *Land Stop L1.* Old Providence: Northern wall of main cleft in Split Hill. Material is a coarse, late Miocene volcanic conglomerate that prograded northward in giant "fore-sets" towards Marshall Hill. Note that some of the large poorly rounded clasts almost reach meter-size. September 3, 2000.

Hill belongs to a pyroclastic and epiclastic series of directed flows which originated in the central island area. It extends at least to Marshall Hill and Jones Point in the N.

From the hilltop, we have a great view of the morphology of the northern part of the island, including Sta. Catalina Bay, Crab Cay, Maracaibo Hill, and the surrounding reef complex. The round-trip hike from Mountain takes up to 1 or 2 hours.

Land Stop L2: Columnar basalt at eastern shoreline of Jones Point

This peninsula is formed by young pyroclastic and epiclastic rocks in continuation of the northward-dipping series of Split Hill. These overlie black alkali olivine basalt which yielded a K-Ar age of 7.4 +- 0.4 million years. Columns of the underlying basalts crop out at the eastern shoreline of Jones Point. Many of the columns are dislocated by coastal erosion, but others remain in their original position.

Land Stop L3: Epiclastic rocks overlying basalt in road cut at Jones Point

Epiclastic rocks (volcanic ashes with large, almost meter-wide blocks) overlie a black basaltic lava flow more than 3m thick. Equally black basalts were seen at Maracaibo Hill and on the low foothills lying to the W of the main road between Mc-Bean's Hill and the village of Mountain.

Land Stop L4: Panorama from Marshall Hill

This hill may be ascended over a steep grass slope starting near the hospital at Sta. Isabel. Volcanic conglomerates form the hill. Its top is capped by a basalt flow.

The view covers Sta. Catalina Harbor, the town of Sta. Isabel, and Sta. Catalina Island, as well as the eastern lagoon with Crab Cay. In the years after discovery, Sta. Catalina and Old Providence were still a single island (called Sta. Catalina). Both parts were connected by a sandy or muddy tombolo, which was probably protected by mangrove vegetation. During the early occupation of the island in the 17th century, a trench was cut as an additional defense to the fortifications that would become Morgan's Fort (later named Fort Aury). Since that time, currents, especially during hurricanes, seem to have widened the trench to the present Aury Channel (see Geister 1992:7). Today the islands are connected by a floating bridge. For the panorama of Sta. Catalina Harbor and Aury Channel with Sta. Catalina.

Land Stop L5: Volcanic scoria at Morgan's Fort (or Fort Auryl)

The fortifications have been built on reddish volcanic scoria accumulations. Scoriaceous rocks are distributed widely on Sta. Catalina. They also form Morgan Head, a spectacular volcanic block that weathered out at the coastline some 700 m to the NW of Morgan's Fort. The rocks of Sta. Catalina appear to be among the youngest eruptive rocks, which lie in continuation of the stratigraphical sequence of Split Hill to Jones Point. The strata dip roughly to the N and NW. The rocks are highly vesicular and thus very porous. The vesicles are filled with freshly formed minerals.

8.3 Visit to Holocene atoll environments of Courtown Cays

Trip M: Full day trip by ocean-going boat from San Andrés to view islets and submarine environment (maps figs. 37 and 38). Sites to be visited are marked on plan fig. 118).

Sea Stop M1: Windward fore-reef communities

This is a gently dipping calcareous terrace with low-relief calcareous ridge-like structures. Shallow furrows between the ridges are filled with calcareous sands. Gorgonians (*Pseudopterogorgia* spp.), scattered massive coral heads (Montastraea spp., *Colpophyllia natans*, *Siderastrea siderea*), and large sheets of excavating sponges (*Cliona* spp.) are conspicuous. The terrace descends at low angle to about -20 m, where it gives gradually way to a subvertical slope below - 30 m.
Sea Stop M2: Windward perpheral reef with grooves

At this locality, the windward reef wall is indented, the reef crest becomes discontinuous, and a well-developed groove-and-spur system appears. The 2- to 5 m-deep grooves allow small boats to pass through the emergent barrier during calm seas. Profuse growth of *Millepora complanata* and *Porites porites* is seen on the spurs. Snorkelers can often watch reef sharks (*Carcharhinus perezi*) and nurse sharks (*Ginglymostoma cirratum*).

Sea Stop M3: Visit to East Cay (figs. 119)

East Cay is a small arrow-shaped island on the lagoon terrace. It is densely vegetated by coconut trees, Tournefortia, and Scaevola shrubs. This cay currently is connected to nearby Sand Cay by a tombolo formed of sand and shingle. Recent beach accretion appears to be to the NW. Several bands of beach rock paralleling the windward shoreline of East Cay lie about 50 m to the E on the lagoon terrace. They mark the position of previous shorelines and indicate that the cay is migrating toward the lagoon. Submerged beach rock is mostly overgrown by coralline and green algae and contains dense populations of boring sea urchins (*Echinometra lucunter*). The only seagrasses (Syringodium and Halodule) present on this atoll occur as a single small meadow on the sheltered leeward side of East Cay.

Sea Stop M4: Leeward reef communities

The southernmost peripheral reef is partly emergent at low tide and mostly coated by calcareous red algae (Porolithon pachydermum and others). It resembles a true algal ridge without having the thick massive melobesioid framework. Numerous boreholes made by chitons (Choneplax lata) perforate the algal crust. Scattered colonies of *Diploria* and *Millepora* encrust the reef flat. At 3 to 7 m of water depth, on the subvertical walls, *Dendrogyra cylindrus*, *Agaricia agaricites*, branching octocorals, and dense growths of *Halimeda* are common.

Stop M5: Leeward communities of outer reef wall and sand slope

The leeward terrace dips from the shallow reef flat of the atoll sill to -17 to -20 m depth in a distance of no more than 250 m, giving way suddenly to a steep sand slope or to a vertical cliff On the outer margin of the terrace, diversity and abundance of scleractinians is very high. Massive *Montastraea* spp. and *Colpophyllia natans* form large dome-like structures, between which "sand falls" can be sighted from the surface. The vertical cliff is mostly devoid of corals, but large tube-like sponges and antipatharians are attached to the rather smooth substratum.

Stop M6: Lagoonal reef communities with anastomosing patch reefs

Elongated lagoonal patch reefs dominated by *Montastraea annularis* and *M: faveolata* coalesce and form an intricate system of anastomosing reefs. The white sand-covered lagoon floor between the reefs is nearly 8 m deep. Most reefs are deeply submerged, but some almost emerge at low tide. The latter may exhibit scattered, mostly dead thickets of *Acropora cervicornis* at their crests. Brown algae (*Dictyota, Lobophora*) largely overgrow the dead coral heads.

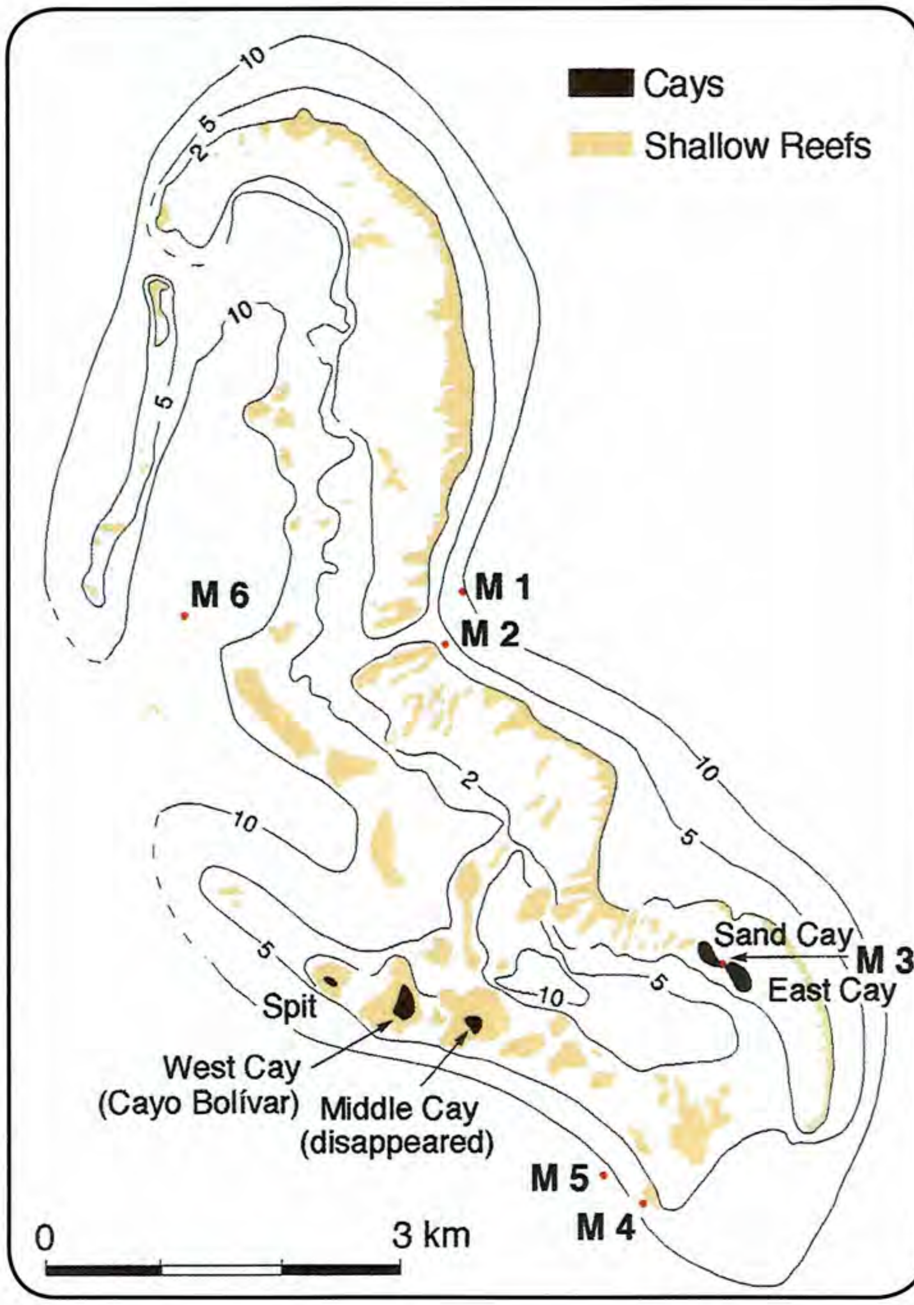


Figure 118. Sketch map of Courtown Cays atoll. Stops M1 to M6 are indicated. See also figs. 37 to 38. Adapted from Milliman (1967a).

Figure 119. *Estación en el mar M4. Courtown Cays: Vista desde East Cay hacia el SE a lo largo del tómbolo que conecta actualmente este cayo con Sand Cayo Mayo de 1994.*

9. OVERFIGHT OF THE ARCHIPELAGO BY CHARTERED PLANE

An Overfight in a chartered plane from the San Andrés airport will permit examination of the gross morphology of the following reef complexes: San Andrés barrier reef, atolls of Courtown Cays, Albuquerque Cays, Roncador Bank, Serrana Bank, and Quitasueño Bank, as well as the Old Providence barrier reef (see fig. 2). The best view of the reefs, especially for taking photographs, is at midday when the high sun yields deepest light penetration in the water and minimum reflection. The round-trip flight in a small plane will take some 3 hours and may be combined with the transportation of the group to Old Providence.

Figure 120. San Andrés: German Point with leeward barrier Bar from the air. Note the "trail" of sediments that bypassed the point. See also fig. 64. June 20, 1996.

Due to time and fuel limitations, the Overfight will not cover Serranilla Bank, Alice Shoal, and Bajo Nuevo, the northernmost reefs of the Archipelago.

9.1 San Andrés Island and barrier reef complex from the air

(see map fig. 15)

This reef complex measures approximately 17 km from N to S, including the insular shelf.

* After the take-off from San Andrés airport, the plane will fly over German Point, where we may clearly see the apron of fine current-transported sediments that bypassed the northern tip of the island and were deposited at the fore-reef terrace (fig. 120) and on the outer slope. Note submerged pre-Sangamon cliff (in dark) with seaward escarpment (distinct line). The cliff line lies in the southward prolongation of the leeward barrier named Bar (in center left of fig. 120).

* The leeward barrier appears to the left. It ends in the N with the wave-swept algal ndge of Top Blowing Rock, which is unprotected from the NE.

* In the Johnny Cay area, the barrier reef exhibits spurs and grooves directed towards the lagoon. Shallow patch reefs are visible on the lagoon terrace and in the deep lagoon basin nearby.

* Heading S, the barrier of East Reef will be seen. It has a distinct groove-and-spur system directed towards the fore-reef terrace, which is especially well-developed in the Haine Cay area (background).

The lagoon terrace appears as a broad apron of reef debris and sand transported by waves and currents towards the W, where it ends abruptly at the drop-off of the sand cliff (fig. 121) to the eastern lagoon basin (best visible near Haine Cay).

Deep and shallow patch reefs in the lagoon basin are distinguishable by their clearer or darker hues.

* The plane will pass near Cotton Cay to view its fringing reef (fig. 122).

* To the S of San Luís village, the barrier approaches the coast to become a fringing reef. The latter is intempted at Rocky Point, where we shall see the deep blue "scallop" of Bocatora Hole (fig. 123) at the outer margin of the fore-reef terrace.

* Along the west shore, the -4 m terrace becomes clearly visible (fig. 124) with its dark seaward margin. The sharp line of the submarine cliff marks the beginning of the inner sandy zone of the - 20 m terrace. The clear sediment cover

Figure 121. San Andrés: Aerial view of the E side of the San Andrés reef complex. East Reef (with shipwreck) and lagoon terrace and basins. View to S. June 21, 1993.

Figure 122. San Andrés: Cotton Cay with shallow fringing reef in the San Andrés harbor. Summer 1969. See also fig. 68.

Figure 123. San Andrés: Windward fringing reef at the SE coast is interrupted at Rocky Point. Dark blue "scallop" in the fore-reef terrace marks the vertical drop-off at Bocatora Hole. August 22, 1998.

Figure 124. San Andrés: View of leeward coast S of Southwest Cove. The shallow -4m terrace is visible as a dark band along the coast. The clear band seaward of this terrace corresponds to the sandy inner margin of the -20m terrace. The dark tones seaward from here indicate the coral carpet of the -20m terrace. August 22, 1998.

Figure 125. San Andrés: Leeward coast at Poxhole (inlet at center). Note the Holocene -4m terrace that fringes the coast N of Poxhole (left). A very narrow -4m terrace is developed to the S. Sam Wright Hill is seen on the left. August 22, 1998.

Figure 126. San Andrés: Panorama covering central hill to Duppy Gully valley with Big Pond in center. Northend town in background to the left. June 20, 1996.

is patchily overgrown by dark algae. The coral carpet of the "-20 m terrace" (in dark) lies seaward. The outer edge of the terrace, where sediment tongues plunge down the outer slope (fig. 125), will be barely recognizable from the air.

* From above the center of the island, we shall view the Hill with Duppy Gully and Big Pond in the middleground (fig. 126) and a beautiful panorama of the reef complex with Haine Cay (fig. 127).

9.2 Courtown Cays atoll from the air

The atoll lies 22 km ESE from San Andrés and 47 km NE of Albuquerque. Including the fore-reef terrace, the NW to SE extension is more than 13 km. The northern half is trending NNE and the southern half trends NW, giving a kidney-shape to the atoll. (See plan figs. 118)

* The northern half of the deep lagoon is overgrown by a dense meshwork of anastomosing patch reefs.

* A rather wide windward fore-reef terrace ascends at a low angle from the outer margin of the atoll towards the seaward reef wall. Dark ridge-like structures and light sand-covered furrows lie perpendicularly to the reef wall over the entire width of the terrace.

* The continuous peripheral reef bends towards the lee of the atoll at both its NW (fig. 128) and SE ends.

* Wide sediment aprons prograde to the lagoon basin, where they end at a distinct sand cliff (fig.128).

* Sand Cay and East Cay on the windward lagoon terrace are fused by a recently formed tombolo (fig. 129, and fig. 130).

* The seaward reef wall is distinctly indented at two places. No reef crest is present at either place; instead, a groove-and-

Figure 127. San Andrés: Panorama from central hill (red roof is from First Baptist Church on Mission Hill) to eastern part of reef complex with Haine Cay. June 20, 1996.

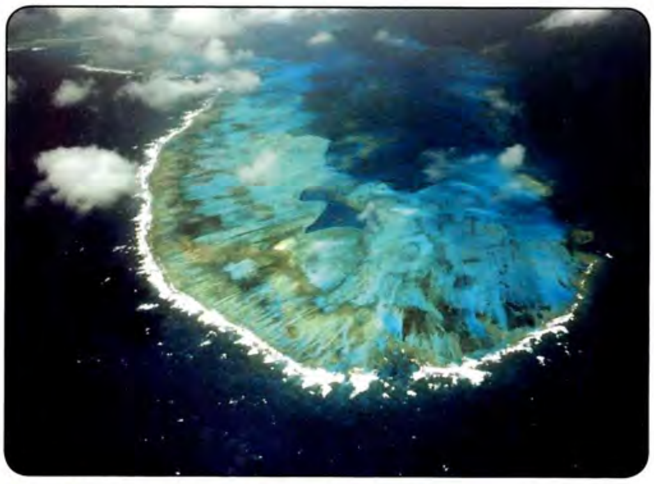


Figure 128. Courtown Cays atoll: View from the N. Note westward bulge of windward peripheral reef (upper left). June 20, 1996.

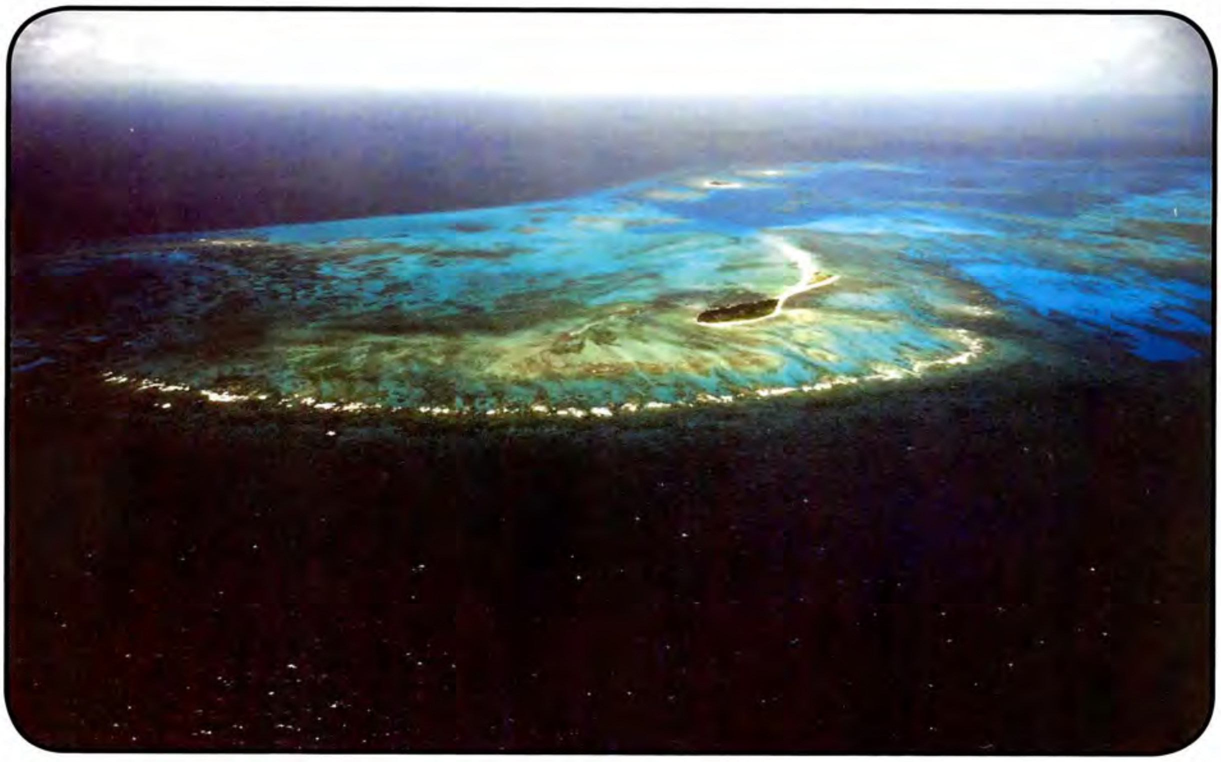


Figure 129. Courtown Cays atoll: View from E with East Cay (left) and Sand Cay on the windward lagoon terrace. West Cay and Sand Spit (left, background) are recognizable on the leeward lagoon terrace. Sea Stop L3. October 28, 1994.

Figure 130. Courtown Cays atoll: East Cay (left) and Sand Cay connected by a tombolo. View towards S, September 12, 2001. Sea Stop L3.

Figure 131. Courtown Cays atoll: Westward bulge of windward atoll rim with groove-and-spur zone. Sea Stops M1 and M2. October 28, 1994.

spur system is well developed and can be clearly distinguished from the air (fig. 131).

* Several leeward shoals form a discontinuous sill which partly encloses the lagoon basin (fig.127). Most of these reefs are emergent at low tide. They are almost completely coated by calcareous red algae and resemble algal ridges.

* Cayo Bolívar (West Cay), the white sand spit, and the disappeared cay (Middle Cay) formed as rubble and sand accumulations on such peripheral reefs (fig. 129, background).

* The rapidly darkening hue moving eastward from the peripheral reefs indicates the steepness of the leeward fore-reef terrace and the outer slope of the atoll (fig. 130). The terrace usually ends at -15 to -20 m depth and gives way to a nearly vertical drop-off.

* A major sedimentary ramp may be vaguely recognizable at the terrace margin off West Cay (lighthouse!). Here reef sediments are evacuated from the lagoon, falling out to greater depths on the seaward slope of the atoll (fig. 131 background).

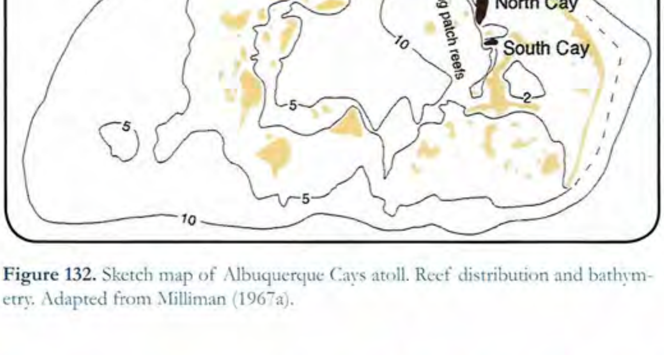


Figure 132. Sketch map of Albuquerque Cays atoll. Reef distribution and bathymetry. Adapted from Milliman (1967a).

9.3 Albuquerque Cays atoll from the air

The almost-circular atoll of Albuquerque Cays lies about 3 5 h SW of San Andrés Island. It measures about 8km in E-W diameter from shelf-edge to shelf-edge (figs. 130 and 131).

* Toward the north and eastern sides of the atoll, an almost continuous windward peripheral reef is well developed.

* By contrast, a peripheral reef is largely absent in its lee. Ill-defined leeward reef segments in the W are detached from each other by wide gaps and channels (fig. 133)

* Two small islets, North Cay and South Cay, rise hardly 2 m above low-sea level. They are separated from each other by a shallow; 250m-wide channel (figs. 133 and 134).

* A few semi-emergent "miniature atolls," as well as some anastomosing patch reefs (dark colored) of Montastraea, can be well observed in the lagoon basin near the cays.

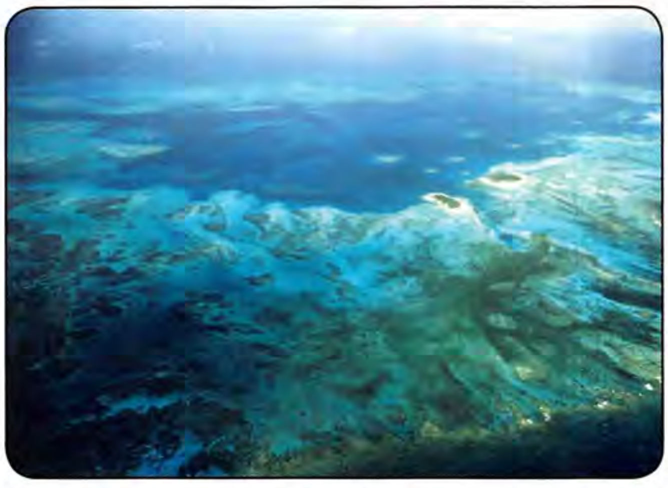


Figure 133. Albuquerque Cays atoll viewed from SE, featuring South Cay (left) and North Cay (right) on the windward lagoon terrace. Some of the patch reefs in the lagoon basin are "miniature atolls". October 28, 1994.

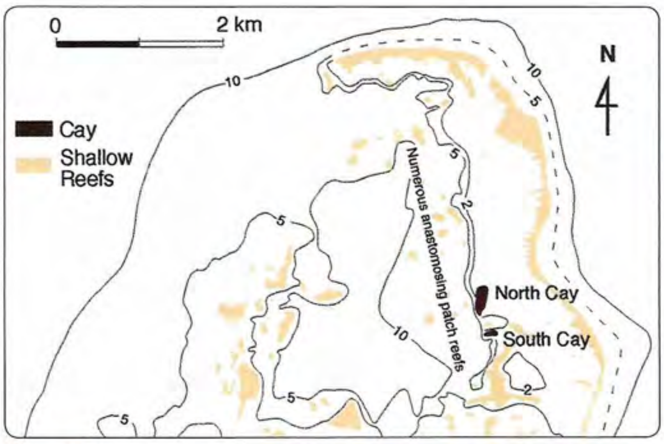


Figure 134. Albuquerque Cays atoll: View from W. The entire windward reef rim is shown (background). In the foreground lies the leeward terrace margin with sand slopes. Note shallow lagoon terraces (clear) and deeper parts of lagoon basins (dark). June 20, 1996.

Figure 135. Albuquerque Cays atoll: View from NE. Note peripheral reef, lagoon terrace and lagoon basin. June 20, 1996.

Figure 136. Albuquerque Cays atoll: View from South Cay towards North Cay. Windward shore of South Cay with eroded beach-rock. It parallels the shoreline and is covered by green algae. September 9, 2001.

Figure 137. Quitasueño Bank half-atoll: Eastern peripheral reef (with shipwreck) and "secondary barrier" (to the right). Note fore-reef terrace with erosional features (fore-ground), lagoon terrace and patch reefs.

* Two navigable channels, in the NE and SW, connect the lagoon basin with the open sea.

* Note that nearly 25 % of the lagoon floor at Albuquerque is covered with patch reefs.

9.4 Quitasueño Bank half-atoll from the air

* The peripheral reef is spectacularly developed. Note a "secondary barrier" that joins the main reef from the lagoonward side. It is densely covered by rhodoliths. Clear sandy lines indicate areas of sediment transport by currents and storm waves from the fore-reef to the lagoon terrace. A sand cliff is developed on the leeward side. The submarine topography on the fore-reef terrace reveals a pre- Holocene relief heavily abraded during storms (fig. 137).

* There is a deep reef pass in the peripheral reef.

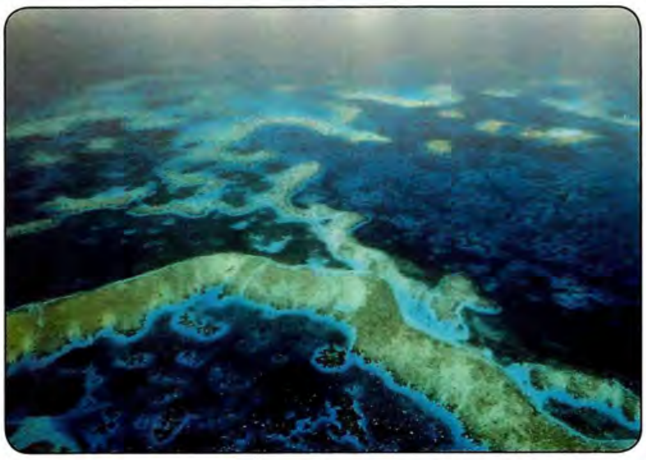


Figure 138. Quitasueño Bank half-atoll: Lagoon with shallow ribbon reefs and deeper anastomosing patch reefs. August 22, 1998.

* In the lee of the peripheral reef wall, irregular patch reefs occur almost everywhere in the lagoon.

Ribbon-like patch reefs (fig. 138) and anastomosing patch reefs are most important, the latter showing several stages of development (figs. 139 to 141).

* Sediments shed from the reef cover patch reefs and incorporate them into the lagoon terrace (figs. 142 to 143).

* The water deepens gradually from the reef wall to the W. The "lagoon" is completely open to the W because a leeward reef wall is not developed.

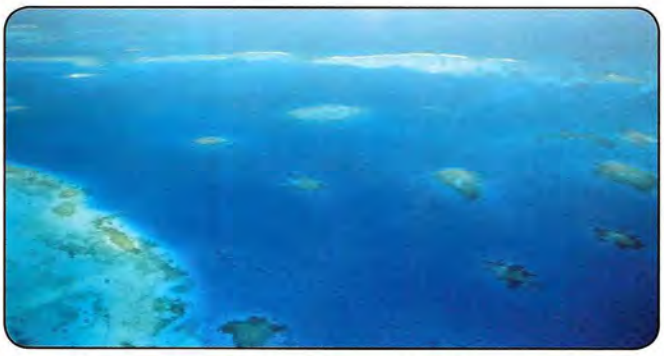


Figure 139. Quitasueño Bank half-atoll: Lagoon with shallow patch reefs and incipient anastomosing reefs in deeper water. August 22, 1998.

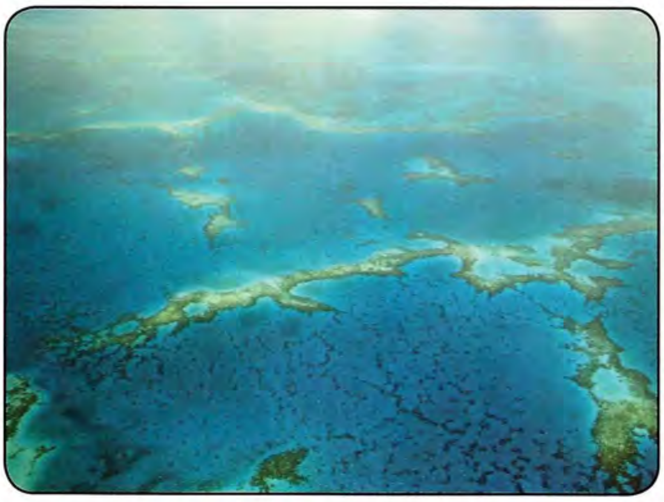


Figure 140. Quitasueño Bank half-atoll: Lagoon with irregular shallow ribbon reefs reaching shallow water and incipient anastomosing reefs on the deeper lagoon floor. Peripheral reef to the E (in background). August 22, 1998.

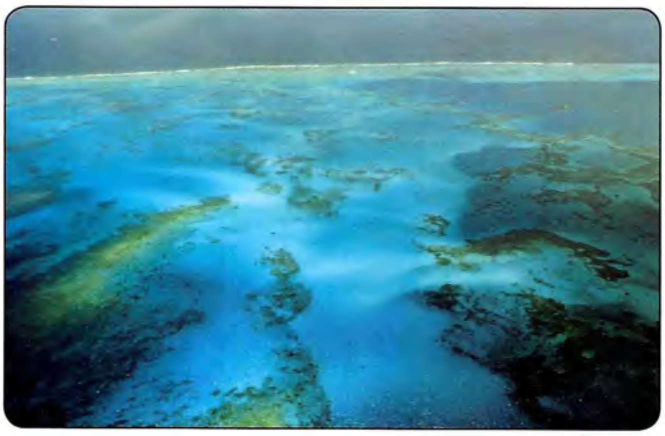


Figure 143. Quitasueño Bank half-atoll: Patch reefs and lagoonal sands. Peripheral reefs in background. August 22, 1998.

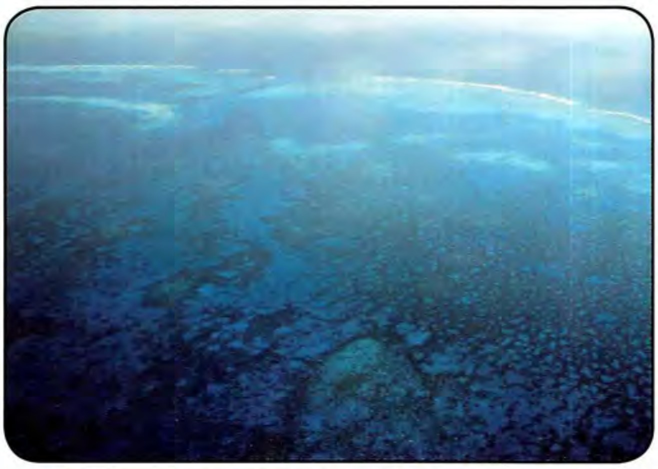


Figure 141. Quitasueño Bank half-atoll: "Densely knit" anastomosing patch reefs cover the floor of the deeper lagoon floor. August 22, 1998.

Figure 142. Quitasueño Bank half-atoll: The sand sheets of the sand cliff (foreground) prograde gradually over anastomosing reefs fused to larger patch reefs. August 22, 1998.

9.5 Serrana Bank atoll from the air

This atoll lies some 80 km NNW of Roncador Cay. It is the largest atoll in the Archipelago. It is about 36 km long in NE-SW direction. The width is about 15 km. (see plan fig. 144)

Note that, with the exception of its western and southwestern margins, the bank is fringed by a peripheral coral reef interrupted only by three major passes.

The plane will approach the atoll from the S, flying over Serrana Cay or "Southwest Cay" (with lighthouse) at the extreme southwestern end of the peripheral reef. This cay is 500 by 200 m. Sand dunes rise to about 10 m, though most of the island is only a few meters high.

The western and widest part of the lagoon is a rather monotonous sand plain with only localized patch reef formation. It is completely open to the ocean in the W. An appreciable amount of sediment here is formed by modern oolites.

Leaving Serrana Cay, the plane will turn in a NE direction along the southern branch of the reef wall and approach Narrow Cay and Little Cay (fig. 145). A recently wrecked ship can be sighted on the way. Note patch reef growth in the lagoon near Little Cay. The lagoon bottom is covered by marine vegetation. Grazing reef fishes make halos in the vegetation cover around the patch reefs.

The plane will continue in an easterly direction along the peripheral reef to East Cay (fig. 146). From there it will fly to the N to meet the northern branch of the reef. Note formation of "secondary barrier reefs" (fig. 147) near North Cay.

During the flight, it will become obvious that a sandy ridge (or sandbank) divides the lagoon in an eastern and western basin.

Note that the predominance of intricate reticulate reefs and other patch reefs is in the easternmost sector of the lagoon. The western sector is mainly formed by oolite shoals almost without patch reefs.

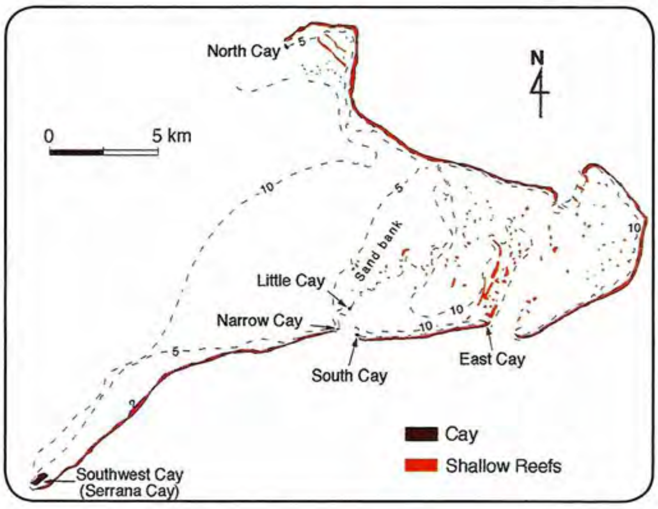


Figure 144. Sketch map of Serrana Bank atoll showing distribution of reefs and bathymetry. Adapted from Milliman (1967a).


Figure 146. Serrana Bank atoll: Peripheral reef at East Cay as seen from NE. Lagoon with patch reefs. June 20, 1996.

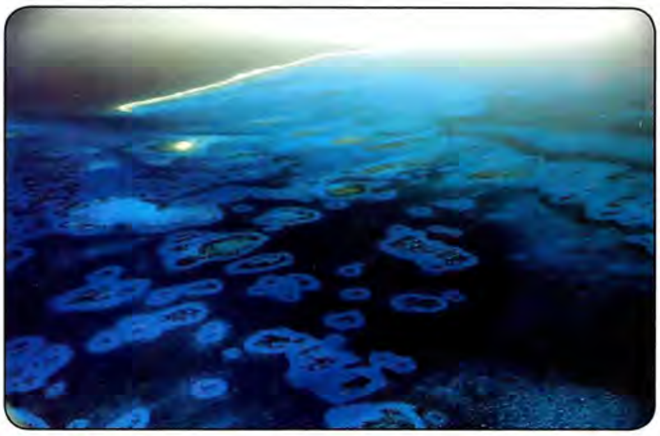


Figure 145. Serrana Bank atoll: Lagoon with Little Cay (right) and Narrow Cay as viewed from NE. Lagoon basin with patch reefs. Bottom covered by algal growth. June 20, 1996.

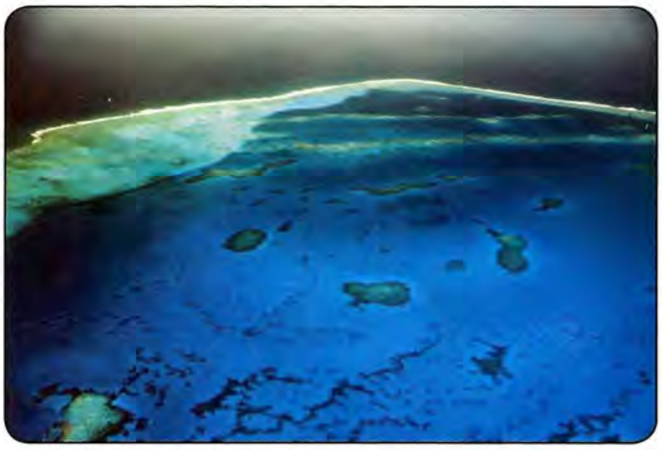


Figure 147. Serrana Bank atoll: Northern bow of peripheral reef near North Cay (to the left of view field) with secondary inner barrier and lagoonal patch reefs. June 20, 1996.

9.6 Roncador Bank atoll from the air

Roncador Bank atoll is about 13km by 6km and lies some 100km S of Serrana Bank.(see plan fig. 150)

* The plane will approach from the N and fly first over Roncador Cay, a small, roughly 4m high, unvegetated shingle islet situated on the reef near the northern point of the bank (fig. 149).

* From Roncador Cay, the plane will fly in a southeasterly direction along the continuous windward peripheral reef (figs. 150 to 152). Note the large emergent reef blocks lining the outer reef flat. The sand cliff is prograding rapidly towards the lagoon basin, "suffocating" numerous patch reefs on its way.

* The remnants of a wrecked ship can be seen near the southern end of the windward reef wall.

* The floor of the lagoon basin deepens gradually to the W. Dense concentrations of anastomosing patch reefs formed

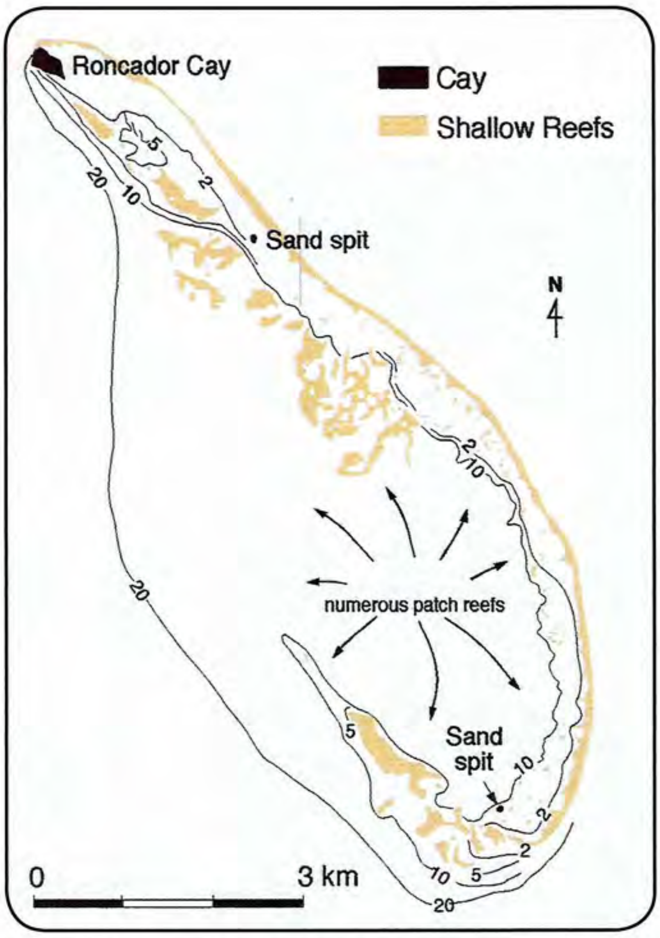


Figure 148. Sketch map of Roncador Bank atoll showing distribution of reefs and bathymetry. Adapted from Milliman (1967a).

by the star coral Montastraea cover the Bottom of the deeper lagoon basin.

* Shallow patch reefs of the stag horn coral Acropora cervicornis rise to the surface.

* The lagoon is completely open to the W, as no leeward coral reef is developed.

9.7 Old Providence Island and barrier reef complex from the air

The entire reef complex, including the shelf margin, is 33 km long and trends NNE. (map fig. 31)

* The plane will approach the reef complex from the N, passing between Low Cay (coral shingle with lighthouse) and the NE bend of the barrier (The Elbow). See figs. 97 and 153.

* To the N and E, the continuous barrier reef (figs. 154) protects a half-lagoon more than 20 m deep (Point Blue). It is open to the W.

Figure 149. Roncador Bank atoll: Roncador Cay, a coral-shingle islet at the NE tip of the peripheral reef. June 20, 1996.

Figure 150. Roncador Bank atoll: Peripheral reef with Roncador Cay in background. June 20, 1996.

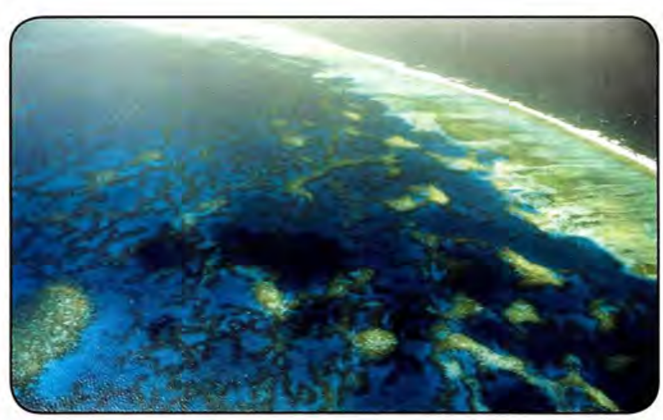


Figure 151. Roncador Bank atoll: Lagoon with well developed anastomosing patch reefs. June 20, 1996.

* Patch reefs in the shallow lagoon are generally platform reefs, some of which are more than 100 m in diameter (figs. 151 and 152). Deeper lagoonal patch reefs are mostly of the knoll reef type. Their tops may be as deep as -20 m.

* The incomplete lagoon basin of Point Blue is separated from the lagoon basins to the S (Long Shoal Blue and Moore Bar Blue) by two shallow sills overgrown by coral patches (mainly *Acropora palmata*). The sills, Pearstick Bar (Second

White Water) and First White Water, are separated from each other by Sea Devil Channel (figs. 153).

* Note isolated shallow patch reefs on the fore-reef terrace to the E.

* To the S of Moore Reef, there is a transition from the continuous barrier into a discontinuous barrier reef formed by a broad band of thousands of patch reefs.

* In the lee of Sta. Catalina Island are the fringing reef N of Morgan Head and Lawrance Reef.

* To the NW we may see Channel Mouth, a submerged Pleistocene stream valley cut into the reef platform during Pleistocene sea-level lowstands.

* Note the "miniature atoll" of White Shoal in the lagoon basin S of Crab Cay. The largest mangrove area of the island is seen at the shoreline around McBean's Lagoon (fig. 156).

* Off Iron Wood Hill, the barrier becomes continuous for some 2 km. Note that the wide band of patch reefs forming the discontinuous barrier in the N continues as a chain of patch reefs on the lagoon terrace.

* These patch reefs on the lagoon terrace in the S become more linear. Some of them lie parallel to the barrier. Some circular patch reefs in the lagoon basin near Tinkham's Cut are dominated by *Montastraea* and lie in water deeper than 15 m.

Figure 152. Roncador Bank atoll: Peripheral reef. Patch reefs of the lagoon basin became incorporated into the lagoon terrace by the prograding sand cliff. June 20, 1996.

Figure 153. Old Providence: The NE bend of the barrier reef (The Elbow) viewed from SW. Platform reefs in foreground occupy the fairly shallow lagoon basin. The lagoon terrace and sand cliff are visible as a clear lagoonward fringe of the barrier. August 22, 1998.

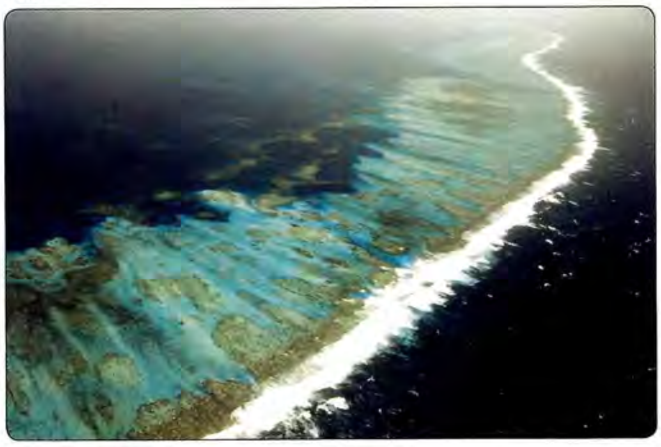


Figure 154. Old Providence: Northwestern end of barrier reef with Table Rock (last coral patch at left) and Low Cay (white blotch). Patch reefs. June 12, 1993.

Figure 155. Old Providence: Looking to the E over Pearstick Bar. Sea Devil Channel to the right. August 22, 1998.

* After crossing Aury Channel (fig. 154) between Sta. Catalina and Old Providence Islands, the fringing reef off Maracaibo Hill will appear (fig. 155).

* In the Crab Cay area, a spectacular concentration of pinnacle reefs becomes visible. It forms a broad belt replacing the continuous barrier reef.

* The southern part of the island becomes visible between Kalaloo Point and Manchioneal Hill. Note the spectacular sand cliffs prograding into the lagoon basin (fig. 158).

* W of Manchioneal Bay, we see the Pleistocene coastal fringing reef and outcrops in Miocene coral rocks at South Point.

* Flying northward from South Point along the western shoreline, leeward coral patches and seagrass flats become conspicuous on the insular shelf.

Figure 157. Old Providence: Sta. Catalina Island viewed from the NW. Lawrance Reef (Sea Stop P1) In the foreground (right). The northern peninsula (Jones Point) of Old Providence is visible in the background. August 22, 1998.

Figure 158. Old Providence: Aury Channel as viewed from the NE. Old Providence lies to the left with Sta. Isabel town (the capital) and Sta. Catalina Island to the right of the channel. Note lagoonal patch reefs in the left foreground. August 22, 1998.

Figure 159. Old Providence: East coast of the island with Maracaibo Hill (peninsula in center) and the Ironwood Hill peninsula (middleground). Note lagoonal fringing reef in front of Maracaibo Hill (Sea Stop F1) and irregular patch reefs in the lagoon basin (foreground). August 22, 1998.

Figure 160. Old Providence: Pinnacle reef belt in the Crab Cay area (Sea Stop G1). Crab Cay is seen in upper center of picture. June 20, 1996.

Figure 161. Old Providence: Eastern lagoon at the Ironwood Hill peninsula viewed from E. The clear patch in the center is the "miniature atoll" of White Shoal (Sea Stop G2), an annular reef with a shallow sand plain on top and steep reef slopes to the lagoon basin. The coast around McBean's Lagoon (seaward of the landing strip) is the largest mangrove area at Old Providence. August 22, 1998.

Figure 162. Old Providence: The southern lagoon basin between Kalaloo Point and Manchioneal Hill. Note the prograding sand cliffs. August 22, 1998.