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Barrier Island Evolution on the Subsiding Central Pacific Coast, Colombia, S.A.

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ABSTRACT

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The remote barrier islands of Colombia's Pacific Coast exist on a leading edge, subsiding fringe of coalescing small deltas from rivers draining the Northern Andes Mountains. The islands are covered by dense tropical rain forests and are backed by extensive mangrove forests. Four of the 20 islands fringing the Micay, Naya, Yurumangui, Raposo, and Anchicaya Rivers' delta plain near Buenaventura, were studied in detail. El Soldado, Santa Barbara, Chamuscado and El Aji Islands are subjected to moderate wave energy, high sand supply, high mesotidal range, general south-to-north sand transport, and subsidence. The islands are of low elevation (less than 2 m) above spring tide level, and between 5.5 and 8.6 km in length. The shallow stratigraphy is dominated by three general facies: beach sands, washover sands, and mangrove swamp muds. Extension of the overwash facies to almost 2 m below the spring tide line suggests subsidence is a factor in island evolution, which, in part, is a function of an equilibrium between subsidence rate and sand supply. Islands narrow after a subsidence event, and rapidly widen between such events where the sand supply is high. The regressive phase is dominated by accretion of beach ridges that grow as spit-like features along the island front. The islands provide a model for barrier island evolution on a tectonically active, leading-edge coast.

ADDITIONAL INDEX WORDS: *Delta, sedimentary facies, spits.*

INTRODUCTION

Barrier islands make up a significant portion of Colombia's Pacific coast (MARTINEZ *et al.,* 1995). Sixty-two barrier islands were identified and mapped on a reconnaissance basis along the narrow alluvial coastal plain as an outcome of the Instituto Nacional de Investigaciones Geologico-Mineras de Colombia (INGEOMINAS) coastal mapping program (GONZALEZ and MARIN, 1989; MARTINEZ and CARVAJAL, 1990a,b; MARTINEZ and GONZALEZ, 1997). The project was the first systematic geomorphologic mapping of Colombia's Pacific coast since the work of WEST (1957). The barrier islands had gone unrecognized in part because of their low elevation, the dense cover of mangrove swamp and rain forest, and their remote location.

These barrier islands are unique globally with respect to their geologic and climatic setting as well as some of the related processes of island evolution, however, they show most of the geomorphic response types defined by MCBRIDE *et al.* (1995). Geologically the islands are located on a leading-edge coast in a region of active seismicity; impacted by historic earthquakes, related tectonic subsidence and tsunamis (HERD *et al.,* 1981). The fluvial plain which the islands fringe is relatively narrow compared to coastal plain systems like the southeastern U.S., and is fed by a high density of large rivers that derive a high sediment supply from the adjacent Andes Mountains. Petrologically the island sands are first-cycle sediments dominated by sand-sized rock fragments, high percentages of heavy minerals, and high mica content.

Although the dearth of climatic and oceanographic data restricts our knowledge of local conditions, several general aspects are in contrast to the more familiar barrier islands of the U.S. The islands lie between 1° 25′ and 7° 13′ North Latitude in a tropical zone with some of the highest annual precipitation rates in the western hemisphere (>5000 mm/year or nearly 200″/year). The high rainfall is responsible for high run off, dense cover by mangrove and rain forest over the islands and associated river/delta plains, rapid vegetation of newly accreted spits, washover fans, and beach ridges, and a corresponding near elimination of aeolian dune formation.

The absence of frequent storm-related, cross-island processes allows the westerly to southwesterly waves to generate a regional pattern of north-flowing longshore currents that are an important driving force in island evolution. Wave energy is moderate (wave lengths 10 to 50 m; average wave heights 0.5 to 1.5 m) in the study area, but storm waves reach heights of 1.5 to 3.5 m, and most beaches are dissipative. El Niño conditions are known to raise sea level another 20 to 30 cm, and erosional shore retreat can be rapid on spring tides. El Niño conditions alter the dynamics of the system further due to increased wave energy, higher rainfall/runoff and presumably higher sediment supply.

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This coast is tide dominated with an average mesotidal range of 3.5 m near Buenaventura, but ranging into spring macrotides of 4.9 m. The maximum island elevation above the high-tide line in the study area is only 2.5 m, and most islands are much lower. The general pattern of net longshore transport is from south to north, with pronounced spit elongation on the north ends of the islands.

The larger inlets between islands appear to be stationary in association with river estuaries. These large estuarine inlets are analogous to the large, deep-throat stable inlets of the Georgia Bight (HAYES, 1994). The larger estuaries commonly have elongate sand bars in their channels. Strong ebb currents and river discharge form large ebb-tidal deltas, analogous to OERTEL'S (1977) type D ebb deltas of the U. S. Georgia coast. These deltas are characterized by elongate, shore-perpendicular sand bars that form horn-like extensions bordering the central channel of the ebb delta. Detachment of these shoals allow small, strongly recurved spits to build into the inlets on the south ends of all four islands. These local reversals of the regional longshore drift pattern are a function of currents associated with the ebb-tidal deltas. Spit growth may cause temporary narrowing of inlets, but, based on air photos, no significant inlet migration has occurred in the last 40 years.

Tidal creeks and channels dissect the mangrove swamps behind the islands. Tidal flooding of the troughs behind the frontal beach ridges sometimes overtops ridges and incises outlets through the frontal beach ridge. Outlets may also form when erosional retreat cuts through to a tidal creek. Tidal flushing maintains flow in and out of these outlets via the troughs that develop as the next bar welds to the beach and then accretes laterally as a spit along the island front.

The growth of these frontal spits is an important mechanism during the widening phase of the islands, although no signature facies is produced (*i.e.,* they consist of beach and overwash facies), and when the beach ridge is incorporated into the island its origin is not apparent.

STUDY AREA AND OBJECTIVES

MARTINEZ *et al.* (1995) defined five groups of barrier island chains along Colombia's Pacific coast based on natural geomorphologic divisions such as individual delta lobes or chains bounded by local upland terraces that form cliffed coasts. The objective is to move from regional reconnaissance to looking at four selected islands (El Aji, Chamuscado, Santa Barbara, and El Soldado) in greater detail to determine the processes and history of island evolution (Figure 1). Through coring, the general stratigraphy and facies were defined, short-term migration patterns established (*e.g.,* transgressive or regressive), and evidence sought that might indicate subsidence, and signature or cyclic events such as sediment liquefaction due to earthquakes, tsunami deposits, or repetitive El Niño events.

The northern half of island group 3 (MARTINEZ *et al.,* 1995) was chosen as a representative set of islands (Figure 1). These exist at the edge of a coalesced fluvial-deltaic plain of several large rivers, and provide the least difficulty in access and logistics (the islands are accessible only by boat). The reach of the islands examined extends for over 80 km from the Rio Naya on the south to Bahia de Buenaventura including the mouths of the Rio Yurumangui, Rio Cajambre, Rio Raposo, and Rio Anchicaya, all of which head in the Andes, as well as several smaller rivers. A chain of six islands extends from the estuarine mouth of the Rio Naya to a cliffed upland cut in an outlier of Pliocene sandstone and mudstone of the Mayorquin Formation. The largest islands in this chain are El Aji and Chamuscado (Figure 1).

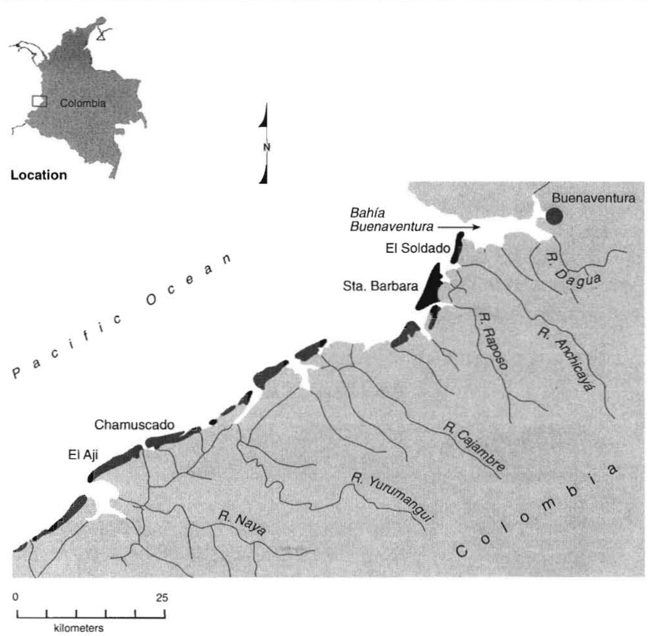

Figure 1. Index map of the study area from Buenaventura Bay to the mouth of the Rio Naya showing the location of El Soldado, Santa Barbara, Chamuscado, and El Aji Islands.

North of the upland, a chain of four islands front the delta complex of the Rios Raposo and Anchicaya, and is located in a slight reentrant; sheltered by the upland which forms the north shore of Buenaventura Bay. This deep embayment and the marked change from deltaic lowlands on the southern side to the cliffed upland northern shore suggests activity along the Buenaventura Fault which traces through the bay. Streams draining off of the upland into the bay are incised in youthful valleys, suggesting uplift, while the delta front is a complex of barrier islands and mangrove swamps cut by estuaries and tidal creeks. Santa Barbara Island is the largest in this chain and is characterized by tidal stream outlets along its front. El Soldado is offset from Santa Barbara, and adjacent to Buenaventura Bay.

Very little information exists on nearshore, continental shelf or estuary bathymetry, character of the tidal deltas, or fluvial sediment loads. Reference benchmarks such as tide levels, fixed survey points, and topographic maps are lacking. Profiles across the islands to identify landform features, establish maximum island elevations, and establish the elevation of the tops of cores, were referenced to the maximum high tide mark as seen in the field (*e.g.,* wrack line, or observed spring tide line). Air photo coverage of variable quality is available for approximately the last 40 years.

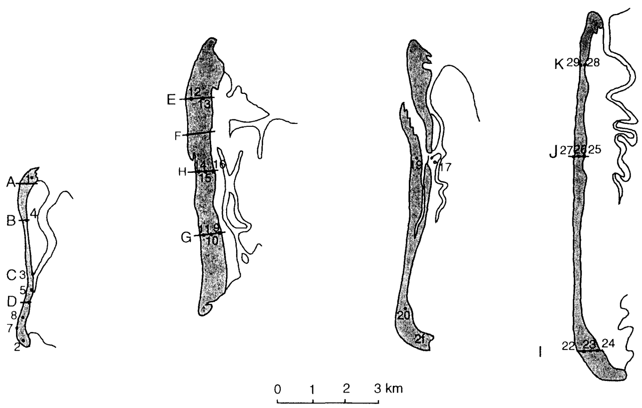

Figure 2. Comparison map views of the four islands showing lines of topographic profiling and numbered core locations. From left to right the islands are El Soldado, Santa Barbara, Chamuscado, and El Aji.

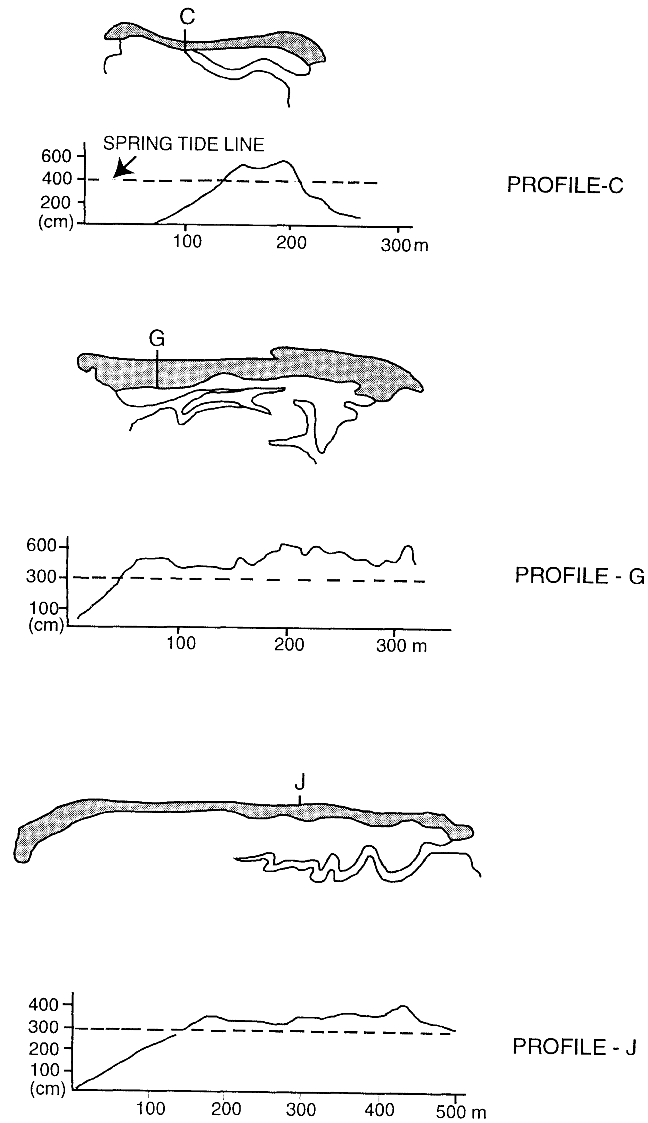

Figure 3. Representative cross-island topographic profiles for El Soldado (top), Santa Barbara (middle), and El Aji (bottom). The dashed line represents the spring tide line on all three profiles.

Field sampling included taking push cores of representative surface environments, 30 vibracores and hammer cores (Figure 2), and five cross-island trenches to depths of 2 m. Trenches and cores were sampled for textural analysis and reference peels of all cores were made in the field. Eleven cross-island topographic profiles were surveyed to describe features such as beach ridges (Figures 2 and 3). As indicators of age, size of trees was noted, and the absence or presence and thickness of the surface soil profile measured. The largest trees are approximately a century old, and for these sandy sediments under tropical conditions a soil oxidation depth of 50 to 70 cm can develop in as little as 100 years (Pedro Botero, IGAC, *personal communication*).

The rapid change and very young age of significant areas of these islands can be seen in the air photo sequences from 1961 to 1992, and is reflected in the core stratigraphy. An anthropomorphic time horizon is preserved in the overwash sediments because large amounts of refuse and flotsam (*e.g.,* plastic, glass bottles, metal cans) are flushed out of Buenaventura Bay and carried by tides and waves onto El Soldado and to a lesser degree Santa Barbara, and buried by washover.

General Facies

The facies presented here are generalized to illustrate the growth trends of the islands (Figure 4). Mangrove facies are consistently structureless muds with variable amounts of mangrove roots. Overwash deposits are well-sorted sands, tending to be structureless or faintly bedded and parallel laminated. In the trenches, overwash bedding is gently inclined landward with rootlet horizons marking revegetated surfaces buried by the next overwash. The upper beach facies shows more variability including thinly-bedded parallel and cross-laminated units, as well as highly diagnostic thin beds of concentrated wood chips. Such wood chip concentrations presently are found accumulating at the back of the beach, and along the low tide line of the lower beach. Similar wood chip layers together with interbedded fine sands that are typically cross laminated to cross bedded, and sometimes shelly, represent the lower beach facies. The present beaches are low in shell content, but shell concentrates are more common along the low-tide line, and scattered in other beach facies. Calcareous shells, however, seem to be removed from the sediment column in a relatively short time by dissolution. Tidal flat (mud) and channel facies (gravely sands) occur locally, usually near the ends of the present islands.

ISLA SOLDADO

Isla Soldado is 5.5 km long and extremely narrow, averaging less than 55 m in width at spring high tide, but three times that width at low tide (Figure 3). Maximum elevation is typically 2 m above the spring high tide line. The island is

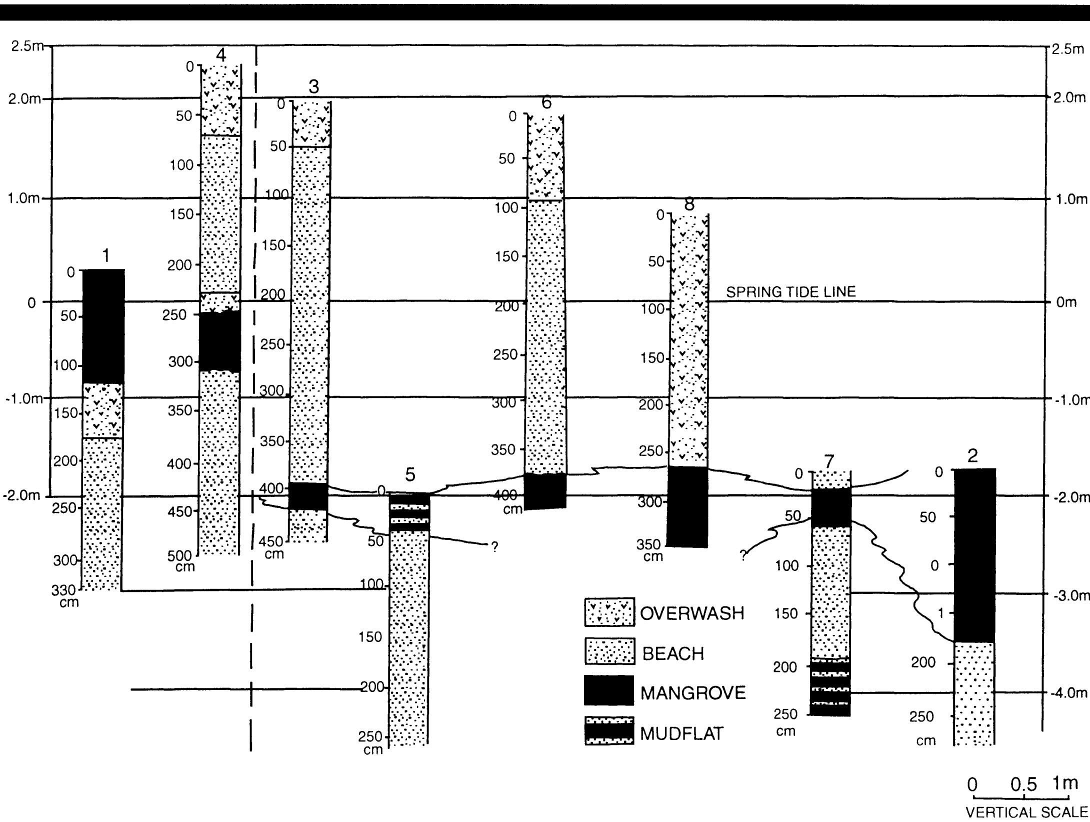

Figure 4. Representative core stratigraphy showing the generalized facies. These cores represent a composite cross-section along the length of El Soldado Island from north (left) to south (right). The zero reference line represents the approximate level of spring high tide. See Figure 2 for numbered core locations. Note overwash facies extending to nearly 2 m below the spring tide line atop mangrove muds.

bounded by Buenaventura Bay to the north and Santa Barbara inlet to the south.

Soldado is a transgressive island as indicated by the following:

- The open ocean shoreline position of the 1992 island is behind the backside or lagoon shoreline of the 1961 island for the southern ⅓ of the island, *i.e.,* in 30 years the island has narrowed and partially migrated a distance equivalent to its entire width (Figure 5).
- The abundance of post-1960 plastic and glass refuse as a component of the overwash sediment column in the entire subaerial sediment column.
- The lack of soil development.
- The lack of large or old trees in the vegetative cover.
- The absence of surface drainage.

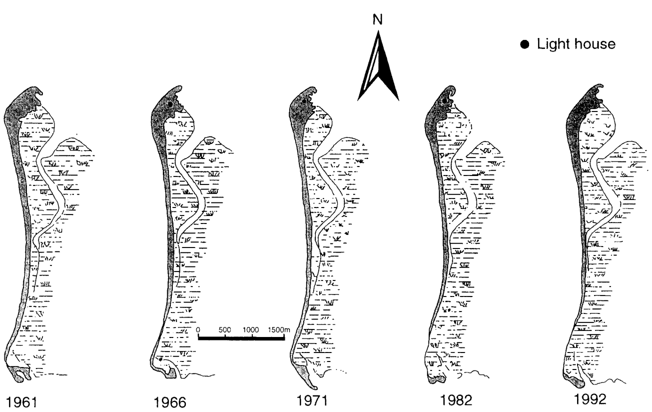

Figure 5. Comparison sketch maps of El Soldado Island from aerial photos: 1961–1992. Note in-place thinning in the southern half of the island as well as some landward rollover at head of tidal creek. Accretion is occurring along the more northern segment of the island.

Net long shore transport is to the north. At the north end, the actively growing, recurved spit has extended northward into Buenaventura Bay. An average accretion rate of 1.0 m/yr was calculated for the period of 1961–1992 from air photos. The ebb tidal deltas consist of two, 2 km long "horns" of sand extending perpendicular to each end of the island. These features are similar in origin and evolution to ebb-tidal deltas of the U.S. Georgia coast (OERTEL, 1977, type D deltas). The shoals are sometimes attached during which time the inlet margin erodes, and the flank of the shoal may accrete onto the island front, forming beach capes. When the shoal is detached, as at the south end of the island at present, a local reversal of the longshore drift pattern occurs, the adjacent beach erodes and a recurved spit builds into the channel behind the ebb delta. Like ebb-flow dominated estuaries in other barrier island systems, no flood tidal-delta development is apparent.

Figure 6. View along El Soldado Island, which has been narrowing. Note the taller tree line, which marks the boundary between the back of the island and the mangrove swamp. The lighter colored vegetation zone along the front of the island is dominantly cane which marks the area of historic overwash. Refuse is common in these deposits to a depth of 0.9 m.

Another extensive sand bar, probably part of the ebb tidal delta system, runs parallel to the shoreline in front of the island at a distance of about 1 km. The combined off-shore shore-parallel bar and the tidal delta horns result in low wave energies at low tide, and accumulation of mud layers and organic debris on the broad, gentle platform fronting the island. Although these bars are important dampers on the impact of storms and perhaps even tsunamis on Soldado Island, most sand movement on the beach occurs at mid to high tide levels when the wave dampening effect of the ebb tidal delta is decreased.

Soldado Island is heavily vegetated, reflecting the tropical conditions. Except at the island ends, fast growing cane on the seaward side is the dominant salt-resistant plant type, covering more than ½ of the island's land area (Figure 6). A dense mature mangrove swamp abuts the landward side of the island. Tidal channels meander against the landward side of the island in two places, eroding sharp 2–3 m sand bluffs, which expose apparent overwash deposits. Elsewhere the island/mangrove forest contact is also sharp, usually marked by a relatively steep, 1 to 2 m sand slip face at the landward edge of the washover terrace. This type of island-mangrove contact is absent on the other three islands. The outline of the island's landward side appears to be more or less straight and parallel to the open-ocean shoreline.

Broad, low, shore-parallel sand ridges mark the surface of the island. The ridges, usually 1 to 3 in number, are 10 or 15 m wide and have less than 1 m of relief. There is little vegetative difference between troughs and ridges, hence surface topography cannot be positively discerned from air photos.

The subaerial sediment cover consists primarily of overwash sand, perhaps combined with a minor aeolian contribution. The principal evidence for the overwash origin is the ubiquitous presence of plastic refuse throughout the surficial (1.5 m) sediment column. In some trenches, the trash is found 70 cm below the level of the spring high tide line. The plastic debris and associated trash arrived on the island as a result of improper solid waste disposal at Buenaventura. Under proper tide and wind conditions, the trash floats to the island and is deposited on the beach to be later overwashed into the island interior. The upper beach of Soldado Island nearest to Buenaventura Bay has a dense debris cover of plastic containers, glass bottles, metal cans, and related flotsam. Plastic and related debris can be found in varying densities on the surface of the entire island.

The lack of dunes and the apparent lack of any significant aeolian contribution to the island are puzzling. Winds of appropriate velocity and direction to transport sand to the island's interior exist and landward aeolian sand transport was observed in the field; but accumulations were observed only as ripples and wind-shadow deposits on the upper beach. Possible explanations for the lack of dunes and aeolian sand include:

- general lack of sustained strong winds
- wetting of the sand by the frequent occurrence of rainfall
- rapid seaward growth of stabilizing vegetation across the dry beach

The age and origin of the sediment column are strong arguments that subsidence has played a major role in the evolution of the island. We suggest that the island's morphology and sediment column point to periodic subsidence, of a meter or two, followed by island reconstruction through the formation of progradational beach ridges during storms and spring tides. There is no indication of overwash events crossing the entire island into the mangrove swamp. Rather island build-up with overwash and aeolian sand appears to be restricted to the seaward most 10 meters or so, or to the seaward most beach ridge. In other words, as subsidence occurs, the island becomes a submerged shoal or near shoal only to be rebuilt by subsequent beach ridge formation.

The principal lines of evidence pointing to the subsidence of Soldado Island are:

- The presence of post-1960 plastic refuse throughout much of the sediment column above the spring high-tide line, indicating recent island submergence and repair. This also means that the entire surface veneer of the 55 km wide island is post-1960 in origin.
- The overwash sediment column extends almost 2 m below the spring high-tide line.

- In the mid-island area the steep slip face, 1 to 3 m in relief, facing the mangrove forest, has built-up vertically as the island has narrowed, but not migrated into the mangrove forest since 1961. On adjacent Santa Barbara Island, the back island slope grades imperceptibly into the mangrove forest without a slip face or scarp (except at tidal channels).
- The shallow platform, more than 2 km wide, seaward of Soldado may reflect an immature shoreface, which has not yet caught up with the island's rapid long-term migration related to subsidence.
- The stratigraphic sequence is transgressive.

The island stratigraphy consists of units from three environments of deposition: overwash, beach and mangrove swamp (Figure 4). Except for cores at the ends of the island, taken in exposed mangrove mud layers, the upper portions are entirely overwash sediment. The overwash sections are continuous, with only fine rootlet horizons to suggest multiple events, but lacking soil profiles. Because overwash occurs in a subaerial environment, island submergence is suggested by the core stratigraphy, particularly the extension of the overwash column to almost 2 m below the spring high tide line. Burial of a 20 to 100 cm-thick mangrove mud layer, which overlies beach facies with the diagnostic wood chip layers, also suggests subsidence.

The stratigraphy of the cores suggests no widespread single-events such as entire-island flooding by a tsunami, or correlative bed from a single large storm. Retention of beach ridge topography with no apparent drainage or burial pattern, the lack of sand layers in the adjacent mangrove platform, and the lack of interfingering of island sands with mangrove deposits, all point to an absence of major catastrophic depositional events. Conceivably, the storm overwash that built up Soldado Island is El Niño related, but no rhythmic small event sediment layers are evident. El Niño events are known to be responsible for major erosion problems in the San Juan delta area to the north, and seaside resorts along the nearby Ecuador coast where higher sea levels and increased storminess are documented during El Niños (*e.g.,* the 1997–1998 El Niño raised sea level along the Colombian coast by 20 to 30 cm).

The ramifications of the mechanics of Soldado Island's evolution for the people of the small village (Caserio del Soldado) at the island's south end are severe. In 1971 a large sand body existed in front of the village which was located in a mature mangrove forest behind a recurved spit. As the ebb-tidal delta changed (shoal detachment), the pattern changed from accretion to severe erosion that completely removed the protective sand body and killed much of the mangrove forest. At high tide the shoreline is now under houses once located within the mangrove forest. Much of Caserio del Soldado was recently moved back across its access tidal creek to avoid the destruction faced within the coming decade.

ISLA SANTA BARBARA

Santa Barbara is an 8.4 km long, 300 m wide island with a maximum elevation of 2 m above the spring high tide (Figure 3). The island has a large volume of subaerial sand (Figure 7), but absolute island size is difficult to establish because the landward side of the island is difficult to discern. Both aerial photos and radar images were not useful in this regard.

Santa Barbara contrasts sharply with El Soldado in both age and processes. Overall the island is regressive, although the present process response is rotational instability. The tropical rain forest on Santa Barbara is mature and some trees exceed 100 years in age. In addition, the island has an extensive soil profile and well-developed drainage. This island is probably the oldest or most stable of the four islands studied.

Santa Barbara also illustrates two processes important to the growth of these islands: lateral accretion of frontal beach ridges, and the influence of the adjacent ebb-tidal deltas. Figures 8 and 9 show a beach ridge accreting in front of Santa Barbara; elongating from south to north as a spit-like feature. The trough in back of the ridge is flooded and drained on the tidal cycle through its mouth outlet. As noted, outlets may form during the accretionary phase when tidal flooding tops the beach ridge and incises an outlet, or during the erosive phase when the shore migrates into a trough or tidal creek. Troughs may either remain open, or fill with overwash. Some troughs accumulate layers of the wood chip debris and muddy sediment, and are colonized by mangroves. The result is a low-energy microfacies included in beach sediments.

Multiple accretionary events produce alternating shore-parallel troughs and ridges. The former outlet channels incised through the ridges connect the troughs. The result is a trellis drainage network of shallow tidal channels oriented both parallel (troughs) and perpendicular (outlets) to the general island linear trend. This trellis drainage network is mostly flooded at high tide, and presently drains through three active outlets across the beach.

The channels of the trellis drainage are typically 10 to 20 m in width, and are navigable by small boat at high tide, but may be dry at low tides. Their outlets lack significant tidal deltas. The upper reaches of the channels fill with organic detritus and are colonized by mangroves. This pattern of island evolution in which the spit-like features accrete along the front of the island also is seen on Chamuscado and El Aji Islands, as well as other islands in the Colombian Pacific chains. These spit-like features are analogous to those of barrier islands in the U.S. Georgia Bight, and the process is indicative of lateral movement (McBride *et al.,* 1995).

The influence of the adjacent ebb-tidal deltas also is important to the dynamics of Santa Barbara's beaches. The present outlets are near the center of the island, where a nodal point of head-on meeting longshore transport occurs; the pivot point of rotational instability. Dominant direction of longshore current in the whole region is from south to north (Martinez *et al.,* 1995), but the aforementioned nodal point is a clear indication of locally significant north-to-south transport.

The distributaries of the Rio Raposo bifurcate in the mangrove forest behind the island and empty to the sea through the inlets (Raposo Inlet to the south, and Santa Barbara Inlet to the north). Although the offshore bathymetry is poorly known, the long horn-shaped deltas, characteristic of mesotidal inlets (Oertel, 1977) and found at both ends of this island, must profoundly impact longshore current directions and intensities. For example, a sand bar of the ebb delta 1

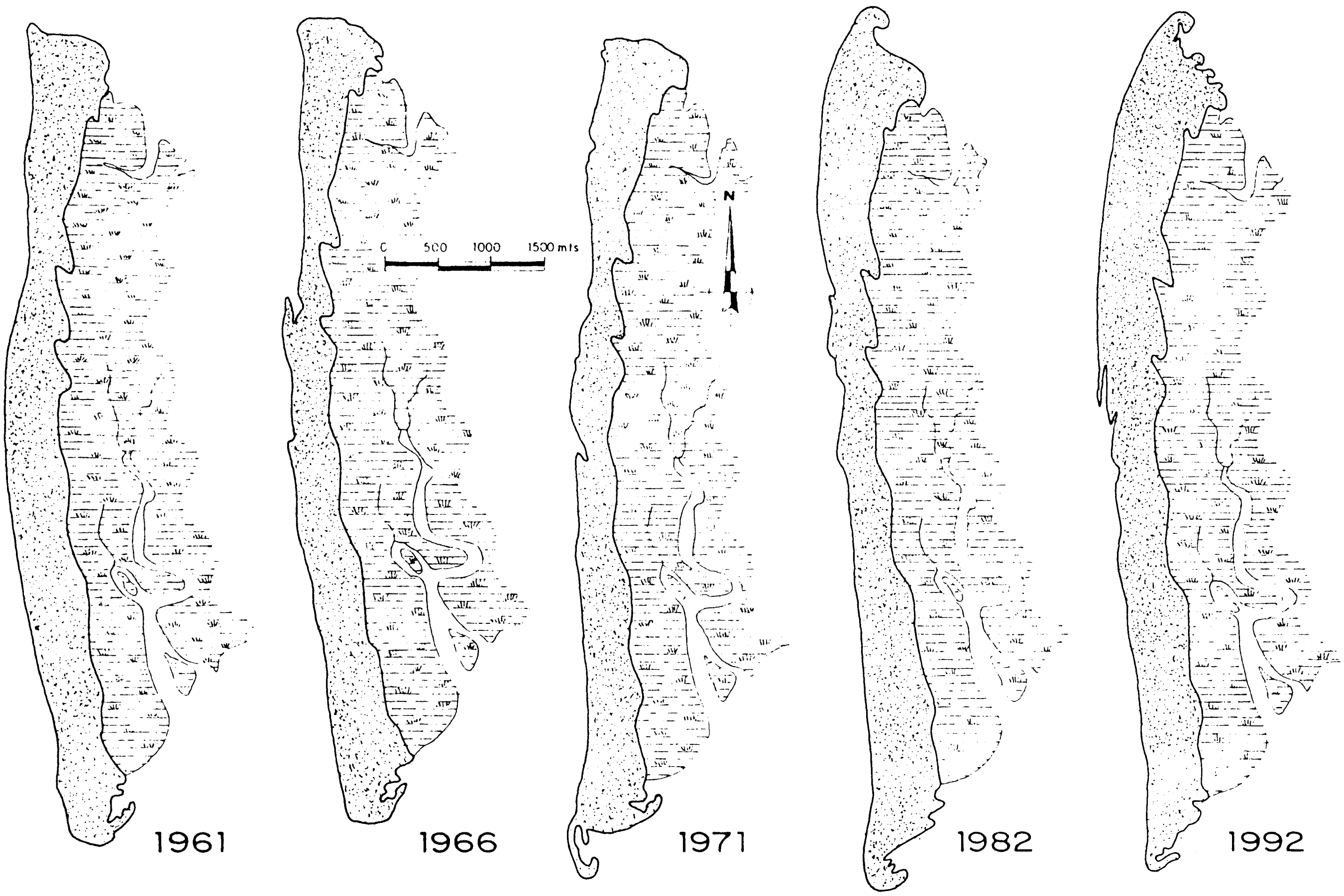

Figure 7. Comparison sketch maps of Santa Barbara Island from aerial photos: 1961–1992. The spit-like features which accrete along the front of the island are not seen at this scale, although the irregularities along the middle of the island hint of their presence. The middle island reach also is where the drainage outlets occur. Note the widening of the northern part of the island.

km south of Santa Barbara Inlet acts as an offshore breakwater allowing significant beach accretion (Figure 9).

Cores on the front side of Santa Barbara reflect the accretion and are dominated by beach facies (Figure 10) which persist both vertically and laterally. Thin mud facies may reflect local trough fill rather than a more extensive and correlative mangrove swamp horizon. The inner-island stratigraphy of coarsening upward sequences (mangrove mud to beach to overwash) suggests former transgressive episodes.

Although there has been some logging and subsistence agriculture on Santa Barbara, the island remains uninhabited. Since the early 1960s the southern half of the island has experienced local erosion rates as high as 8.3 m/yr while accretion rates for the northern half have been as high as 10 m/yr, exclusive of the rapidly accreting end spits (Figure 7).

CHAMUSCADO ISLAND

Chamuscado island is 8.5 km in length (Figure 11), bounded by the Bocana el Ajicito on the south and Bocana Chamuscado on the north. Both inlets are mouths of Naya River distributaries with large ebb deltas. The maximum width of the central part of the island is estimated to be approximately 500 m because the profiling party could not penetrate to the backside. The maximum elevation of the beach ridges on the new spit were approximately 1.0 m above the spring-tide debris line. Relief between ridges and troughs in the interior is subdued because the troughs are nearly filled with water-saturated organic detritus from the dense forest cover.

Figure 11 shows the dynamic change in island geometry between 1966 and 1992, and the process of alternate thinning (1966–1971) and rewidening by rapid lateral growth of a large island-front spit. By 1970 erosion breached the narrow ridge at mid-island, but without any apparent rapid landward migration of the sand body into the mangrove swamp. Breaching formed an island segment to the north that behaved as a detached spit. At the southern end, a swash bar welded to the island and formed a mini-headland from which a spit-like beach ridge began to grow along the front of the island. Between 1982 and 1992 this feature had grown approximately 800 m, creating a shallow trough between the new ridge and old beach face. Like the smaller features on Santa Barbara, the outlet mouth of this trough persisted as the spit continued to accrete to the north.

Figure 8. Aerial view of spit-like feature in front of Santa Barbara Island. The beach ridge is accreting to the north (left), forming a trough in front of the former beach. Vegetation rapidly colonizes the new ridge, and mangroves sprout from the shallower part of the trough. An accretionary frontal spit can be seen to the south.

Figure 9. The offshore bar which is part of the ebb-tidal delta complex acts as an offshore breakwater resulting in rapid beach accretion. Note the drainage channel across the beach. Such channels are incised through the frontal beach ridge indicating that the outlets can form by flood overtopping of the beach ridge from the backside.

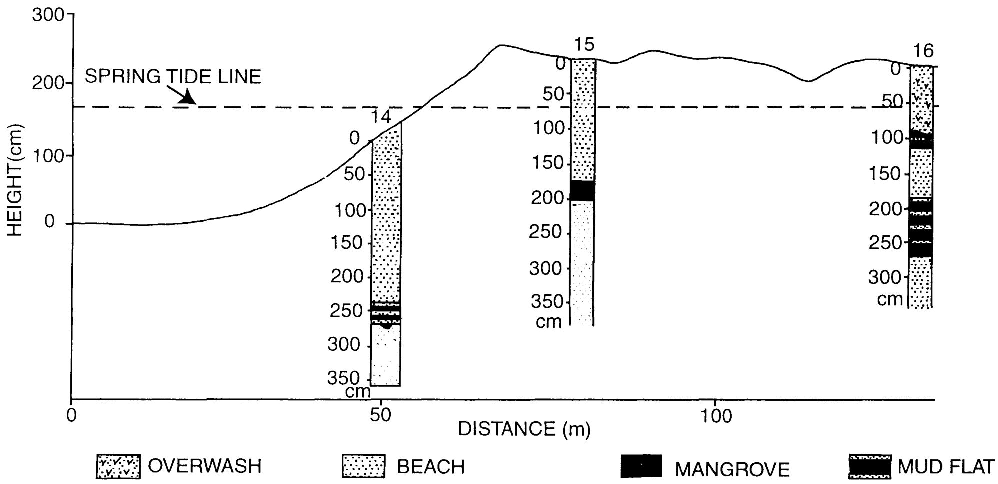

Figure 10. Topographic profile across central Santa Barbara Island and associated core stratigraphy. See Figure 2 for numbered core locations.

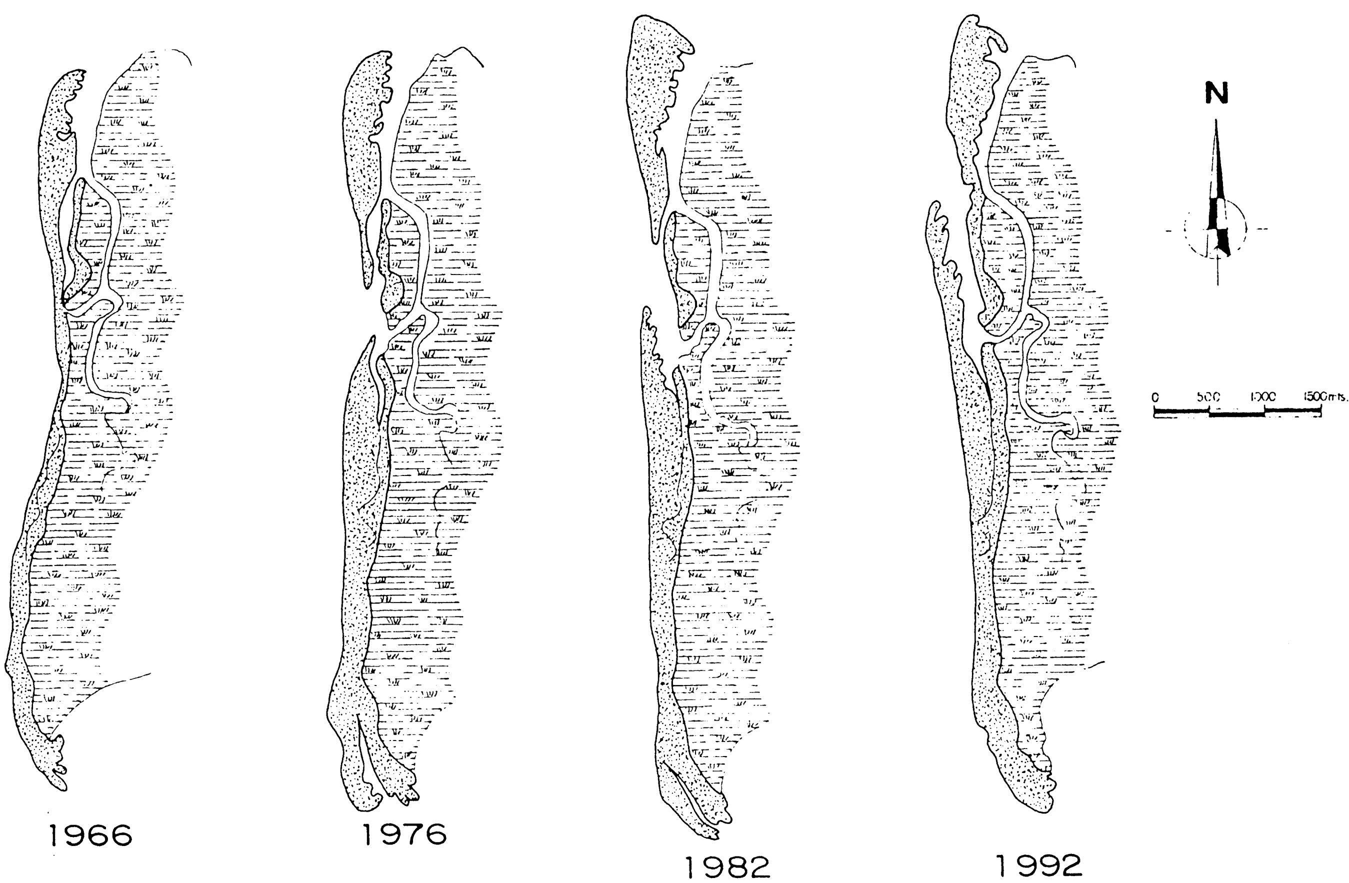

Figure 11. Comparison sketch maps of Chamuscado Island from aerial photos: 1961–1992. Narrowing and breaching between 1966 and 1976 was followed by the rapid growth of a new spit in front of the breach inlet. The detached spit to the north reattached to an earlier remnant of the island and mangrove swamp platform.

Again, these troughs are often colonized by young mangroves, which trap organic debris and muddy sand to produce a low-energy microfacies within the beach sediments. Repetition of the process occurs when new updrift bars weld onto the shore. The beach ridges paralleling the shoreline result in a trellis drainage, and tidal drainage within the trough sometimes produces an erosional scarp along its landward bank. Washover regularly tops the frontal spit-like feature so the trough fills in, subduing the relief, and burying the erosional scarp on the landward side.

The resulting stratigraphic succession is simple. Overwash sediment, extending generally to the spring tide line is underlain by beach sediment containing thin mangrove muds reflecting the back-beach troughs. The overwash facies is generally found above the spring high tide line indicating lack of recent subsidence in contrast to the other islands. The island sediment cover is not datable or characterized by plastic or other debris content as in the case of Soldado and Santa Barbara because the island is more distant from Buenaventura, the source of most of the refuse.

The known short-term evolution of Chamuscado is confirmed by soil profiles as an indicator of age. Cores and test pits on the inner ridge (Figure 2) show soil development to a depth of 50 cm while cores from the post-1966 accretion zone lack soil development; younger than Aji and Santa Barbara Islands. The older segment also has mature forest; however, past timbering removed some tree cover. Chamuscado is utilized for light agriculture with a small herd of cows grazing the grassy acres of the new spit, and by wild pigs that forage over the island. A small village of 10 houses exists on the backside of the southern end.

EL AJI ISLAND

El Aji is an 8.6 km long, 750 m wide, low island (<1 m above spring high tide), extending from Bocana de Micay, a large sand-filled estuary, to the Bocana El Ajicito. Both estuaries are at mouths of the Rio Naya, and have large ebb-tidal deltas whose specific geometry is unmapped. The south end of the island recurves and hooks back into the inlet. The dominant sand transport, however, is south to north, and a well-developed beach ridge fronts the island.

Since 1966 the geometry of El Aji has been thinning and elongating, by spit growth in front of the mangrove swamp at the north end, and by erosional narrowing along the southern mid-island (Figure 12). The interior is characterized by two to three low, gentle beach ridges, cresting approximately 0.5 m above the spring high tide line, and separated by wide swales (Figure 3). These ridges reflect an earlier regressive phase. Troughs on the backside of the island are filled with fine, organic-rich, water-saturated mud that prevented extending the profiles into the mangrove stand. One of the inner ridges, 100 m from the present beach, is scarped on the ocean side. Similar, partially buried, relic scarps occur on the other islands and are probably analogs to the present scarps that are eroded by tidal drainage in the troughs. As the trough fills in with overwash, the former backbeach trough scarp is partially buried, but the upper face may remain on

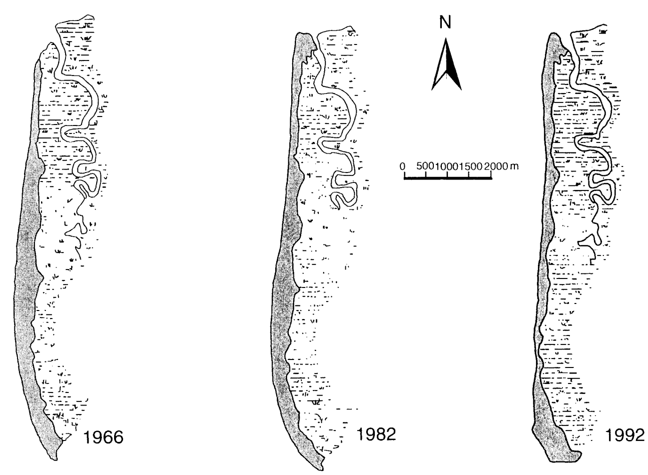

Figure 12. Comparison sketch maps of El Aji Island from aerial Photos: 1966–1992. Much of El Aji has undergone in-place narrowing, however, by 1992 a swash bar had attached to the southern end of the island and a spit-like structure was lengthening to the north. The island has widened at its northern end.

the incorporated beach ridge. The rapid growth of vegetation may account for preservation of the scarp.

Figure 13 shows the topographic profile across the south end of the island where a swash bar has welded onto the island (Figure 12, 1992). The profile shows a prograding pattern of active beach ridge, trough, and previous beach face. The resulting mini-headland (Figure 12, 1992) and lateral shoal in front of the south end of the island provide the conditions to permit the extension of the new beach ridge laterally by longshore drift. At the same time, the new ridge grows subaerially by overwash which fills the trough. The resulting stratigraphy is overwash facies over beach facies as seen in the cores (Figure 13). Recent overwash events seem to penetrate only a few tens of meters into the island's interior.

The wedge of overwash facies thickens toward the backside of the island (Figure 13), but the surface material is considerably older as indicated by soil profiles up to 65 cm thick, in contrast to the fresh frontal overwash sands. This reversal in the pattern of overwash thickness also suggests that as much as 1.5 m of subsidence has occurred.

COLOMBIAN BARRIER ISLAND EVOLUTION

The barrier islands of Colombia are generally narrow, low in elevation, and have very low subaerial sand volumes. Three out of the four islands studied are regressive (Soldado being the only transgressive exception). The major inlets separating the islands are stable, becoming slightly wider and narrower as the north ends of the island temporarily extend into the inlet mouths in response to the south to north longshore sand transport.

The sand supply to this system is apparently very large. The generally narrow estuary channels are probably filled to capacity in equilibrium with the strong mesotidal currents flushing them. The northern Andes mountain chain begin less than 25

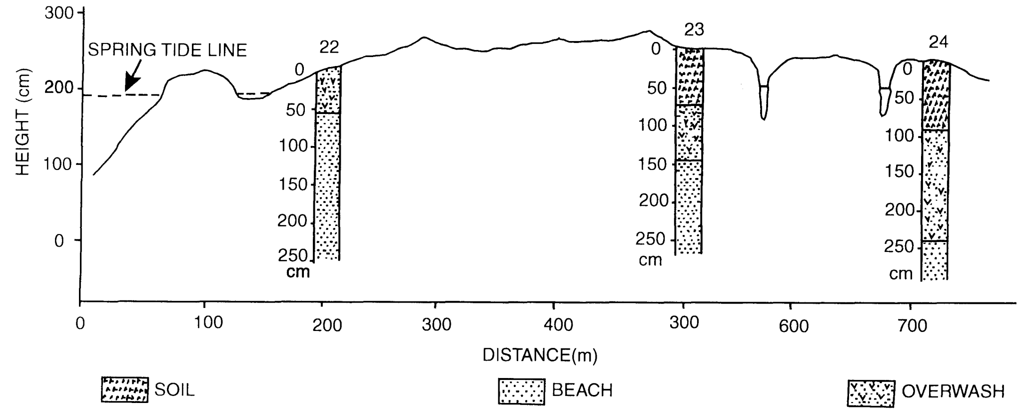

Figure 13. Topographic profile across the southern end of El Aji Island (Figure 2). Note the recently attached bar which produced the characteristic frontal trough. The shallow stratigraphy is dominantly beach and overwash facies, and the overwash facies thicken toward the backside of the island indicating subsidence. Well-developed soil profiles in the overwash in the interior of the island also indicate these deposits are older.

miles from the coast and 5 rivers within this 80 km long shoreline reach, empty onto the narrow leading edge shelf.

The bulk of the low volume subaerial portion of the islands is made up of overwash. The aeolian contribution is small, the low-relief beach ridges found on most of the island segments are not dunes. The dense vegetation extending to the spring high tide line precipitates any aeolian contribution which is then incorporated into the next overwash event. The Colombian Pacific Coast is generally not a region of frequent high winds, which, along with very high rainfall in this tropical region, may explain the lack of dunes. No wind rose is available for this area, to our knowledge. Fresh overwash rarely extends more than a few meters into the islands, thus previously formed beach ridges are preserved in the island interiors. Dense vegetation may halt most overwash penetration. This and other indications point to the minor role of major storms in island evolution.

No evidence was found indicating any role of tsunamis in island evolution; this despite the certainty that such events must have occurred in this area. Four historic large tsunamis have been recorded, the most recent of which struck the island of San Juan de la Costa in 1979 resulting in the deaths of 220 villagers. Tsunamis of large magnitude occurred in 1836, 1868, 1906, 1958 and 1979. According to HERD *et al.* (1981) the 1906 tsunami produced above-island water levels ranging from 2–5.9 m. All houses on the sparsely settled islands were destroyed between the Ecuador border and Micay, a small village at the southern edge of the present study area. Half of an island was washed away near Tumaco at the Ecuador border.

The apparent lack of tsunami deposition may be due to several factors, including the possibility that tsunami deposits may indistinguishable from storm overwash, due to the uniform well-sorted nature of the sand. In addition, if tsunamis occur at low tide their passage would be restricted by extensive offshore sand bars and tidal deltas. A small low-tide tsunami might only result in minor swash flow affecting the subaerial island. The 1979 San Juan de la Costa tsunami, however, struck at low tide and resulted in 2 meter-deep flooding of the island. No evidence of liquefaction that might be related to seismic events was found in the cores.

During El Niño's sea level rise and increased storm frequency, the frequency of overwash must increase and possibly leave evidence of rhythmic sedimentation on a decadal time frame. For some of the same reasons outlined above for the apparent lack of tsunami deposits, El Niño events could not be identified.

These Colombian islands fringe small coalescing deltas. In addition they are on a tectonically active leading edge of the South American plate. For these reasons, subsidence is a likely possibility and evidence exists that it may be an important parameter controlling island evolution. As a result of the earthquake which produced the 1979 tsunami, islands in the vicinity of San Juan de la Coasta subsided up to 1.6 m, and according to HERD *et al.* (1981) 1 m of the 2 m water depth that inundated San Juan de la Costa was due to subsidence that occurred before the tsunami arrived. Tide gauge measurements in the city of Buenaventura indicate a long term subsidence rate of 1 mm per year (AUBREY *et al.,* 1988). Buenaventura is situated on the mainland at the head of Buenaventura Bay 15 km from Soldado Island. To the north, in the region of the San Juan River delta, the 1970 Bahía Solano earthquake may have caused coastal subsidence (RAMIREZ, 1970).

Stratigraphic evidence of rapid subsidence is especially strong on Soldado Island. Plastic and glass refuse of post-1960 origin is contained within the subaerial barrier island to depths of 70 cm below the spring tide line. In other words, the entire subaerial island was deposited since 1960. In addition, the subaerial overwash sand layer in several cores extends without apparent breaks or change in sediment character below the spring high tide line to the approximate mid-tide level. The overwash sand bottoms out in a mud layer containing mangrove roots. Similar island stratigraphy was noted in cores from Chamuscado and El Aji islands. In one core on El Aji the overwash sand extended 2 m below maximum high tide level.

Subsidence is not uniform on the islands along their shoreline reach. Santa Barbara Island has identifiable overwash facies in the sediment column only slightly below the level of spring tide. One mangrove mud layer, however, was penetrated 2.5 m below maximum tide level. Santa Barbara may have the most mature vegetation and soil profile as opposed to Soldado Island with only small trees and bushes and no soil profile.

One line of evidence argues against high rates of subsidence. The presence of an Indian mound in the mangrove swamp approximately 1 km behind El Soldado is characteristic of a culture believed to be at least 1000 years old. Although the base of the mound is now flooded at high tide, it has not subsided 4 m as might be suggested by the rate of recent subsidence implied by the cores. The implied subsidence, however, is neither uniform nor constant. The evidence suggesting subsidence is significant for these islands, and the 4 to 5 m cores, even those taken at low tide level on the beach, penetrated sediments that are probably no older than a few hundred years.

The islands, with the significant exception of Soldado, possibly have remained in place at least for the last millennium and have alternatively widened by regressive seaward build-out between subsidence events and narrowed in response to major subsidence events. If this is the case, the islands at least in recent decades are building upward at a rapid rate; forming a virtual column of barrier island beach and mangrove sediment. Isla Soldado is at the thin end of the island spectrum. The stratigraphic column largely reflects a recent history of subsidence and island retreat. El Aji is in a narrow phase, but may be in the very initial stage of recovery. Chamuscado Island is in the recovery or regressive stage, having substantially widened by spit growth since the 1960s. Santa Barbara's internal ridges, trellis drainage and core stratigraphy indicate the island has gone through a recent history of regressive accretion. Since both subsidence and sand supply vary from island to island, the rate of the alternate thinning and widening or regressive and transgressive behavior of each island varies.

Although the islands show aspects of the standard transgressive and regressive types, the subsidence parameter has a major impact on island evolution here. Their geomorphology is similar to the U.S. Georgia barrier islands (HAYES, 1994), a region of tectonic downwarping and delta-front barrier islands separated by large estuaries with a similar tidal regime, and associated ebb-tidal deltas of similar morphology (OERTEL, 1977). They differ, however, in the strong climatic overprint in which the dense vegetation cover minimizes aeolian processes, reducing elevation build-up by dune formation, and replacing salt marshes with mangrove swamps. Furthermore, their greatest difference is in their location on a tectonically active, leading-edge coast, where subsidence also plays a role.

On a short time frame, the changes seen in these four Colombian barrier islands are also analogous to the geomorphic response-types seen in the U.S. Gulf Coast barrier islands (MCBRIDE *et al.,* 1995). Aspects of the lateral movement response type occur in all four islands with longshore transport building the spit-like frontal beach ridges, and elongating spits on the north ends of the islands. El Soldado shows both in-place narrowing, and some landward rollover on its southern end as the thin, narrow beach migrates into the mangrove stand. Santa Barbara shows counter-clockwise rotational instability about a nodal point. Chamuscado has experienced breakup, similar to other Colombian barrier islands associated with deltas, although the dominant lateral movement has reformed the island in front of the breach. El Aji has experienced recent in-place narrowing, but lateral movement is again lengthening, and causing some widening of the island. As MCBRIDE *et al.* (1995) point out, the greatest changes occur in areas of highest relative sea level rise, and Colombia's Pacific barrier island coast is experiencing such change; due, in part, to subsidence.

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