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Tropical Barrier Islands of Colombia's Pacific Coast

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ABSTRACT

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Sixty-two barrier islands on the Pacific Coast of Colombia are reported and described. The islands, covered by tropical rainforest and backed by mangrove forests, line the seaward margin of a narrow, extensive, deltaic plain formed from rivers draining the northwestern Andes. The islands are of interest because of a combination of factors including: their position on a leading-edge coast which contributes to relative sea-level rise through long-term subsidence; short-term seismic subsidence and tsunamis; their tropical setting where deltaic sedimentation and heavy vegetative cover influence island dynamics in terms of subsidence, river channel switching and quality and quantity of sand supply, the possible short-term influence of El Niño events; and the lack of human influence on island dynamics.

Five genetic island groups are identified: two groups associated with straight stretches of coastal lowland and three delta lobe groups (Rio San Juan, Rio Patia, and Rio Mira deltas). A few of the islands formed due to spit detachment. Initially the islands were probably transgressive, then became regressive for an indeterminate period before recent reinitiation of a transgressive phase, and severe island front erosion. Many of the islands are sand starved due to sediment supply loss when distributary switching occurred, or because they are in areas with little sand in the associated mangrove substrate and no fluvial sand supply.

The recognition of the barrier island nature of this coast provides a new management tool to guide coastal hazard mitigation and future development. Future stratigraphic studies may provide a basis to identify the frequency of short-term events such as El Niño and tsunamis and to establish recent sea level history for specific island groups.

ADDITIONAL INDEX WORDS: *Barrier islands, Colombia, Pacific, tropical, mangrove, delta, coastal subsidence, mesotidal, El Niño.*

INTRODUCTION

Five centuries of exploration, bathymetric charting, and coastal zone mapping have not exhausted the possibilities for discovery! Sixty-two barrier islands (Figure 1) are recognized and described for the Colombian Pacific coast; most for the first time in the periodic literature. These genetically related island systems occur throughout the 1,300 km Colombian coast between Panama and Ecuador; most of the islands occurring along the southern 800 km and extending a short distance into Ecuador (not included in this study). These unique islands represent an important environmental and economic asset to Colombia and require a new view of the country's coastal environmental management and development policies.

Only five of these islands previously bore the designation *isla* on old maps. West (1957) mapped these features as beach fringe along a mangrove-covered alluvial plain, and McGill (1958) recognized only a few of the islands in the vicinity of the Colombia/Ecuador border. The barrier island systems were not recognized in the Colombian literature or maps prior to the reports on which this paper is based. Herd *et al.* (1981, p. 444) noted the coastline south of Buenaventura consisted of "low, broad alluvial plains, meandering rivers, barrier islands, and lagoons." No maps, elaboration on barrier island recognition or distribution were given, and it is assumed the term ***barrier islands*** was in reference to the same distinct offshore islands noted by McGill (1958).

Colombia's 1,300 km Pacific coast is divided between cliffed upland shores, such as the northern Baudo Range, and low alluvial plains. The latter coastal lowlands are the depositional prism

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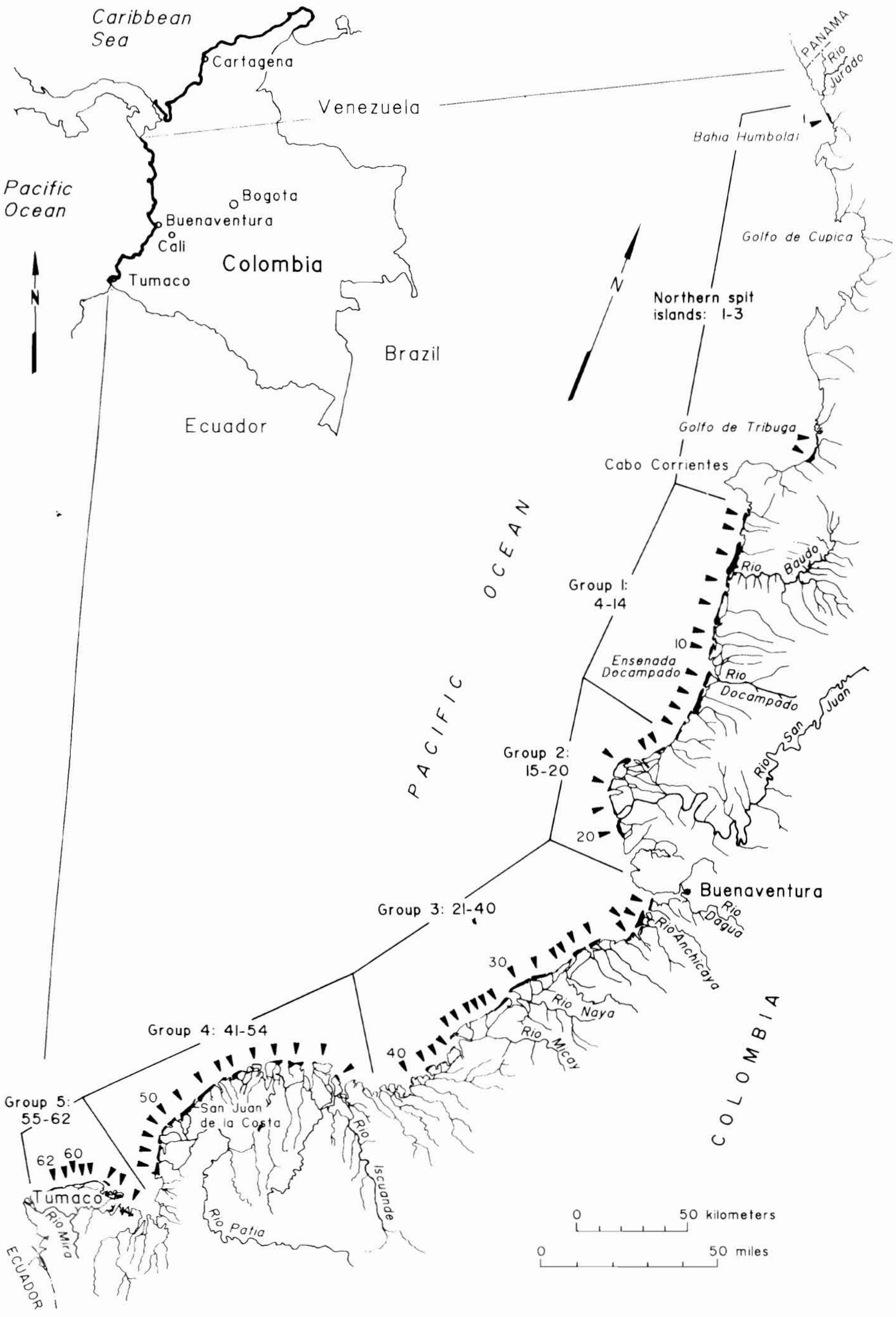

Figure 1. Index Map: the coasts of Colombia (inset) and locations of the 62 Pacific barrier islands. Locations of the 5 island groups are associated with larger river deltas or the alluvial plains of smaller streams.

of numerous rivers coming off the Western Cordillera of the Andes. The coalesced deltas of such rivers as the Baudo, San Juan, Micay, and Patia (Figure 1) form a constructional tropical coast covered by mangrove forest. Tumaco is the only major town located on a barrier island, but occasional small villages dot the island's ocean and estuarine shores where fishing and subsistence agriculture support a population at risk from extreme coastal hazards. New construction of ports and roads, development of aquaculture, tourism, forestry, and potential mineral resource extraction in these coastal lowlands are threatened by the same hazards (CORREA and LOPEZ-RENDON, 1991). As a basis for future planning, the Instituto Nacional de Investigaciones Geologico-Mineras de Colombia (INGEOMINAS) initiated a coastal mapping program in 1987 to produce a general atlas for Colombia's Caribbean and Pacific coasts. The atlas volumes comprise the first comprehensive evaluation of the entire coast in terms of environments, geomorphology, shore types, areas of erosion/accretion, and preliminary evaluation of coastal hazards. An outgrowth of the mapping of the Pacific alluvial plain coast is the recognition that the zones of mangrove coast fringed by beaches are dominated by barrier islands (Figure 1). Sixty-two barrier islands were identified and their general environments and processes described (GONZALEZ and MARIN, 1989a,b; MARTINEZ and CARVAJAL, 1990a,b).

The purpose of this paper is to summarize the character of these barrier islands, their setting, evolution, and significance for the entire coast. In particular, these tropical barrier islands (1°25′N to 7°13′N Lat.) suggest that similar chains may have gone unrecognized in other tropical regions where obscured by mangrove cover.

Previous General Studies

The classic study by WEST (1957) defined the Pacific Lowlands of Colombia and subdivided their coast into mangrove coast, sand beach, and cliffed coast. Although he used the term barrier beach, recognized older beach ridges, and essentially diagrammed a low barrier island (WEST, 1957:Figure 4, p. 59) with a back-island mudflat and lagoon, he did not recognize barrier islands or define their associated processes (*e.g.*, inlet migration and tidal delta formation, build up by overwash, eolian processes. This work and associated reports (WEST, 1954, 1956) have stood as the definitive study for over thirty years, primarily for two reasons. First, the Pacific coast is largely inaccessible and definitely inhospitable. Only two roads cross the Western Cordillera to Tumaco and Buenaventura, and coastal land access is nonexistent. High surf and poorly charted waters make small boat access difficult, and dense mangrove cover impedes profiling and field mapping. Second, frequent cloud cover, dense tropical rainforest and mangrove-swamp cover hinder standard photogrammetric surveys. The islands probably were overlooked by conventional topographic mapping because their 1 to 2 m relief is not detected at conventional contour intervals (*e.g.*, they are not shown on U.S. Department of Defense maps).

Wave Erosion and Tsunami Destruction

WEST (1957) noted the presence of beach ridges, 100 to 200 yards wide, that appeared to have been eroding for the past 50 years, a conclusion backed up by stories of old natives of the region and tree stumps in the surf. He also suggested that erosion could be rapid and due to catastrophic events, particularly tsunamis such as had occurred in 1836, 1868, and 1906. Tsunamis affecting the Colombian coast typically result from earthquakes with epicenters off southwestern Colombia/northwestern Ecuador having a magnitude ≥7.5 and result in runup heights of 2.0 to 5.9 m (LOCKRIDGE and SMITH, 1984).

The tsunami of January 31, 1906, destroyed several coastal villages, including part of Tumaco; killed from 500 to 1,500 people, and eroded beaches and mangrove swamps along 100 km of coast in the vicinity of Tumaco (SZIERTES, 1911; WEST, 1957; LOCKRIDGE and SMITH, 1984). Tumaco was damaged by a tsunami again on January 19, 1958, but the most significant coastal alteration occurred in association with the Tumaco earthquake and tsunami of December 12, 1979. Six villages were destroyed, including San Juan de la Costa (Figures 1 and 2) where at least 220 were killed (HERD *et al.*, 1981; LOCKRIDGE and SMITH, 1984). The highest tsunami wave was 2.5 m greater than high tide at San Juan and 0.8 m greater than high tide at Tumaco. The flood depth at San Juan village was 2.0 m over the island; however, HERD *et al.* (1981) state that half of the flood depth was due to the pre-tsunami subsidence associated with the 8.1 magnitude earthquake. They note that regional subsidence occurred along the coast from Ecuador to as far north as Guapi, and

Figure 2. (A) 1979 tsunami destruction at San Juan de La Costa. Note the shoreline position relative to the circular, open church building. From the cover photo of *Science* Magazine, Volume 211, 1981 by D. Herd. Copyright 1981 by the AAAS. (B) The circular church building at the beach line in 1989. Approximately 100 meters of shoreline retreat occurred over the 10 year interval.

maximum subsidence was 1.6 m. Along 200 km of the coast, the resulting submergence killed trees and shrubs, flooded former beaches and mudflats that were previously exposed at high tides (*e.g.*, Isla Gorgona), and increased lagoonal areas. Ground shaking and liquefaction caused sand boils and ground cracks at San Juan village prior to the tsunami and contributed to building failure.

Both HERD *et al.* (1981) and WEST (1957) observed that tree kills along the ocean front were present prior to the 1979 earthquake. Our recent mapping shows that downed trees, ocean-front standing dead mangroves, beach scarping and ocean-front mangrove peat exposures are common along many of the barrier island fronts. Figure 2 illustrates approximately 100 m of shoreline retreat due to wave erosion at San Juan village since the 1979 tsunami. The question remains, how much of this erosion is due to the global sea-level rise, ongoing wave erosion, subsidence due to compaction of delta fill, subsidence due to diastrophic downwarping of the continental margin atop the subducting ocean plate, or earthquake-induced catastrophic subsidence to which the shoreline position is still adjusting? Certainly regional differences between the northern and

Figure 2. Continued.

southern (earthquake subsided/tsunami flooded) barrier island chains may reflect these variables.

General Setting

This tide-dominated coast is mesotidal with average tidal ranges increasing from 2.5 m at Tumaco to 3.5 m at Buenaventura to the north, and crossing into the macrotidal range for spring tides (*e.g.,* 3.9 m at Tumaco, 4.9 m at Buenaventura, and 4.3 m at Jurado) (Figure 1). Ebb tidal deltas are the dominant tidal delta form, extending for up to 3 km seaward, but small flood tidal deltas also are present. Inlet frequency is high, and island shape tends to be short and stubby, sometimes of the "drumstick" form as in the mesotidal model of HAYES (1979).

Dominant wave directions are from the west and southwest with the direction of the Colombian Current. Wave energy is moderate with wave lengths of 10 to 50 m and average wave heights of 0.5 to 1.5 m along the southern shores to 0.8 m along the San Juan River Delta, increasing to the north (*e.g.,* 1.3 m at Bahia Humboldt). Storm wave heights range from 1.5 to 3.5 m, and most beaches are dissipative. Longshore drift is from south to north; however, local reversals occur in the vicinity of ebb tidal deltas.

Wave erosion is dominant during high spring tide, and as much as 10 to 15 m of retreat occurred within a few days at El Choncho (Figure 1, Island 19) during the perigean spring tide of April, 1989. As much as one meter loss occurred on each high tide (NEAL and GONZALEZ, 1990). Storm washover is common, but not at the scale seen on nontropical barrier islands. Overwash deposits are difficult to map due to the heavy cover of vegetation. Overwash fan accumulation is held to the back beach where such heavy cover exists, but penetrates into and across narrow islands where they are cleared for subsistence agriculture or village development. The tradition of stilt-house con-

Figure 3. Transgressive beach/dune ridge formation and vegetation zones on island 43. Mangrove peat is exposed on forebeach (left) in area of dead mangrove tree trunks.

struction is probably derived as a means of mitigating flood and overwash risk.

River discharge is highest for the Rio San Juan (annual mean 2,580 m^3/sec), and considerably lower for other delta rivers (Rio Mira 930 m^3/sec; Rio Patia 340 m^3/sec) and alluvial plain streams (*e.g.,* Rio Micay 280 m^3/sec; Rio Anchicaya' 79 m^3/sec). No data is available for fluvial sediment load, however, sand supply generally appears to be low.

Vegetation colonizes accreting beaches very quickly, and a strong plant zonation with distance from the fore beach characterizes tropical barrier islands (Figure 3). WEST (1957) defined three zones that characterize these islands: 1. the low cover of the upper foreshore consists of herbaceous halophytes, mainly creepers and trailing vines (*e.g., Ipomea pre-caprae, Canavalia rosea, Wedelia brasiliensis,* and *Rhabdadenia biflora*) that give way to thickets of high reeds (*Cyperus* sp.), tall, reedy grass (*Uniola pittieri*) and other grasses; 2. a dense thicket of woody shrubs covers the higher beach ridge (*e.g., Hibiscus tiliaceus, Dalbergia* sp.), and patches of rain forest trees are found on older, wider beach ridges; and 3. the mangrove swamp forest on the backside of the island including low troughs between beach ridges. The prop roots of the red mangrove (*Rhizophora*) make the lagoon-swamp nearly impenetrable. The mangrove swamp has its own internal plant zonation.

Dunes are not dominant or even significant features of these tropical barrier islands. Frequent rainfall and rapid establishment of a dense vegetative cover interfere with wind transport, and narrow beaches at high tide do not provide large dry sand-source surfaces for wind transport. Dune formation does occur along the somewhat drier southern island chains with the largest dunes (up to 2 m in height) forming on the west-facing islands of the Patia River Delta, and low dunes are present on the islands near the Mira River.

No evaluation of El Niño effects was made in the present study, but records of ENSO phenomena are recognized in other coastal areas of western South America (ORTLIEB and MACHARE, 1992; WELLS, 1990). The barrier islands are potential loci for surficial (*e.g.*, beach ridges) and stratigraphic records of El Niño events (*e.g.*, raised sea level, increased storminess, increased sediment supply due to riverine flooding).

METHODS

Base mapping utilized a variety of sources including U.S. Defense Department coastal quadrangles, navigational maps, vertical air photos, and satellite imagery. Complete temporal sets of air photos for the entire Pacific coast at a specific tidal position are generally lacking, requiring reliance on older photos which in some cases do not depict the present shoreline positions. The rarity of cloud-free days is partly responsible for the limited amount of imagery. Extensive field verification included accessing all of the island fronts, foot transects across the islands, and boating through the esteros.

Determination of directions of island elongation and, hence, direction of dominant sand transport was based on island shapes, recurved spit and beach ridge orientation, and the course of estuarine channels behind the islands. Backbarrier tidal channel recurvature reflects inlet migration and island growth directions. Beach ridges were identified primarily on the air photos as reflected in vegetation differences controlled by ridge elevation. Field verification of beach ridges indicate that the multiple ridges are often less than one meter in relief, but this is sufficient to result in differences in vegetation. Interridge troughs are sometimes flooded on the back of the barrier, supporting stands of mangroves. Beach and recurved-spit ridges also are exposed in cross section on the eroding ends of some islands.

Field mapping included identification of accretion/erosion, and classification of the erosion as slight, moderate, or severe (GONZALEZ and MARIN, 1989a; MARTINEZ and CARVAJAL, 1990a). Tree stumps, dead and fallen trees, mangrove peat and mud exposed on the beach (Figure 4), and presence or absence of vegetation zonation on the front sides of the islands, and inlet banks, were useful indicators of erosion levels. Interviews with older local residents provided some anecdotal indication of erosion/accretion history.

No core data or stratigraphic information is available for the islands, so their regressive/transgressive nature is somewhat speculative. The larger islands and islands with extensive beach ridges suggest a regressive history. Local beach accretion, some frontal growth of active spits, and local formation of sand dunes, supports a regressive model, but the majority of the islands are narrow, and beach erosion often exposes mangrove peat. Mature stands of back-island mangrove are now on the front sides of some of these islands; all of which suggests that the present pattern is dominantly transgressive.

Barrier Island Recognition

Although previously unrecognized, the six elements which define a barrier island (OERTEL, 1985) are present. These littoral sand bodies consist of a seaward shoreface, barrier platform, and associated tidal inlets and deltas. The islands are separated from the mainland by backbarrier lagoons. OERTEL (1985) noted two lagoonal endpoints: open-water lagoons and expandable tidal lagoons like the Georgia coastal salt marshes. The Colombian backbarrier water bodies represent the latter, but, instead of being expressed as salt marshes, they are filled with tropical mangrove swamps. To the coastal observer, the rain forest-mangrove transitions are much less obvious than the maritime forest-saltmarsh transitions of temperate-zone barrier islands. Tidal creeks (esteros) join behind the islands isolating them from mainland freshwater swamps and rain forests even at low tide.

Interior beach ridges, as well as the upper beach, are covered with thick vegetation that continues into the impenetrable mangrove swamps, so ground definition of the backbarrier lagoon boundary is difficult except where the tidal creeks are navigable by small boat. Mapped boundaries also were determined by imagery tonal differences due to differences in vegetation.

Island form, "drumstick" shape, and frequency of inlets are representative of mesotidal conditions (HAYES, 1979). However, some segments are sand starved or are in areas of abandoned, subsiding deltas (*e.g.*, the north Rio Patia Delta), resulting in very narrow, rapidly migrating islands and broad inlets in contrast to temperate barrier island systems with healthy sand supplies.

ISLAND GROUPS

For convenience, the islands are numbered from north to south (1 to 62) in Figures 1, and 5 through

Figure 4. Eroding island front (island 24) with dead mangrove trees and exposed mangrove substrate.

9 because they lack specific geographic names, although associated inlets are named. Table 1 summarizes the general character of each island including inlet width for the inlet south of each island (except where the next feature is not a barrier island). The figure depiction of each island represents the actual vegetated island area above spring tide level as judged from air photos and corrected by field observations. Mapped beach ridges were identified primarily by vegetation lines in air photos and field checked in some instances. More ridges than shown are present, but cannot be seen in the photographs or without numerous field transects of the islands. Mangrove forest boundaries and older non-barrier deposits (*e.g.*, Cenozoic rocks and Pleistocene deposits) also are shown in figures 5 through 9; however, related features such as mudflats, tidal deltas, sand bars, and similar ephemeral features are not shown.

The three northernmost islands (Figure 5), located north of Cabo Corrientes (Figure 1), are true detached spits, consisting of beach ridges, and formed in embayments between rocky headlands along the dominantly cliffed coast. Reentrants along the northern cliffed coast are occupied by pocket beaches; the larger being backed by low, sandy beach ridges on a plain of finer grained sediment. These mangrove and rain forest covered features may be considered as the tropical equivalent of cheniers. The three northern islands formed as a result of local north-to-south longshore drift with recurved spit growth into small embayments. The beach ridge patterns suggest the islands and cheniers originally prograded.

The remaining islands are all components of barrier island chains, related to the geomorphology of the deltaic coastal plain. South of Cabo Corrientes the cliffed coast gives way to an alluvial plain, bounded by barrier island chains along most of its length. Five distinct island chains or groups are recognized on the basis of natural geomorphological divisions (*i.e.*, islands of related genesis along a specific delta lobe; breaks in the chains by local upland terraces forming short stretches

Table 1. *Individual island dimensions and evidence of accretion/erosion. Note: Inlet widths are given for the inlet at the south end of each island. No inlet width is given if the next reach is mainland coast or nonbarrier island.*

Island Group Designation	Island Number	Inlet Width (km)	Island Area (km^2)	Island Length (km)	Maximum Width (km)	Beach Ridges	Mangrove Substrate on Beach	Fallen Trees on Beach	Scarped Beach
Northern "Spit" Islands	1	1.3	2.6	5.6	1.0	yes			
	2	0.5	2.1	4.0	0.6				
	3	0.3	8.1	9.5	1.8	yes			
Island Group I	4	0.5	4.7	6.7	2.0	yes			
	5	1.3	0.6	3.2	0.3				
	6	0.5	25.2	15.8	2.3	yes			
	7	1.7	4.0	5.3	1.6	yes			
	8	0.8	12.3	15.8	2.5	yes			
	9	1.0	1.8	6.7	1.2		yes		
	10	6.0	3.5	6.8	1.3	yes			
	11	1.0	6.6	6.3	1.4	yes			
	12	0.6	11.6	11.3	2.3	yes			
	13	1.7	1.2	3.8	0.4	yes			
	14	5.0	3.9	10.4	1.0		yes	yes	
Island Group 2	15	0.9	1.5	5.0	0.8	yes	yes	yes	
	16	5.0	0.6	3.0	0.5		yes	yes	
	17	1.0	8.8	11.8	2.2	yes			
	18	1.7	2.6	6.6	1.1	yes			
	19	2.6	2.1	9.5	0.6		yes	yes	
	20		11.2	8.4	2.1	yes			
Island Group 3	21	2.0	3.3	5.5	1.1	yes	yes	yes	yes
	22	2.4	12.3	8.4	2.6	yes	yes	yes	
	23	1.0	1.5	4.7	0.8	yes			
	24		5.2	5.3	1.5	yes	yes	yes	
	25	1.2	6.3	5.9	1.8	yes			
	26	1.5	7.6	6.6	2.6	yes	yes	yes	yes
	27	0.2	2.1	4.1	1.2	yes			yes
	28	0.4	0.9	6.6	0.5	yes	yes	yes	yes
	29	0.5	9.2	9.5	1.8	yes		yes	
	30	2.4	10.1	10.1	1.8	yes		yes	
	31	0.2	6.1	8.3	1.3	yes			
	32	0.2	0.9	2.8	0.4				yes
	33	0.3	0.5	4.1	0.3			yes	yes
	34	1.5	1.1	4.4	0.5		yes	yes	
	35	0.4	0.5	5.6	0.2			yes	
	36	4.0	1.4	3.4	0.5		yes	yes	
	37	2.5	0.7	3.6	0.4	yes	yes	yes	
	38	0.5	1.4	5.1	0.5	yes		yes	
	39	3.7	3.4	4.5	1.3	yes	yes	yes	yes
	40		1.6	3.5	1.1	yes	yes	yes	
Island Group 4	41	4.0	2.4	3.5	1.1			yes	
	42	4.0	0.5	1.4	0.7		yes	yes	yes
	43	2.8	10.8	7.5	3.5	yes		yes	yes
	44	2.0	7.3	8.3	2.1	yes	yes	yes	yes
	45	4.0	1.2	4.4	0.4				yes
	46	2.5	7.0	6.9	2.1		yes	yes	yes
	47	1.0	2.9	5.2	1.8	yes		yes	yes
	48	0.8	13.2	10.1	2.6		yes	yes	yes
	49	2.6	9.7	11.0	2.1	yes	yes		yes
	50	0.9	5.3	4.6	2.1	yes		yes	yes
	51	0.8	2.5	4.8	1.1	yes	yes		yes
	52	0.6	3.5	4.4	1.6	yes	yes		yes
	53	0.4	7.7	7.6	1.9	yes			yes
	54		12.5	6.6	3.3	yes			

Table 1. *Continued.*

Island Group Designation	Island Number	Inlet Width (km)	Island Area (km^2)	Island Length (km)	Maximum Width (km)	Beach Ridges	Mangrove Substrate on Beach	Fallen Trees on Beach	Scarped Beach
Island Group 5	55		2.4	4.8	1.3	yes	yes		yes
	56		4.3	3.4	2.0				yes
	57	2.0	2.0	4.4	0.9	yes			yes
	58	1.0	1.4	4.5	0.6	yes		yes	yes
	59	0.2	0.8	3.6	0.4				yes
	60	0.3	1.3	4.5	0.5	yes	yes	yes	yes
	61	0.3	1.0	3.8	0.7				yes
	62		3.5	6.5	0.9	yes			yes

of cliffed coast; embayments where mangrove-swamp mainland shore forms the coast).

ISLAND GROUP 1

The Alluvial Plain of the Rio Baudo–Rio Docampado Complex (Figures 5 and 6; islands 4–14) is bounded by a chain of 11 islands in a north-south, straight orientation, unlike the delta-lobe chains. Although highly variable in terms of size and shape (Table 1; area 0.6 to 25.2 km^2; length 3.2 to 15.8 km), on average the islands of this chain have the greatest area and length. Island elevation is typically between 1 and 2 m. This chain has the best sand supply, reflecting the closer mountainous source. The islands near the mouths of the larger rivers (Rio Baudo; Rio Docampado) contain the largest subaerial sand volume. Most of the islands have extensive beach ridge development, except islands 5, 9, 13 and 14 that are transgressive. The regional net direction of longshore transport is from south to north as reflected in the island shapes (*e.g.*, 8, 12, 14), all of which exhibit "drumstick" model characteristics (HAYES, 1979).

Although less erosive than the southern chains, local erosion is often severe, particularly along the beaches at mid-island (*e.g.*, 4, 9 and 14), although a few of these areas are accreting. Island 6 (Catripe), the largest barrier island on the Colombian coast, is eroding severely near its northern end, but stable over most of its length.

Boca Siviru, the inlet between islands 10 and 11, is the main distributary channel of the Rio Docampado. The inlet is almost 6 km wide compared to more typical inlet widths in Group 1 of around 1 km (Table 1). The wide inlet may reflect an insufficient sand supply from the river to maintain a cross sectional area in equilibrium with both fluvial and tidal prism flow.

ISLAND GROUP 2

The Rio San Juan Delta (Figure 6; islands 15–20) islands trace the delta arc off Colombia's largest Pacific river. The inlets of this group are at the mouths of fluvial distributaries. The northern islands appear to be sediment "starved" (*e.g.*, short, narrow) while the mid-delta islands are longer (up to 11.8 km) and more robust (Table 1). The northern islands of the group have been breached, and dead mangrove stands indicate strong erosion.

The tidal deltas at Boca Cacagual and Boca Chavica are large, extending at least 3 km seaward. Relatively well developed beach ridges are apparent. Most of the islands appear to be transgressive. Neither the river nor erosion of mangrove substrate are contributing much sand to the island system; and little or no sand is derived from the extensive cliffed coast south of the delta into Malaga and Buenaventura Bays.

ISLAND GROUP 3

The Coalesced Alluvial Plain of the Rios Anchicaya, Naya and Micay (Figures 6, 7, and 8; islands 21–40) and smaller streams forms a northeast to north-trending reach, bordered by 20, mostly small, narrow islands. This alluvial plain is generally narrow (0 to 13 km) and abuts against the fossil sea cliffs of the edge of an extensive terrace cut in Tertiary sediments. The terrace forms an active sea cliff along an 11 km reach between islands 24 and 25. All of the islands are backed by mangrove forest, and broad estuarine tidal-creek mouths are common. Field evidence and island shapes point to a strong northerly direction of net longshore transport and island elongation. The curvature of tidal channels behind the islands also indicates some northerly island extension and inlet migration.

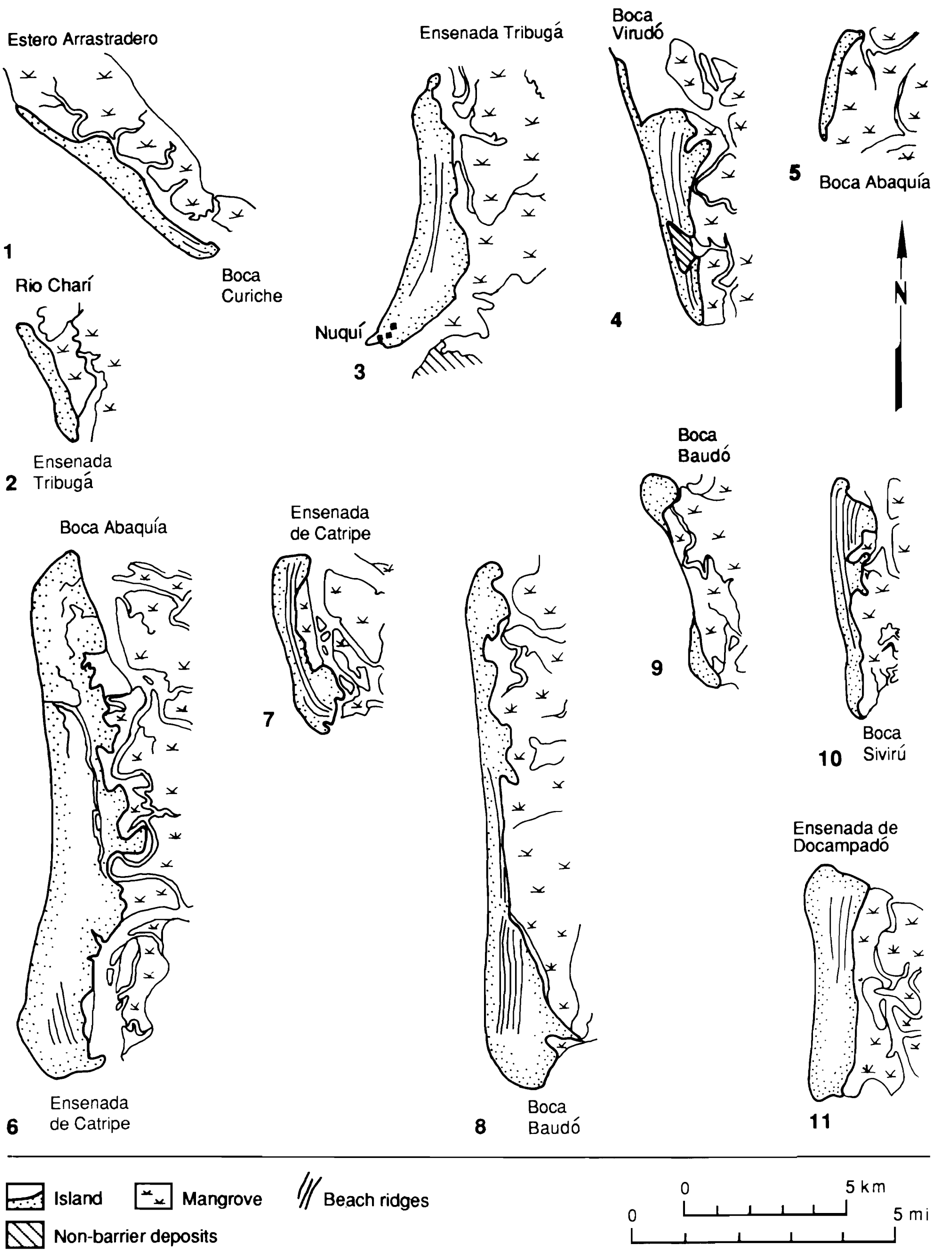

Figure 5. Islands 1 through 11. Islands 1, 2 and 3 are detached spits (north of Cabo Corrientes). Islands 4–11 are part of island group 1. Note north-south orientation; "drumstick" shape of island 8.

Group 3 islands are relatively short and narrow (Table 1), particularly downcoast from island 31 where the islands reach their minimum lengths (2.8 to 5.6 km) and widths (0.2 to 1.1 km). The shorter, extremely narrow islands lack beach ridges (Figures 7 and 8). Several of the islands (*e.g.*, 24, 27, 29, 38) are breached, or have narrow segments that are readily overwashed; and the northern 11 islands have tidal channels that extend well into the islands (Figure 7). These erosional rem-

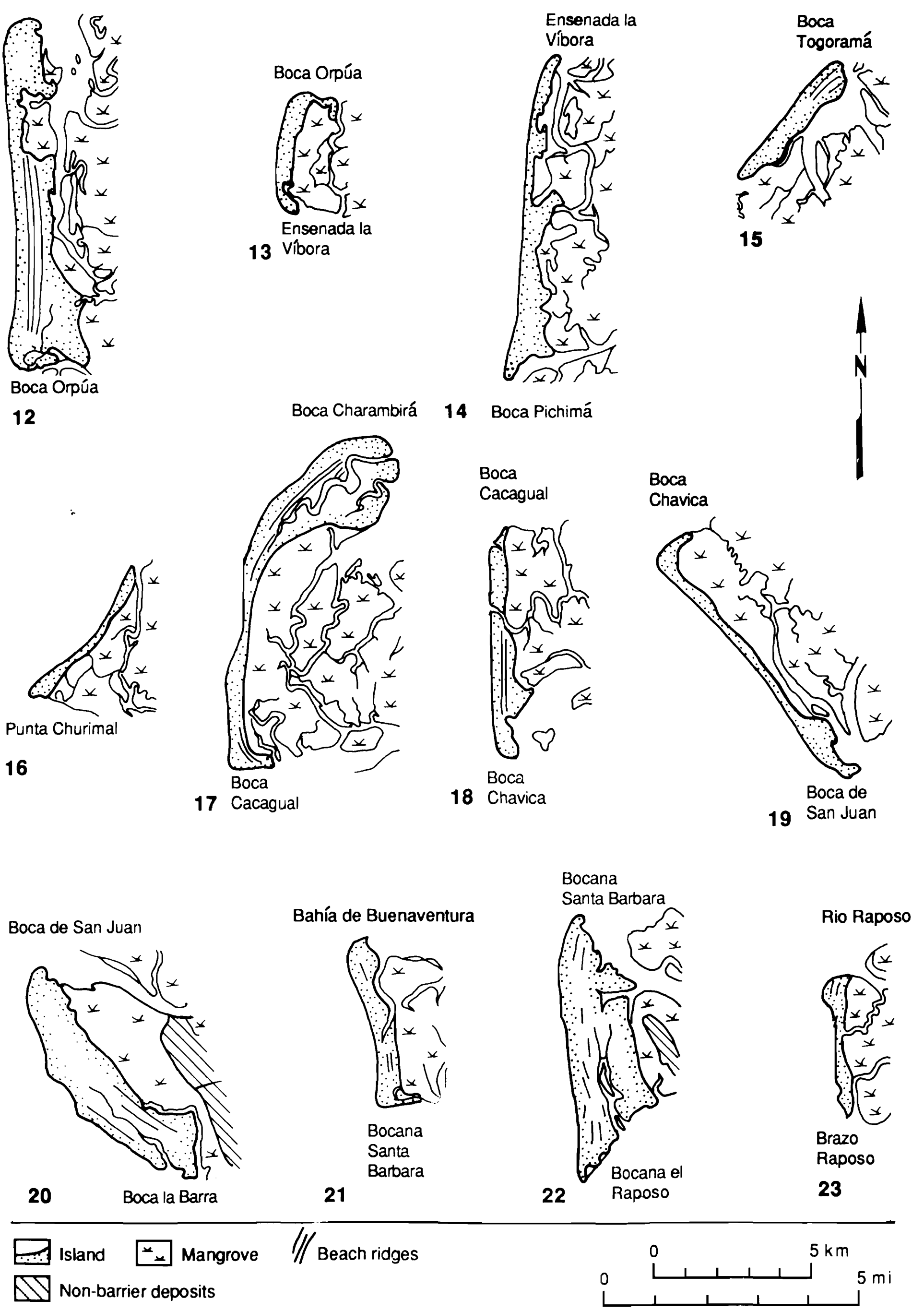

Figure 6. Islands 12 through 23. The variable orientation of islands 15–20 reflects the arc-shape of the Rio San Juan delta lobe. Islands 21–23 belong to island group 3 (see Figure 7).

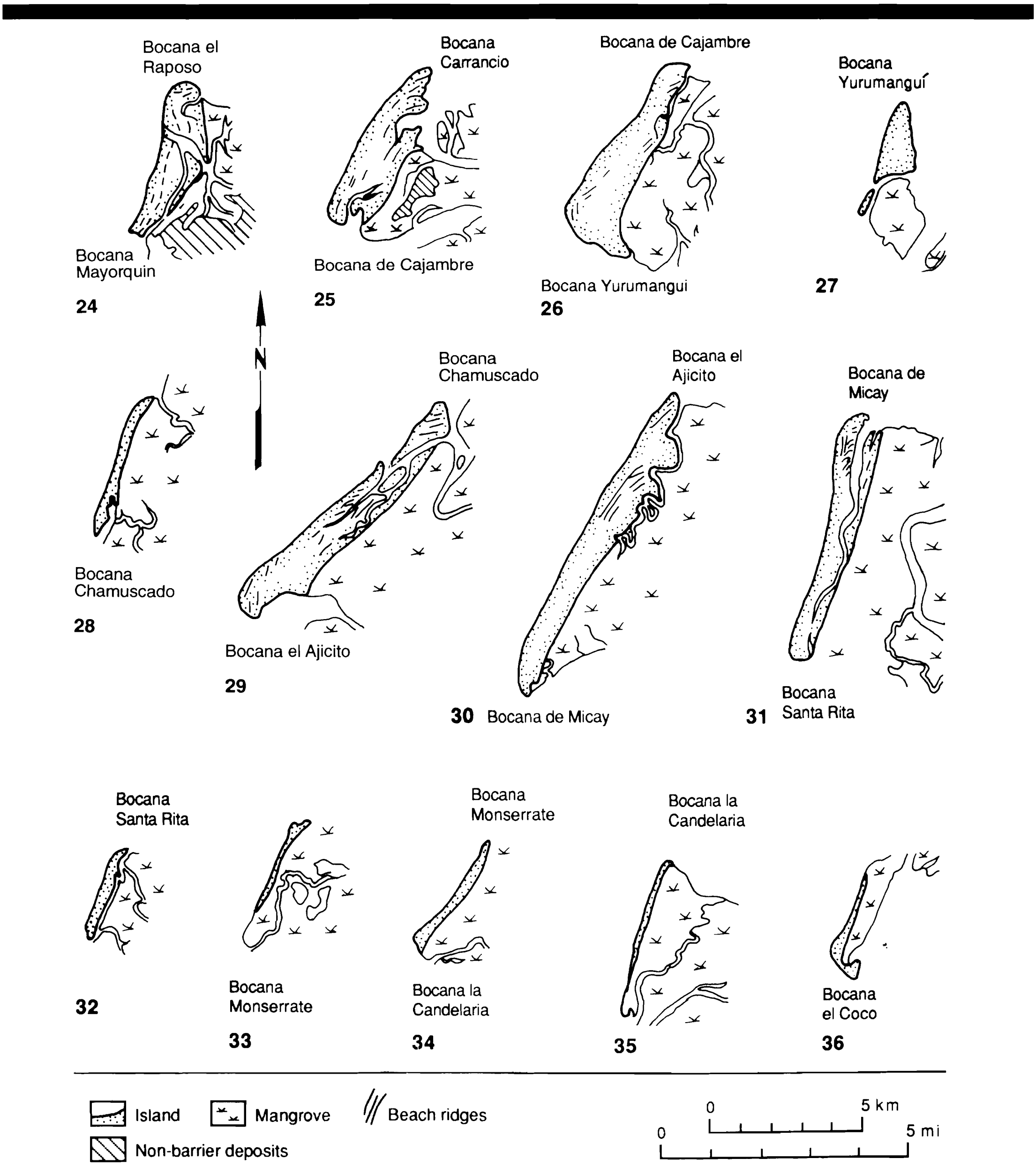

Figure 7. Islands 24 through 36. These islands are all part of island group 3.

nants of once larger islands are near the minimum limits for barrier island designation, but consist of a definitive vegetated sand "ridge" above the active beach.

The relative paucity of sand, the breaching, and overwash suggest that the system is transgressive. Virtually every island in the group shows evidence of erosion including exposed mangrove swamp muds, fallen trees, and backbeach scarping. Relative to mangrove areas to the north and south, the sand content is very low in the mangrove sediments exposed in tidal channels behind the islands and outcropping on the beach. The small sand volumes may reflect the lack of sand carried

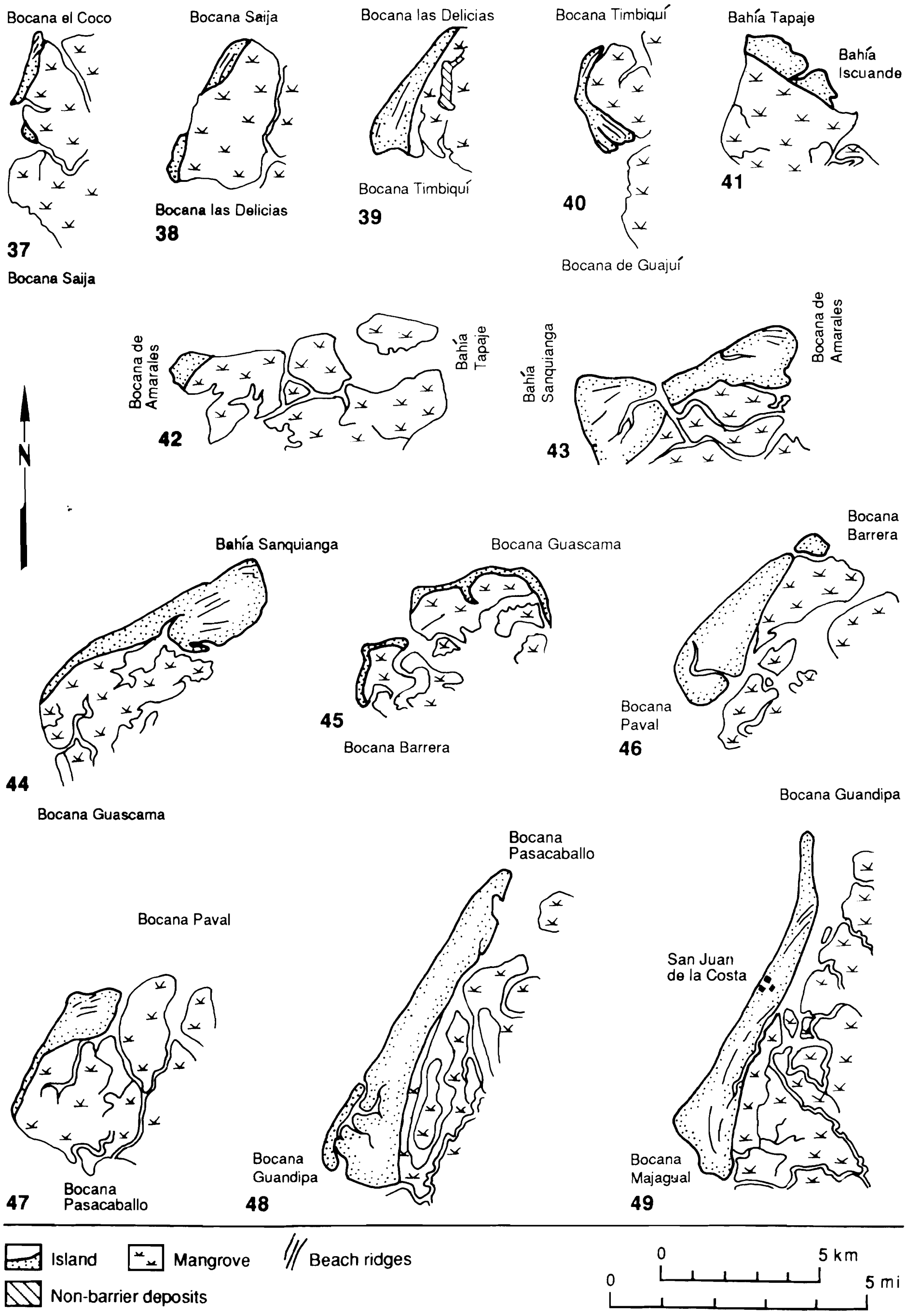

Figure 8. Islands 37 through 49 are representative of the southern islands of island group 3 (37–40) and part of island group 4 (Rio Patia delta).

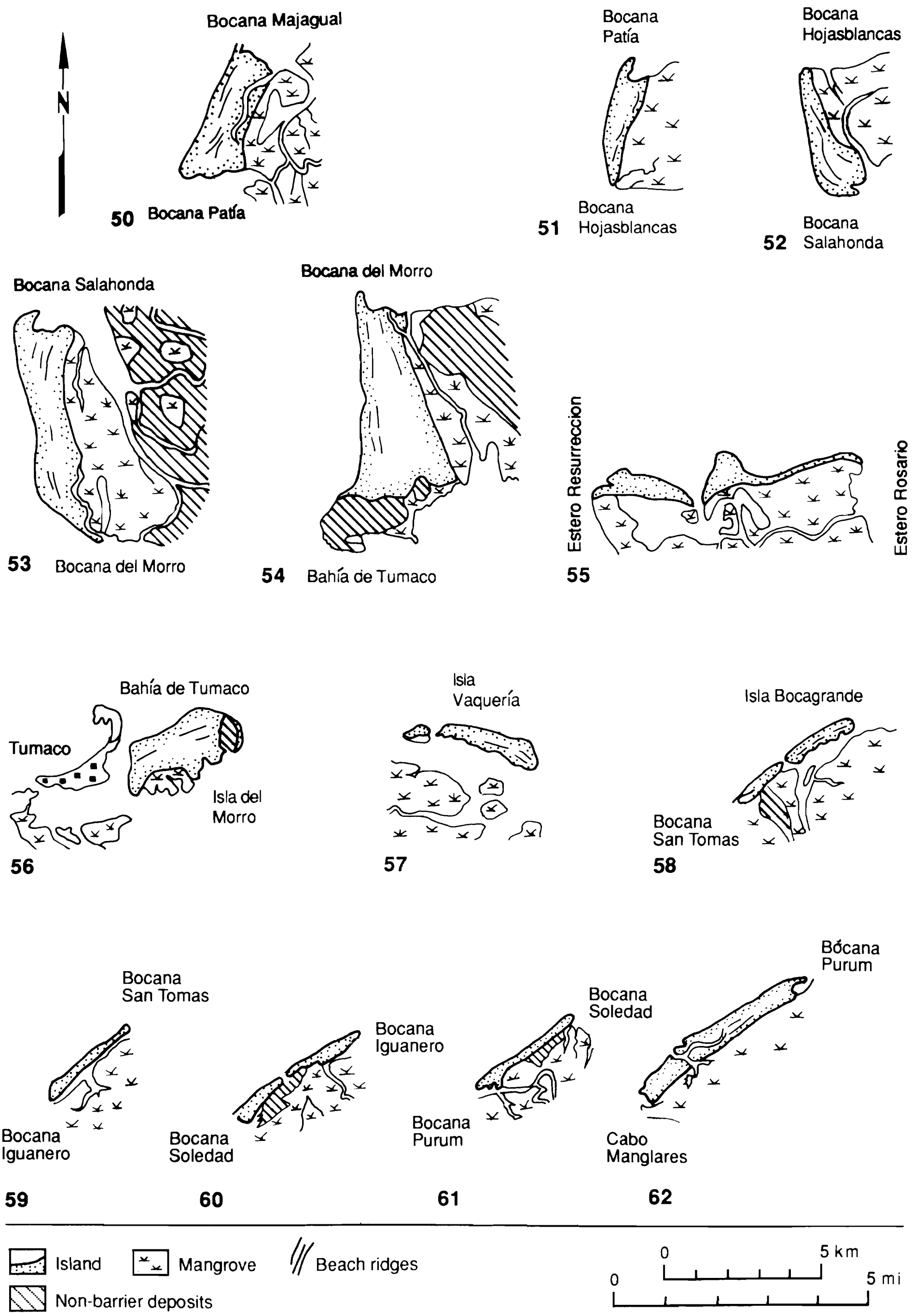

Figure 9. Islands 50 through 62 represent the southernmost barrier islands of Colombia's coast. Islands 55–62 border the delta plain of the Rio Mira (island group 5).

in the small rivers, as well as the sparse volume derived from mangrove substrate erosion. The area of very small islands corresponds to this sand "starvation." Likewise, subsidence due to both tectonism and compaction settling may contribute to differences in island dimensions and sand supply dynamics.

The lack of sand supply combined with subsidence may also explain the coastal change between island groups 3 and 4. Barrier islands are absent for over 30 km along the delta plain of the Rio Guapi and associated streams. Mudflats front eroding mangrove swamp, although local outliers of older fluvial terraces form headlands between wide estuarine channel mouths.

ISLAND GROUP 4

The Abandoned and Active Rio Patia Delta (Figures 8 and 9; islands 41–54) islands fringe the delta margin and are related to numerous delta distributaries. The main channel of the Rio Patia shifted to the south in the Quaternary, probably as a result of tectonic activity (Figure 10; GOMEZ, 1986). The wide variety of island shapes and sizes is related to island position with respect to distributaries, and constructional versus destructional segments of the delta plain (Figure 10). Most of these low-relief islands are short, but range in length from 1.4 to 11.0 km (Table 1). Island 49 is the site of the village of San Juan de La Costa where the previously discussed 1979 tsunami caused so much destruction and loss of life.

Inlets along the northern, subsided part of the Rio Patia delta (Figure 10), are wider on average than the rest of the coast (near 4 km), and tidal deltas appear to be small. These northern islands (41–46) are erosional remnants of once larger islands, and all continue to erode including breaching. Island 42 lies at the south end of an unprotected, highly erosive 7.5 km long mangrove shoreline suggesting that erosion has destroyed most of the protective sand barrier so that the surf zone is now littered with fallen mangrove and a substrate of mangrove peat and mud. To the south, along the more active delta edge (*i.e.*, sediment supply) islands 48–54 are fronted by beaches and are more substantial in area, but also show evidence of erosion. Here the inlets are on the order of 1 km in width, and beach ridges are common to all of these islands.

Active beachfront dune development occurs on the west-facing limb of the Rio Patia delta. Islands 43 and 49 have the most extensive dune development of all of the Colombian islands. Frontal dunes as high as 2 m line the shore. Clearly, the larger sand supply for this southern delta segment contributes to larger islands and active dune formation. The northern segment of the delta lost a significant portion of its sand supply when the main channel of the Rio Patia shifted to the south. The northern inlets are over five times as wide as the southern inlets, reflecting both rapid subsidence in the north and an insufficient sand supply to maintain inlet cross sections in equilibrium with the tidal prism.

ISLAND GROUP 5

Tumaco Bay Shore and the Rio Mira Delta (Figure 9; islands 55–62) island group is similar to groups 2 and 4 in that the arcuate chain of small islands fringes a delta system. Near the Ecuadorian border, the Rio Mira enters the sea via a single channel, as opposed to a series of delta distributaries. The river channel, however, appears to have shifted south, similar to the Rio Patia, and some of the small streams flowing into Tumaco Bay may be part of a former distributary system. Nearly all of the islands are backed by extensive mangrove forest.

The three northern islands of this group (Isla del Morro, Isla Vaquería, and Isla Bocagrande) are backed by open water and have carried the designation *island* on maps for a long time. Tumaco, one of only two major towns on Colombia's Pacific coast, is located on Isla del Morro. The community is at very high-risk due to a combination of shoreline erosion, tsunami potential, various forms of subsidence, and low elevation construction siting.

Except for Isla del Morro which has an area of 4.3 km^2, these islands have the smallest area of any of the island groups (0.8 to 3.5 km^2; Table 1). Despite island narrowness, small beach ridges are commonly present, and low dunes of up to 1 m elevation form on the northwest-facing islands. The islands are breached or have small, tidal channels splitting the island. Mangrove peat and dead stands of mangrove front some beaches.

Island lengthening and migration is to the northeast and east toward Tumaco Bay as indicated by Isla Vaquería which moved nearly its entire length between 1969 and 1989 (Figure 11). Most of the islands of group 5 are transgressive as suggested by Isla Vaquería, however, islands such as 57 and 58 may initially have formed due to spit detachment. Size and distribution of the

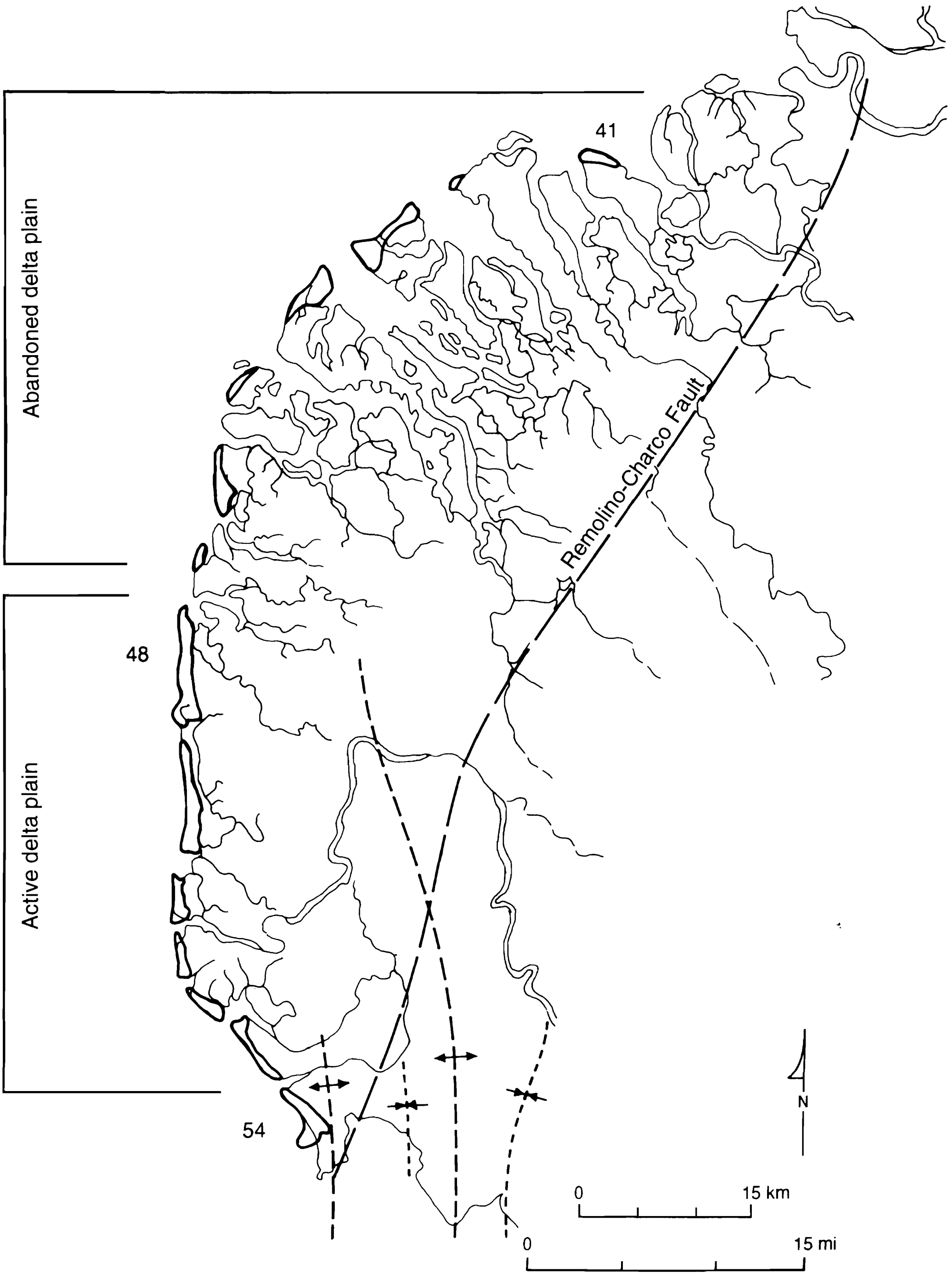

Figure 10. Rio Patia delta showing island group 4 barrier islands. Regional structures are indicated, including the active Remolino-Charco Fault. Rio Patia channel switching to the south resulted in reduced sediment supply to the northern delta. Subsidence, flooding of distributary mouths, and reduced sediment supply resulted in wider inlets and smaller islands. (Modified after Gomez, 1986).

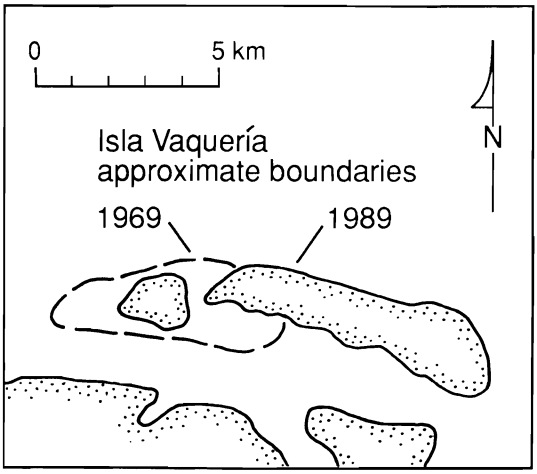

Figure 11. Isla Vaquería migration pattern, 1969–1989.

islands suggest a limited sand supply. One possible reason for their small size and dynamic behavior is the narrow shelf (7 km wide) in this area which results in the highest wave energy on Colombia's Pacific coast. These islands may be impacted more by El Niño induced changes in sea level and storminess (higher wave energy) than islands farther to the north. Although this island chain extends into Ecuador, the study area ended at the border.

DISCUSSION

The barrier islands of Colombia are significant because (1) they exist on a leading-edge coast, (2) they are covered by tropical rainforest, and (3) they are in a near-natural state, not yet impacted by human activity.

The major ramifications of barrier island formation on a leading edge coast is that tectonic activity must play a more important role in island evolution than on trailing margins where most barrier island chains exist. Tropical rainforest provides a different vegetation-sand accumulation relationship relative to the more commonly described temperate zone barriers with vegetated dunes. The combined tropical rainfall, leading edge and proximal high relief of the Northern Andes favor a high sediment supply into a narrow coastal plain/continental shelf setting. The resulting dominant fluvial/deltaic sedimentation produces a clastic wedge that subsides locally due to compaction, isostacy, local seismicity, and longer term tectonism.

The lack of human impact through island stabilization, channel dredging and inlet modification, or major construction in the hazard zone affords an opportunity to view barrier island evolution free of human influence.

These barrier islands exhibit some similarities with those of the Mississippi Delta. Both types are found on the seaward fringes of delta lobes, and both consist of low dynamic islands in a highly erosive state. The sand-to-mud ratio is low in both cases. Mangrove swamps occupy the lagoon in back of the Colombian islands, whereas salt marshes back the Louisiana islands. Dune plants dominate the Louisiana islands, while fully developed rainforest covers the tropical islands.

According to PENLAND *et al.* (1988) the barriers of Louisiana follow a cycle that begins when a just abandoned Mississippi River delta lobe erodes and supplies sand to form barrier islands. The cycle ends when the barrier islands migration cannot keep up with the subsiding, eroding delta lobe and they are lost to erosion. In contrast, the Colombian barriers are forming off active delta areas with continued sediment input, although the sediment supply is much less than for the Mississippi Delta. If the cycle of delta-edge barrier island formation and destruction exists on Colombia's Pacific coast, it is less important because of the closeness and continuity of adjacent fluvial systems making up the nearly continuous alluvial plain. However, the seismic component for rapid subsidence adds another dimension for Colombia's islands not present in the Mississippi Delta.

Overall, Colombian barrier island sand volumes are smaller than comparable North American systems, suggesting some combination of restricted sand supply and rapid relative sea level rise. Beach ridges, a major component of the sand volume of many U.S. Atlantic Coast barriers, are very small on the Colombian islands. The dense tropical rainforest cover on some of the islands may inhibit eolian sand distribution. Certainly the dense vegetation is a hinderance to cross-island distribution of overwash sand.

The length of the Colombian islands ranges from 1.4 km (island 42) to 15.8 km (island 6), and most of the islands are 4 to 7 km in length; short in comparison to North American and most barrier island chains. In part, these island lengths must be controlled by the patterns of the numerous river distributaries, large and small, which drain to the Pacific. The high frequency of inlets also may be a function of the large tidal amplitude (Hayes, 1979) which is in the high mesotidal range.

Inlet widths range from 0.2 km to 6.0 km and are thought to be controlled by three factors: the tidal prism including fresh water discharge between islands, sand supply, and subsidence. For example, the main distributary of the Rio Docampado forms a 6 km wide inlet south of island 10, and the Brazo Churimal, a major distributary of the Rio San Juan, flows through a 5 km wide inlet south of island 16. The smaller Rio Naya and Rio Micay have inlet widths of 2.4 km and 2.5 km, respectively. Large inlets occur between the islands of the northern, abandoned Rio Patia delta, an area of active subsidence.

Low sand supply results in sediment "starved" islands with wider inlets than neighboring "robust" islands. For example, the northern-most islands of the Rio Patia delta island group are sand starved as a result of channel abandonment and river mouth switching to the south. These islands tend to be narrower than the nourished islands of the southern delta edge, near the primary distributary. The sand supply associated with the active distributary may also account for narrower inlets because more sediment is available to build equilibrium channel cross sections.

Rapid subsidence of the entire delta is an additional factor in the fluvial sand supply to the islands. River mouth switching deprives the delta of sediment; as the abandoned areas subside, the older distributary mouths become flooded or drowned. Sand deposition occurs further upstream. These wider inlets have less fluvial discharge than the narrower active distributary inlets, and generally lack significant ebb tidal deltas in the Rio Patia region. Figure 10 shows the abandoned part of the delta plain is starving for sediment and suffering landward inundation (wide inlets and estuarine tidal channels).

Several gaps occur in the Colombian barrier island system. These other shore types include (1) the mouths of large bays (Malaga, Buenaventura and Tumaco), (2) cliffed coasts in terraces of Tertiary and/or Pleistocene sediments where the rivers have not built an alluvial plain, and (3) the severely sand-starved reaches such as the embayed delta plain in the region of the Rio Guapi (between island groups 3 and 4). In the latter zone, the shore consists of mangrove peat and associated sediments of the mainland delta plain exposed to direct wave attack, protected only by a very narrow sand beach. This type of coast was implied for almost all of the coastal lowlands in earlier works (*e.g.*, West, 1957).

Table 2. *Factors controlling Colombian barrier island evolution.*

- Wave and Tidal Current Energy
    - Island Orientation
    - Shelf Width
    - El Niño
    - Tsunamis
- Sand Supply
    - River Sediment Type/Volume
    - River Mouth (Distributary Switching)
    - Composition of Backbarrier Substrate (Shoreface Bypassing)
    - Wave Climate
    - Tidal Amplitude
    - Island Orientation
    - Subsidence (Tectonism and Compaction)
    - Vegetative Cover
- Relative Sea-level Rise
    - Global Sea-Level Rise
    - Catastrophic Change: Earthquakes
    - Long-term Downbuckling
    - Subsidence (Delta Mud Compaction)
    - El Niño

These leading-edge barrier islands are almost entirely in a state of ocean-side erosion. The major factors controlling island evolution and the highly variable rates of erosion are wave and tidal current energy, sand supply and the relative sea level rise (Table 2).

Wave Energy varies according to island orientation and continental shelf width. Island group 5, the southern chain, fronts the narrowest shelf (7 km) and has the highest wave energy which may be a factor in the islands' highly erosive nature. Sand supply from relatively small rivers is a factor as well.

El Niño impacts are little understood for Colombia's barrier islands, but in the case of the Ecuador and Peru coasts where El Niño sea-level rise and increased storminess is more profound, this phenomenon must play a role in shoreline evolution (Ortlieb and Macharé, 1992; Komar and Enfield, 1987). Beach ridges in Peru have been associated with individual El Niño events (Sandweiss, 1986). The relative importance of El Niño and tsunamis should increase from north to south on the Colombian Pacific coast, and may be reflected in the stratigraphic record of the southern islands. The presence of dense tropical rainforest cover, however, may limit the extent of sand deposition from these extreme events on the islands. Coring is needed to determine if El Niño and tsunamis have left a record (*e.g.*, increased overwash deposition, beach ridge evolution, changes in island elevation, increased shoreline retreat).

Sand Supply to the islands varies according to the factors noted, none of which have been even quantitatively evaluated. Island orientation plays a role as evidenced by the relatively extensive dune development on the west facing limb of the Rio Patia delta. Clearly, the quality and quantity of the sediment load of the rivers forming the coalesced deltaic coast is a critical (but quantitatively unknown) factor in the sediment budget equation. The importance of river sediment load is demonstrated by the north to south river mouth switching of the Rio Patia as previously discussed.

The differing sand content of mangrove substrate may be responsible for the narrowness of islands 32–40 and their absence immediately south of island 40. Field observations indicate a distinct relatively lower sand content in the banks of tidal channels behind the islands. Thus, the fraction of sediment contributed to the island from mangrove erosion during island migration is reduced.

Relative Sea-level Rise is unquestionably a major factor involved in the evolution of these islands. Because of both tectonic and compaction subsidence components, the relative sea-level rise is variable along this coast for even short distances of a few kilometers. As noted, limited tide gauge data (Buenaventura and Tumaco) indicates a general slight regional sea-level rise in recent decades. No records are available that could indicate the mangrove substrate compaction component of the sea-level rise. The most important local differences in sea-level rise may be catastrophic changes due to rapid elevation change from earthquakes. The apparent 1979, 0.9 m sea-level rise reported by HERD *et al.* (1981) in the area north of Tumaco is a very recent example of this phenomenon. He also suggested a longer term sea-level rise component related to the crustal downbuckling of the continental South American plate over the subduction beneath the continental plate boundary.

EVOLUTION OF THE BARRIER ISLAND CHAIN

With the exception of the few detached spits north of Cabo Corrientes and a few of the Group 5 islands, the Colombian island chain is hypothesized to have formed seaward of the present position and migrated landward with the Late Holocene sea level rise. The migration was across a broader delta plain that was submerged and reworked in the transgression. Wider islands with sequential beach ridges indicate that much of the system underwent a regressive phase reflecting a slowdown in sea-level rise and/or an increase in sand supply. Since no Holocene sea level curve is available for this area, no conclusion can be drawn as to the time of island widening. More recently, the islands have returned to a regional transgressive pattern, particularly the narrow, sand-starved islands. Mangrove substrate frequently outcrops on the barrier beaches and in the immediate nearshore mudflats. This response is to a relative sea-level rise resulting from the combined effects of compaction subsidence of the delta prism, catastrophic subsidence over a large area as described by HERD *et al.* (1981), and the global sea-level rise. Recent El Niño episodes may account for accelerated erosion.

As the islands initially transgressed landward in response to rising sea level and tectonic events, they gained sand by shoreface bypassing. That is, as tidal channel and mangrove substrate deposits came to the seaward side of the islands and were eroded, their sand fraction was available for the islands' subaerial buildup. During migration, sea-level rise rates were probably irregular, due to tectonism in this seismic area. Rapid sea-level rise promoted narrow islands; slower rates of rise resulted in island widening with a regressive stratigraphic framework.

Sand also was contributed to the islands directly by deposition of fluvial-derived sediments during extensive floods, on adjacent ebb and flood tidal deltas, and eventually came ashore along with the shoreface bypassed material. During island transgression, inlets migrated both to the north and south, and new inlets formed by incision through breaches similar to those seen on today's islands. As distributaries of the deltas shifted, inlets also were displaced.

Island elevation building occurred where sand dunes accreted and overwash occurred; both primarily on the front sides of the islands. Dune accumulation probably was favored on west-facing shores subject to higher wave energies from south and southwestern winds, and well supplied with sand. Although speculative, times of El Niño may have favored increased fluvial sediment supply (*e.g.*, flooding) and more rapid sand accumulation, both by eolian and overwash processes.

CONCLUSION

Recognition and mapping of the 62 barrier islands of the Colombian Pacific coast provide an important basis for future management of the area. Because barrier islands have been extensively studied elsewhere, a large reservoir of information can now be applied in managing and protecting these islands during their future development; an initiative receiving special government attention beginning in 1992. Immediate guidance can be provided to planners and officials regarding placement, expansion or relocation of endangered coastal communities, such as a current study for Tumaco.

The islands provide an excellent model of a barrier system on a tropical, leading-edge coast. Colombia's Pacific barrier islands, and their short extension into Ecuador also hold promise as a site to examine the potential record of El Niño frequency and magnitude. Understanding El Niño is recognized as a key to safe development of the coasts of Peru, Ecuador and Colombia. The stratigraphic framework of these islands remains to be defined; however, this record holds the possibility of evaluating the complex set of controls that have determined the dynamics of these islands, namely the sea-level rise, sediment supply, rates of subsidence, and the impact of short-term events such as tsunamis.

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□ RESUMEN □

En la costa del Pacífico colombiano sesenta y dos islas barrera han sido reportadas y descritas. Las islas, con una densa cobertura de bosque tropical y antecediendo una extensa planicie de manglar, definen el borde costero de un angosto y extenso prisma deltáico, formado por los ríos que drenan esta parte de los Andes. Las islas son interesantes por varias razones entre las que se incluyen: su posición en una margen costera tectónicamente activa, que a través de subsidencia a largo plazo produce aumentos relativos del nivel del mar; subsidencia sísmica a escalas de tiempo más cortas; tsunamis; su ubicación en un ambiente tropical, donde la sedimentación deltáica y la densa cobertura de vegetación afectan la dinámica de las islas en términos de subsidencia, cambios en el curso de los ríos, y calidad y cantidad en los aportes de arena; la posible influencia de los eventos asociados al Niño; y la no intervención humana en la dinámica de las islas.

Cinco grupos de islas genéticamente relacionados fueron identificados: dos de ellos asociados a tramos rectilíneos de la costa y los otros tres asociados a lóbulos deltáicos. En una etapa inicial las islas fueron probablemente transgresivas, posteriormente y por un período de tiempo indeterminado se hicieron regresivas, antes de la reciente reiniciación de una nueva fase transgresiva y de severa erosión. Unas pocas islas se formaron por desprendimiento de espigas. Muchos de las islas estan empobrecidas en sedimentos debido a la pérdida de los aportes producida por cambios en los distributarios o porque algunas de ellas se encuentran en áreas de turbas lodosas con poca arena y escasos aportes fluviales.

Futuros trabajos estratigráficos serán la base para identificar la frecuencia de eventos como tsunamis y el Niño, y para establecer la historia reciente de cambios de nivel del mar y entender como han afectado cada prupo de islas.