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Coral Reefs

Controls on Reef Development and the Terrigenous-Carbonate Interface on a Shallow Shelf, Nicaragua (Central America)

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Abstract. Marine geology and physical oceanographic data collected during two field projects (~4 months) on the Caribbean shelf of Nicaragua indicate a surprising dominance of carbonate deposition and reef growth on a shelf that is receiving an abnormally large volume of terrigenous sediments. High rainfall rates (~400–500 cm/year), coupled with a warm tropical climate, encourage rapid denudation of the country's central volcanic highland and transport of large volumes of terrigenous sediment and fresh water to the coast. Estimates suggest that three times more fresh water and fifteen times more sediment are introduced per unit length of coastline than on the east coast of the United States. Distribution of the terrigenous facies, development of carbonate sediment suites, and the location and quality of viable reefs are strongly controlled by the dynamic interaction near the coasts of highly turbid fresh to brackish water effluents from thirteen rivers with clear marine waters of the shelf. Oceanic water from the central Caribbean drift current intersects the shelf and moves slowly in a dominant northwest direction toward the Yucatan Channel. A sluggish secondary gyre moves to the south toward Costa Rica. In contrast, the turbid coastal water is deflected to the south in response to density gradients, surface water slopes, and momentum supplied by the steady northeast trade winds. A distinct two-layered flow is commonly present in the sediment-rich coastal boundary zone, which is typically 10–20 km wide. The low-salinity upper layer is frictionally uncoupled from the ambient shelf water and therefore can expand out of the normally coherent coastal boundary zone during periods of abnormal flooding or times when instability is introduced into the northeast trades. Reef distribution, abruptness of the terrigenous-carbonate interface, and general shelf morphology reflect the long-term dynamic structure of the shelf waters. A smooth-bottomed ramp of siliciclastic sands to silts and clays mantles the inner shelf floor in a linear belt paralleling the coast. This belt generally corresponds to the western flank of the coastal boundary zone. Occurrence of reefs is generally confined to areas outside this zone. Terrigenous clays and silts of the inner shelf are abruptly (<20 km from the coast) replaced by *Halimeda*-rich sediment of the middle and outer shelf. Within the carbonate facies belt, reef complexes thrive as small, isolated masses; large, reef-capped platforms; reef fringes around islands; and shelfedge structures with vertical relief that can exceed 25 m. In general, the frequency and proliferation of reefs increase away from the turbid coastal boundary layer and toward the cooler and saltier water that upwells at the shelf margin.

Introduction

Until recently (Roberts and Murray 1978; Owens and Roberts 1978; Murray et al. 1982), the eastern shelf of Nicaragua, commonly referred to as the Miskito Bank, had remained a virtually unstudied platform for recent sedimentation bordering the Caribbean basin. In contrast to the gradually deepening nature of most continental shelves, the eastern Nicaragua shelf quickly deepens to about 20–40 m and maintains this general depth to the shelf edge, which is very abrupt and slopes steeply into deep water, much like a carbonate bank or insular shelf margin (Fig. 1). Although we now know that this generally wide (~250 km at the north to ~20 km at the south), shallow shelf supports a broad suite of carbonate depositional environments, only localized reef buildups have accreted sufficiently close to present sea level to be evident from the surface. If reef fringes and shoals associated with small offshore cays and islands were not present, it would be difficult to imagine the Miskito Bank as the vast carbonate platform that it is. In marked contrast to these few visible reminders of active reef growth, the recent sedimentary history, recorded in the geomorphology and topography of the entire coast and nearshore shelf, is dominated by interactions between abundant terrigenous sediment deposition and physical processes of the inner shelf and shore zone. Owens and Roberts (1978) and Murray et al. (1982) have shown that the abundance of terrigenous sediments

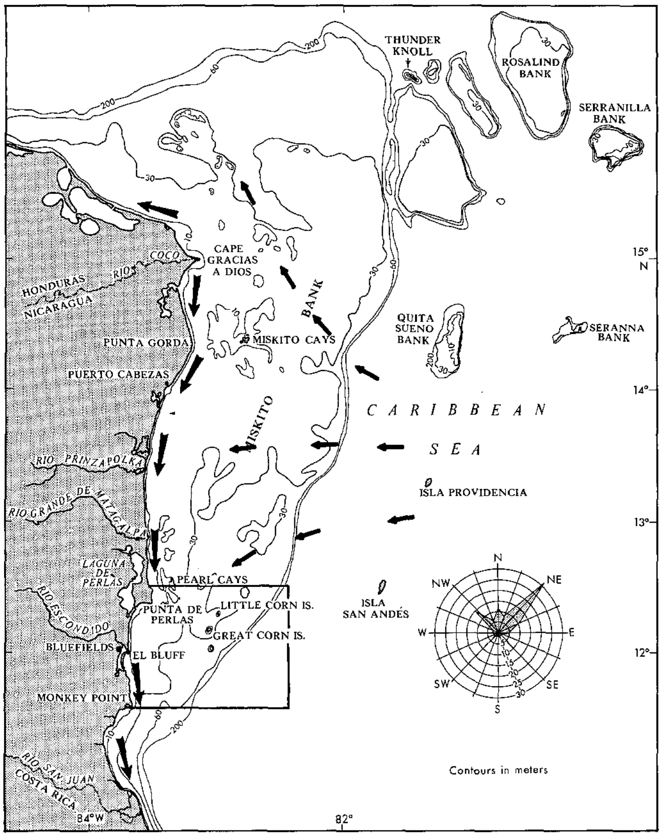

Fig. 1. General bathymetric map of the eastern shelf of Nicaragua illustrating a shallow platformlike structure and steep margin. Note the wind rose and strong signature of the northeast trade winds. Although reconnaissance-level studies were conducted along the entire coast and over much of the shelf, detailed data on sedimentology and physical oceanography were collected across the south-central part of the shelf. Enclosed area shows location of detailed investigations

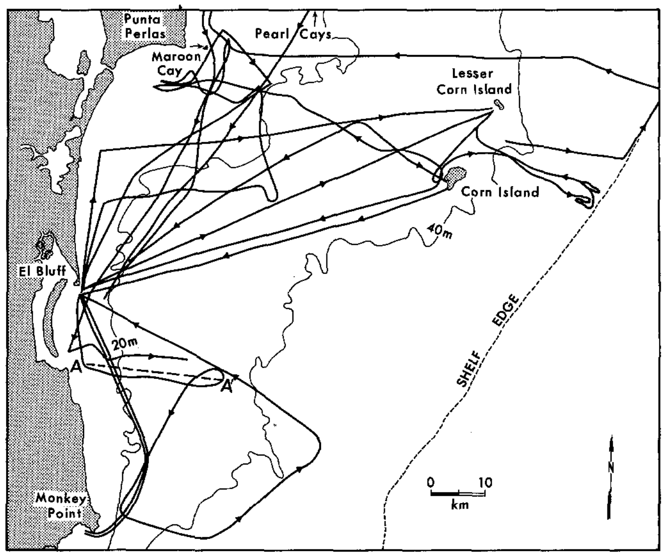

Fig. 2. Ship tracks within the study area on which physical oceanographic and marine geologic data were collected during August 1976 and September – October 1977 (see Fig. 1 for location of main study area)

at the coast and on the inner shelf is a product of rapid weathering of Nicaragua's volcanic highlands, which flank the east coast drainage basins.

A unique aspect of this tropical setting is the abnormal rainfall near the coast. Long-term measurements (United Nations 1968) show that the southern coastal plain receives in excess of 4.5 m/year. In Table 1 rainfall in eastern Nicaragua is translated into yearly estimated fresh water and sediment discharges for each of the thirteen rivers that drain the eastern coastal plain. A cumulative discharge for these rivers is 1.45×10^{11} m^3/year, which is about half the discharge of all rivers along the east coast of the US (Curtis et al. 1973), indicating that the Nicaraguan coast receives three times more fresh water per unit length of coast. Similar comparisons have been made with regard to total sediment flux (Murray et al. 1982). As Table 1 illustrates, the estimated total sediment supply is $24–32 \times 10^6$ metric tonnes/year, which is in neighborhood of fifteen times more sediment per unit length of coast than is delivered to the US Atlantic coast. With this unusually high input of fresh water and terrigenous sediment to a shallow tropical shelf, it seems logical that large areas of terrigenous sediment deposition would exist on the shelf and that the buildup of carbonate structures and sediments would be suppressed. As our field investigations discovered, this pattern of deposition is not the case. Therefore, the objective of this paper is to identify the surprisingly dominant dynamical conditions that affect the distribution of terrigenous sediments on the shelf and the impact this distribution system has on the subsequent development of viable reef systems and associated carbonate sediment facies.

Materials and Methods

A study of reefs on the Nicaragua shelf was part of a much more comprehensive and integrated investigation of the meteorology, physical oceanography, marine geology, and coastal geomorphology (Murray et al. 1982). Long-term records of rainfall as well as wind speed and direction were collected for all available sites along the east coast and for the offshore input sites Isla Providencia and Isla San Andres. These data were supplemental to high-resolution wind and cloud cover measurements made in the field (Hsu 1978). Although survey data were obtained from the entire coast and shelf, detailed investigations were conducted in an area of the south-central shelf between Punta de Perlas and Monkey Point (Fig. 1). Within this shelf segment, current data were collected from moored in situ recording current meters (Marine Advisers Q-16), drifting drogues, and profiling meters at anchor stations (Fig. 2). Anchor station data consisted of current speed and direction at 1.5, 3.0, 4.5, and 6.0 m and at 3-m intervals below that depth to 1 m above the bottom. These data were gathered utilizing a Marine Advisers Q-15 ducted current meter. A Bourns Model 2500 pressure transducer on the current meter provided a precise depth for each measurement. STD profiles (Plessey Model 9060), water samples, and bottom sediment samples were taken at each anchor station site.

Along all ship tracks (Fig. 2), sea-floor data were collected using a variety of methods, including side-scan sonar (Klein system), bathymetric profiling (Raytheon Model 731 echo sounder), bottom sampling (Shipek sampler), and SCUBA. Sediment sampling and direct observation via SCUBA were used to "calibrate" side-scan and echo sounder data. The locations of survey lines, anchor stations, and sample sites were tightly controlled by use of a Decca Del Norte electronic range-range locating system. Position updates were made at 1-minute intervals while collecting side-scan and echo sounder data.

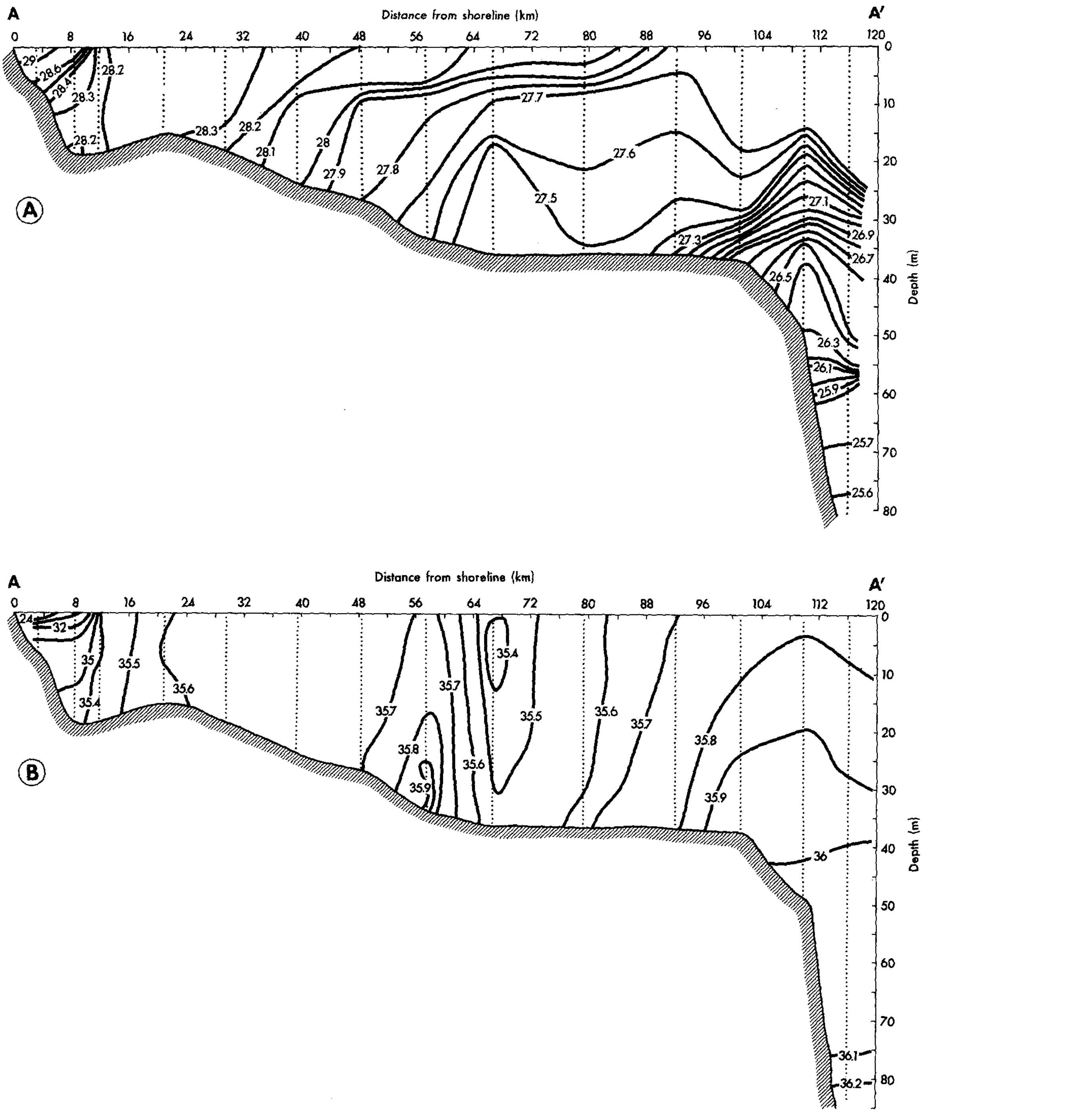

Fig. 3 A, B. Temperature (*A*) and salinity (*B*) profiles across the Nicaragua shelf from near Punta de Perlas east to the shelf margin (Fig. 1). Data were collected during August 1976

Results

Shelf Current Structure

Figure 1 illustrates two major current systems on the shelf: a broad, diverging flow forced by the mid-Caribbean current and a narrow, north-to-south-flowing coastal boundary current. As the east-to-west-flowing Caribbean current, with representative surface speeds of 50–100 cm/s (Crout and Murray 1979), intersects the shelf margin and rides up on the platform, it splits. One branch flows northerly toward the Yucatan Channel, and the other branch turns south toward Costa Rica. Frictionally dominated shallow-water processes of the shelf reduce open ocean drift speeds to generally less than 20 cm/s over the bank. However, this flow continually supplies the shelf with essentially sediment-free oceanic water. Salinity and temperature profiles (Fig. 3) across the shelf at the northern end of the study area support this point. Isotherms and isohalines from the 96-km mark to beyond the shelf edge (Fig. 3) indicate that oceanic water is upwelling onto the

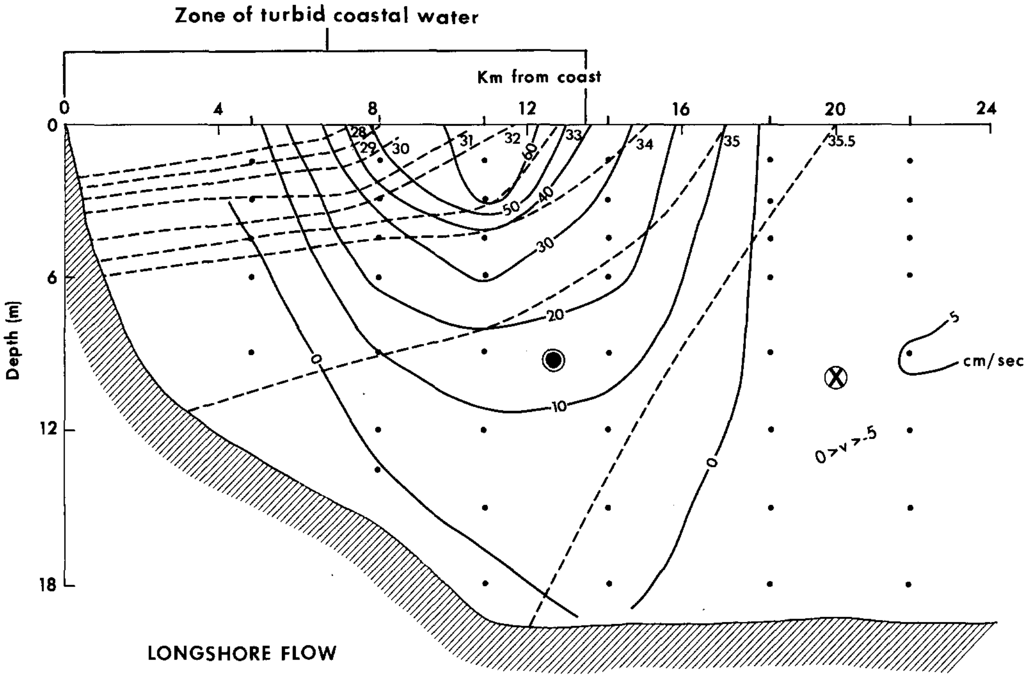

Fig. 4. Distribution of current speeds and salinity across the coastal boundary zone along the line designated A-A' in Fig. 2. *Solid dot* represents current flowing to the reader (southerly). *Crossed dot* indicates current flowing away from the reader (northerly). Current speeds are in centimeters per second

Table 1. Estimated annual discharge and sediment load for rivers draining eastern coastal plain of Nicaragua. Estimated total annual sediment supply from rivers: 24–32 × 10^6 m^3

Drainage basin	Area (km^2)	Estimated annual discharge[a] ($m^3 \times 10^6$/year)	Estimated annual sediment load[a] ($m^3 \times 10^6$/year)
Coco	24,761	36,460	5.5– 7.4
Ulang	3,833	5,840	0.9– 1.2
Wawa	5,548	9,712	1.5– 2.0
Kukalaya	3,707	6,810	1.0– 1.4
Prinzapolka	10,548	20,766	3.1– 4.2
Grande de Matagalpa	17,556	29,104	4.4– 5.9
Kurinwas	5,333	11,064	1.7– 2.3
Wawasang	2,681	5,237	0.8– 1.1
Escondido	12,308	26,464	4.0– 5.4
Kukra	1,494	3,856	0.6– 0.8
Punta Gorda	2,781	7,052	1.1– 1.4
Maiz	877	2,269	0.3– 0.5
Indio	1,822	5,138	0.8– 1.1
San Juan	39,545	59,645	9.0–12.2
Total	132,794		

[a] Annual discharges and sediment loads were estimated from rainfall data, drainage basin size, and gauged values of both discharge and sediment load for the Rio Escondido (United Nations 1968). A runoff ratio to measured rainfall was applied as well as a similar estimate of total sediment flux. Estimating procedures are discussed in more detail in Owens and Roberts (1978) and Murray et al. (1982)

shelf. The trend is for the marine water to increase gradually in temperature and decrease in salinity toward the coast. In the region of the coastal boundary current, about 12 km from shore, temperature and especially salinity change dramatically.

About 20 km from the coast the sluggish onshelf flow, forced by the large-scale mid-Caribbean current, is replaced by a well-defined and narrow belt of very turbid water moving rapidly ($\sim$30–70 cm/s) from north to south parallel to the shoreline. Figure 4 illustrates a typical cross-section of this coastal boundary current, showing the distribution of current speeds and salinities. Crout and Murray (1979) and Murray et al. (1982) characterize this transport system as a distinct jet of southerly directed flow with a surface maximum of 60 cm/s that is confined to a zone generally within 20 km of the coast. The fast-moving core of the coastal boundary current does not always run to the south, but it appears to meander much like a river course. However, the "meander belt" appears to be confined near the coast. No major excursion of turbid coastal waters onto the central shelf were observed during our two years of observations. Crout and Murray (1979) and Murray et al. (1982) have shown that the dynamic structure of the coastal boundary current is controlled by the Coriolis force, baroclinic and barotropic pressure gradients, and internal frictional forces in the on-offshore direction. In the alongshore direction it is controlled primarily by the barotropic pressure gradient and frictional forces. Their analyses show the importance of density gradients, wind stress, and bottom friction in creating and maintaining this coherent flow feature along the coast. In general terms, the cross-shelf density gradients established by large contributions of fresh water by the east coast's thirteen rivers (Table 1) are driving forces for the southward flow. In addition, the role played by the wind is very important. A remarkably persistent input of directionally consistent momentum by the northeast trades confines the

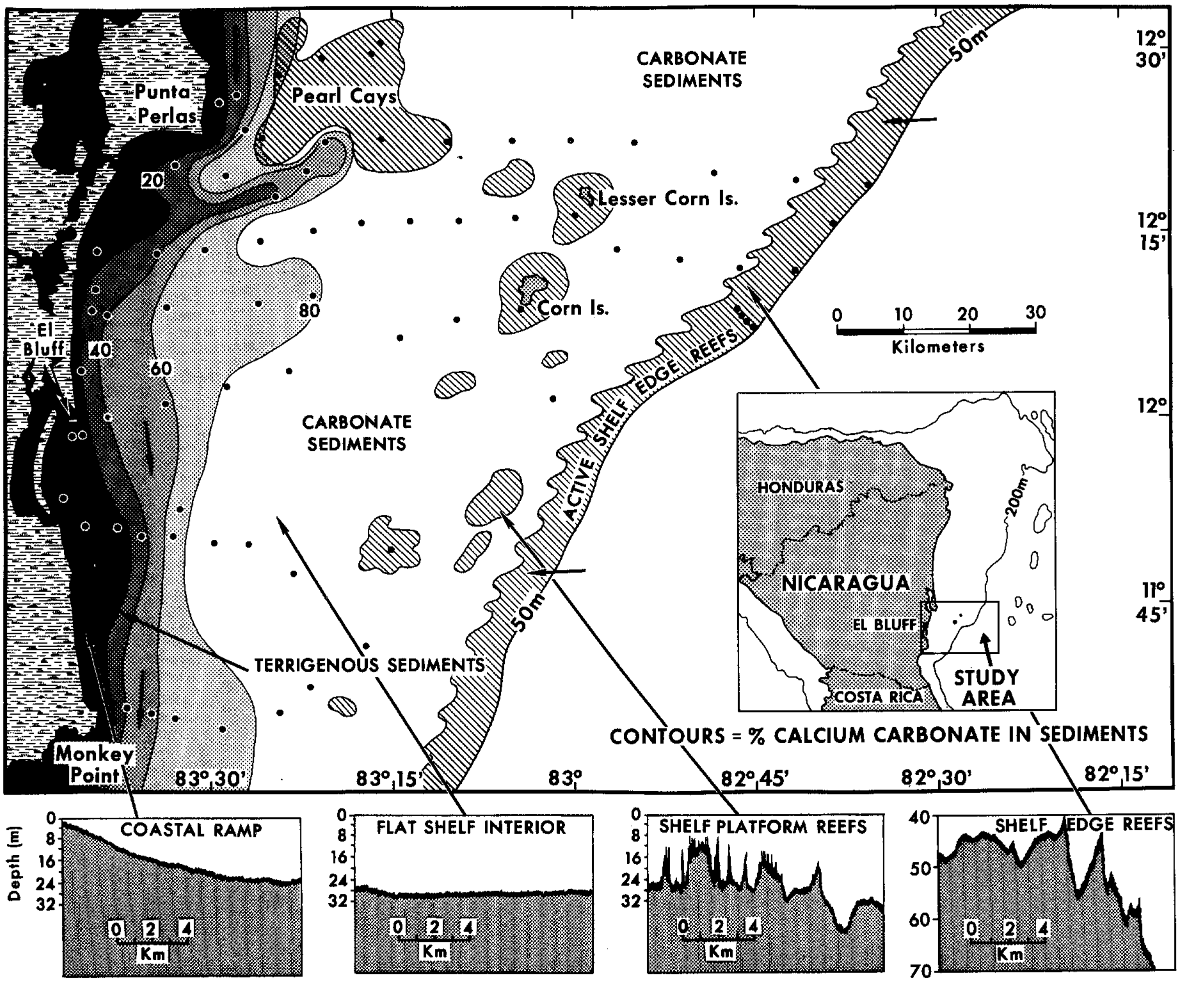

Fig. 5. Contoured percentages of calcium carbonate in bottom sediments. *Dots* represent sample locations. Hatched areas indicate the location of mid-shelf platforms and the shelf margin belt where coral reefs are actively growing. Typical echo-sounder profiles of the various topographical provinces of the shelf are illustrated

turbid water to the coast and supplements the tendency for southern transport. Therefore, the turbid, brackish water is not free to spread over large areas of the shelf. However, if instability is introduced into the trade winds, turbid coastal water will tend to move farther than normal from the coast. For a quantitative treatment of the coastal boundary layer, see the aforementioned references.

The Terrigenous-Carbonate Interface

The presence of the coastal boundary current and its structural details are extremely important with regard to understanding the distribution of sediment types on the Miskito Bank. As pointed out in Table 1, between 24 and 32 × 10^6 metric tonnes/year of sediment are transported to coastal waters each year. Estimates of southerly sediment flux by the coastal boundary current, based on actual observations of suspended load, suggest a transport of approximately 15.8 × 10^6 metric tonnes/year (Murray et al. 1982). An interesting consequence of this current system is the probable transport of a large part of the sediment load off the shelf where the coast changes orientation near the Costa Rican border.

The coastal boundary current's confined nature is the determining factor for shelfward distribution of terrigenous sediments from their riverine sources. Although it has already been stated the core of this current appears to meander like a river, these lateral excursions rarely extend beyond 20 km from the coast. Only when relaxation of the constant onshore wind stress occurs or when the wind blows briefly from a westerly quadrant can the turbid, brackish water plumes migrate onto the shelf. In the yearly wind cycle there is a brief slackening of the trades in April–May. This period (including March) also coincides with the period of minimum rainfall, thus reducing runoff and the subsequent impact of terrigenous sedimentation on the shelf. Although these short-term changes in the coastal boundary current do occur, sediment distribution, as well as details of shelf morphology, reflects the long-term dynamic structure of the shelf waters. Figure 5 illustrates the rapid shift from terrigenous sediments at the coast to recent carbonates in a shelfward direction, indicating confinement of the sediment-laden brackish water near the coast. The excursion of terrigenous sediments onto the shelf south of Punta de Perlas is interpreted as the effect of a perturbation in the coastal boundary current, possibly

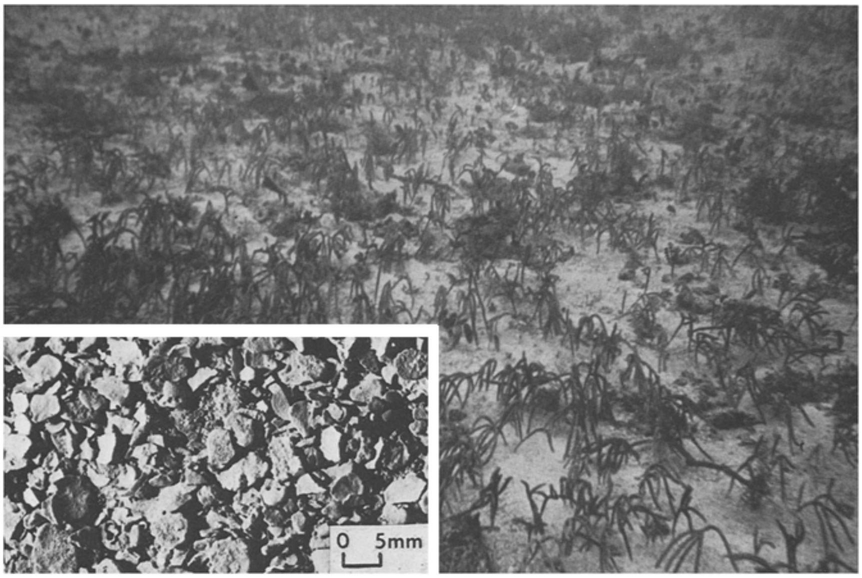

Fig. 6. A typical view of the flat-lying shelf (depth 31 m) showing an abundance of sediment-producing calcareous green algae, the most important of which is *Halimeda*. The inset shows a sample collected from this site. Sand-sized *Halimeda* flakes form the bulk of the sediment constituents

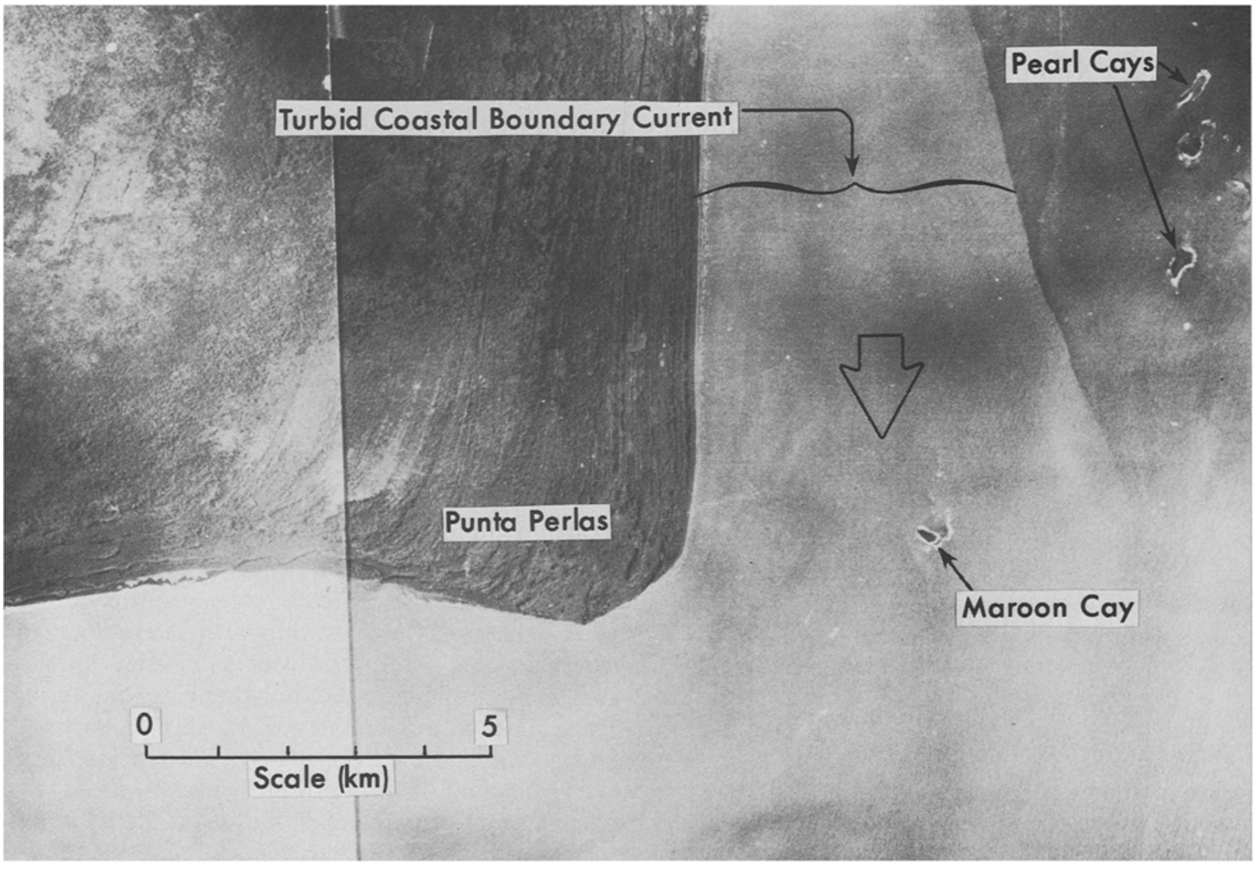

Fig. 7. Air photo of Punta de Perlas (see Fig. 1) and adjacent Pearl Cays. Note the sharp seaward interface between turbid coastal boundary current water and clearer (darker) shelf water. Maroon Cay is situated within the zone of turbid water, but has managed to sustain a growing fringing reef. Beach ridges, clearly visible in this picture, are typical features of Nicaragua's east coast. They indicate seaward progradation of the shoreline related to high input of sediments to the nearshore shelf. Photo taken 31 January 1964

an eddy, established at the downdrift end of Punta de Perlas and the carbonate platform represented by the Pearl Cays. Bottom sediments containing more than 40% terrigenous materials are rarely found more than 20 km offshore, and in most cases these sediments are found in a belt no more than 10 km from the coast. In fact, sediments being deposited from the water column in this zone tend to be forced onshore by the slow (5–10 cm/s) but constant shoreward intrusion of saltier water beneath the coastal boundary current core. Additionally, the fast-moving core

Fig. 8. Narrow fringing reef on the eastern side of Pearl Cays (Fig. 7). *Acropora palmata* is the dominant coral, and coralline algae are abundant at the shallow margin of the reef. Mangroves occupy the cay interiors, which consist of flooded storm rubble and other sediments

(> 50 cm/s), as shown in Fig. 4, helps to limit the shelfward migration of turbid brackish coastal water.

Echo-sounder profiles, side-scan sonar data, and bottom samples confirm that a depositional ramp composed primarily of terrigenous sediments is being deposited in an area reaching from the shoreline to a distance of 5–8 km offshore (Owens and Roberts 1978). This ramp can be seen clearly on the general shelf profile described by Fig. 3 and on the echo-sounder record of Fig. 5. Sediment properties in this nearshore region vary considerably with proximity to major sites of riverine input. Accumulations of poorly sorted, coarse volcanic sand are common adjacent to and downdrift of the major river mouths. Better sorted siliciclastics compose the beach-bar systems. These nearshore sand bodies grade quickly offshore into clays and silty clays. At the toe of the ramp (approximately 6–10 km offshore), terrigenous clays and silts are progressively diluted in a seaward direction with poorly sorted carbonates. The relatively flat bottom of the central shelf is unaffected by sedimentation processes near the coast. The central shelf is developing as a vast area of carbonate deposition (water depths ~30–35 m) where abundant growth of *Halimeda* produces a coarse carbonate sediment (Fig. 6). These and other coarse components (mollusk shells, coral fragments, etc.) are less commonly found in a matrix of aragonitic mud, which also represents disintegration products of abundant calcarous green algae.

Halimeda-rich sediments are replaced by other coarse skeletal carbonates within the vicinity of actively growing reefs. These carbonate buildups occur as small-scale, isolated patches, complex mid-shelf platforms having complicated patterns of reef growth, fringes around islands, and well-defined belts of buildups near the shelf edge (Fig. 5).

Reef Distribution

Reefs of the Nicaragua shelf occur on a variety of scales, from small patches and pinnacles to large (tens of meters in diameter), complicated platforms (kilometers wide) and well-defined belts. They are distributed across virtually the entire shelf, with exception of the narrow zone occupied by the coastal boundary current. However, only a few of the many reefs that occur within our study area are close enough to present sea level to be observed from the surface.

Some of the best examples of shallow fringing reefs are those that form around the small, low islands of the Pearl Cays and as carbonate fringes around high islands such as Corn and Little Corn, near the shelf edge (Fig. 1). The significance of the Pearl Cays complex of shallow reefs is their location close to shore and on the edge of the turbid coastal boundary current (Fig. 7). Because of the Pearl Cays platform, the coastal boundary current is topographically steered near the coast, as is reflected in the bottom sediment composition (Fig. 5). However, migration of turbid water in to the Pearl Cays complex is not uncommon, according to local fishermen. In spite of frequently turbid water, the Cays support a thriving community of *Acropora palmata* colonies on their windward eastern sides (Fig. 8). Only Maroon Cay (Fig. 7), in the coastal boundary current zone, has a poorly developed coral community at the reef crest. Reconnaissance field work suggests that the role of coralline algae is increased at the expense of typical Caribbean reef-building corals in these reefs as compared to their clear-water counterparts. The remaining part of the Pearl Cays platform, especially the eastern section, is complicated by numerous carbonate buildups, many of which do not reach the surface or develop into subaerially exposed cays. Both echo-sounder and side-scan sonar data suggest, by shape and high-frequency surface roughness, that these topographic features are in fact living reefs and not relict forms. Reefs on the remaining parts of the shelf vary from (a) isolated buildups surrounded by vast areas of relatively flat bottom mantled with carbonate sediments rich in *Halimeda*, to (b) midshelf carbonate platforms and island flanks that are

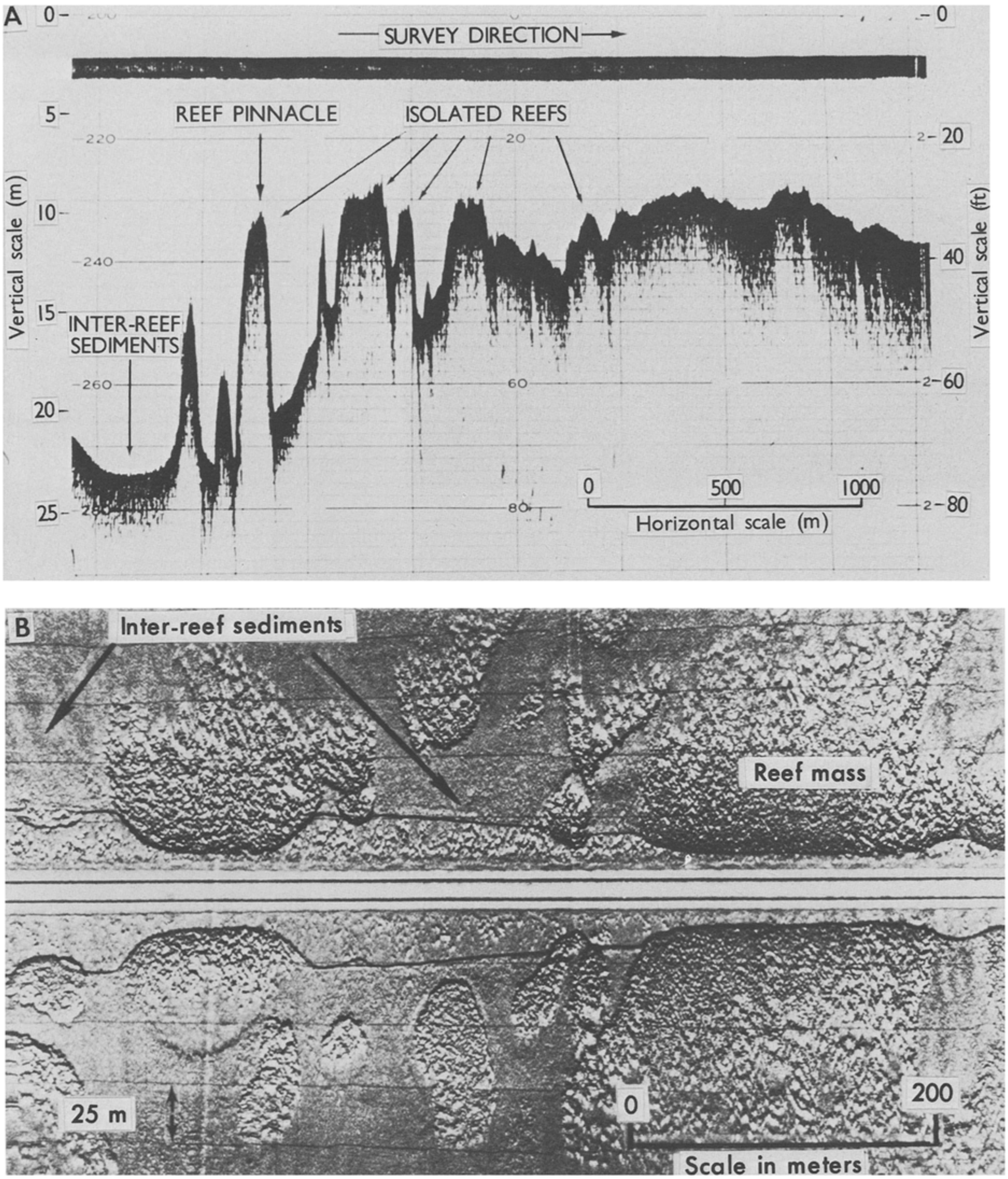

Fig. 9. A Echo-sounder profile off the northwest shelf of Great Corn Island showing a highly erratic bottom trace indicating the numerous thriving patch reefs. **B** Side-scan sonograph of part of the above profile illustrating the rough "living" texture of the reef structures with "smooth bottom" representing sediment cover between them. Reefs of the Great Corn Island platform, like the ones pictured here, commonly have a preferential orientation aligned with the direction of dominant refracted waves. The reef pinnacle indicated in the echo-sounder profile is the large reef at the left margin of the side-scan sonograph

veneered with a complex of living reefs of various sizes and dimensions, to (c) a belt of viable reefs at the shelf margin, some of which have vertical dimensions of over 25 m.

The generally flat, sediment-covered floor of the central shelf is commonly punctuated with small carbonate buildups as well as larger scale reef-covered platforms, some of which may be several kilometers in lateral dimension (Fig. 5). Patch reefs have very little impact on shelf sediment. Large platforms and the reef complexes that colonize the flanks of islands such as Great Corn and Little Corn produce significant quantities of sediment, which affects the composition of surrounding shelf deposits. Coral fragments and coralline algae grains are not common in the *Halimeda*-rich sediments of the flat-lying shelf interior,

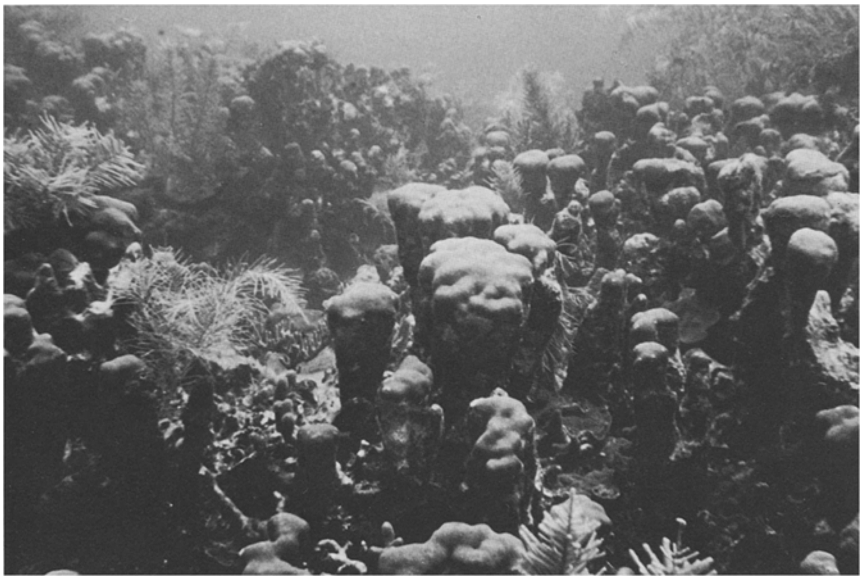

Fig. 10. Underwater photograph of a patch reef off the northwestern coast of Great Corn Island. Note the dominance of *Montastrea annularis*. (Depth approximately 7 m)

but are dominant grain types in these other reef-dominated settings.

Side-scan sonar data indicate preferential reef orientations and lineations (Fig. 9) that are consistent with the input directions of dominant waves and their refracted pathways, especially around Great Corn and Little Corn Islands (White 1977). Although both Great Corn and Little Corn islands have discontinuous but linear shallow *Acropora palmata* reefs around their northern and northeastern flanks (Roberts and Suhayda 1983) most reefs on the platform that surrounds these islands are patchlike in morphology (Fig. 9). The coral communities of these structures are highly biased toward *Montastrea annularis* and *Agaricia agaricites* (Fig. 10), even though many subordinate varieties do contribute to the framework.

Seaward of the Corn Islands, the sea floor deepens to about 60 m and extends to the abrupt break in slope that marks the shelf edge (Fig. 1). At this point, open ocean water is constantly moving onshelf, promoting reef growth. Rugged reef topography characteristic of a belt several kilometers wide parallels the shelf edge (Fig. 5). Some reefs are linear and tend to form a submerged barrier at the shelf margin, and others are isolated pinnacles that attain in excess of 20 m relief above the sea floor. This shelf margin reef belt, as well as the midshelf platforms, supports actively growing carbonate structures that result in very rough sea floor topography. Such bottom roughness is an important factor in the attenuation of waves and currents transiting the shelf toward the coastline.

Conclusions

1. Extreme rainfall and rapid erosion of volcanic rocks under tropical conditions result in the transport of large volumes of fresh water and sediment to the nearshore shelf. Estimates suggest that three times more fresh water and fifteen times more sediment are introduced to the shelf per unit length of coast than along the eastern shore of the US.

2. Persistent momentum provided by northeast trade winds, plus density gradients set up by riverine effluents interfacing with saline shelf waters, are the key elements in producing a strong (speeds exceeding 70 cm/s) north-to-south-flowing coastal boundary current.

3. The lateral distribution of terrigenous sediments onto the Nicaraguan shelf is controlled by the presence and behavior of the coastal boundary current. Therefore, the zone for terrigenous sediment influence is no wider than the band of southward-moving coastal water. The remainder of the shelf has developed into a vast carbonate province as if the terrigenous coast and its abundant point sources of noncarbonate sediment input did not exist. The facies shift from terrigenous clastics to carbonates takes place over the short distance of generally less than 20 km from the coast.

4. Reef growth is essentially uninhibited on the Nicaraguan shelf and therefore develops under the same constraints as other Caribbean carbonate platforms. An exception to this generality is the turbid shoreward flank of the coastal boundary current (a zone approximately 10 km wide), where a ramp of terrigenous sediments forms the interface between the shelf and the shoreline. High turbidity and a shifting substrate eliminate reefs in this narrow belt parallel to the coast. Outside of this zone, reefs flourish even when occasionally impacted by turbid water on the seaward side of the coastal boundary current. Reefs outside of the influence of coastal waters develop as (a) isolated patches surrounded by vast areas of sediment accumulation, (b) reef-covered midshelf platforms, (c) fringes around islands, and (d) a belt of actively growing reefs at the self margin.

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