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Late Holocene Evidence of Coseismic Subsidence on the San Juan Delta, Pacific Coast of Colombia

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ABSTRACT

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The San Juan delta of Colombia formed under a complex physical setting. Among the unusual factors that controlled the delta formation are: its location in an area with one of the highest precipitation rate anywhere in the world, highly variable river discharge and high sea levels of short duration, both associated with El Niño-La Niña climatic disturbance, and high mesotidal range combined with a medium to low wave energy. Of all the aspects that make the physical setting complex, the high seismicity produced by the subduction of the Nazca plate under the South American plate, has perhaps, been the most important controlling factor in the Late Holocene development of the delta. Coring on its SW island retrieved soils buried, 1.2–1.5 m by intertidal deposits; the sharp contact between the soils and the mantling deposits, implies large sudden submergence, which is most simply explained as being coseismic, associated with the high seismicity of the area. Timing of the earthquake that caused subsidence, is placed around 500 years BP. Evidence from recent earthquakes along the South central Pacific coast of Colombia indicates that—subsidence > 1 m requires a M 7.9 or greater earthquake.

ADDITIONAL INDEX WORDS: *Barrier islands, El Niño, sedimentary facies, earthquake, coastal erosion, washover.*

INTRODUCTION

The San Juan River delta located 90 km north of Buenaventura Bay, is one of the most conspicuous geomorphic features along the low alluvial Pacific coastline of Colombia (Figures 1 and 2). The deltaic plain is relatively small (an area of 800 km^2 and a shoreline length of 51 km), however a combination of several aspects make the San Juan peculiar when compared to other modern deltas; among these are: (1) its entire drainage basin is located in one of the areas with the highest rates of precipitation in the world 6 to 8 m yr^{-1} (ESLAVA 1992), (2) the direct impact of El Niño-La Niña climatic disturbance is responsible for big differences between maximum and minimum river discharges *i.e.* 600 m^3 sec^{-1} to 6000 m^3 sec^{-1} (RESTREPO and KJERFVE 2000) and for regional sea-level rises of 20–30 cm, of short duration, with marked effects on the delta's coastline, (3) its high meso-tidal range combined with medium to low wave energy are responsible for complex coastal dynamics along the delta's unstable shoreline.

Perhaps the most important aspect of the complex physical setting under which the San Juan delta formed, is its location near a collision plate boundary dominated by the subduction of the Nazca plate under the South American plate. This subduction zone is characterized by active seismicity in which the occurrence of large magnitude and shallow focus earthquakes is not rare.

Previous studies on the delta are few and of general nature. CORNISH (1955) was the first to classify the delta based on its fan shape, and INGETEC (1971)—described the geology and hydrologic aspects including river discharge and effects of tides. Other published studies only touched some general aspects of the delta, e.g. WEST (1957), IGAC (1980), PRAHL (1989), CORREA (1996), GONZALEZ *et al.*, (1998).

The area on which this study focused is the island on the southwestern corner of the delta, bound by the Chavica and San Juan estuaries (Figures 2 and 3).

The purpose of this paper is to document the occurrence of coseismic subsidence during the late Holocene depositional history of the San Juan delta, based on the interpretation of buried soils and radiocarbon chronology.

METHODS

The identification and three dimensional distribution of sedimentary facies and the recognition of two major depositional events was possible from the analyses of 28 hammer cores, using 7.6 cm diameter and 9.15 m long aluminum pipe (Figure 3). To avoid roots and to get deeper, some cores started in a 1.5 to 2.0 m deep trench, and this meant losing the upper sediment record for some cores. A few cores reached a depth of 7 m, but most penetrated about 4.5 to 5 m. Core shortening was calculated by comparing the penetration depth to the length of core recovered and it ranged between 15 and 40%. The greatest shortening resulted when coring through muddy substrates. Each core was cut vertically and logged in detail for small-scale sedimentary textures and structures, color, nature of contacts and facies succession. Cores were then photographed while wet. Selected core in-

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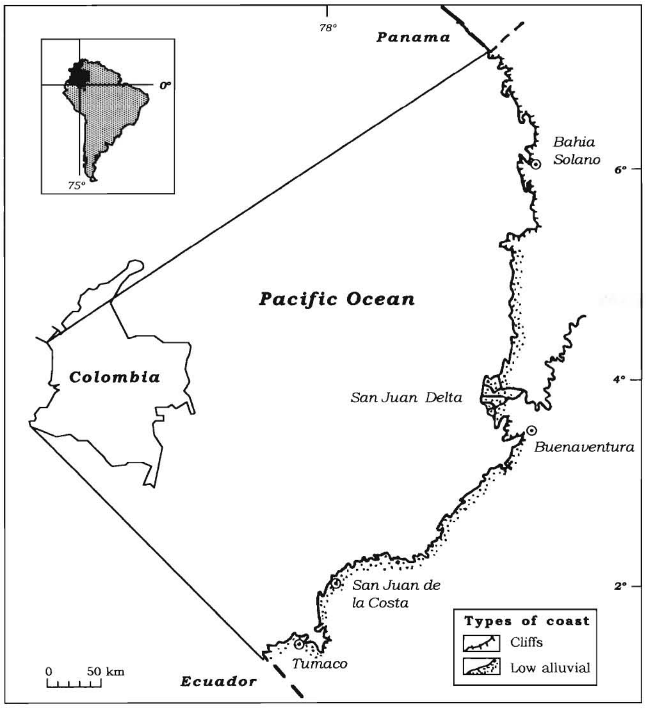

Figure 1. The Pacific coast of Colombia indicating the location of Rio San Juan and its delta. Two types of coastline are observed, cliffs on the north and mangroves fringed by barrier islands on the central and south.

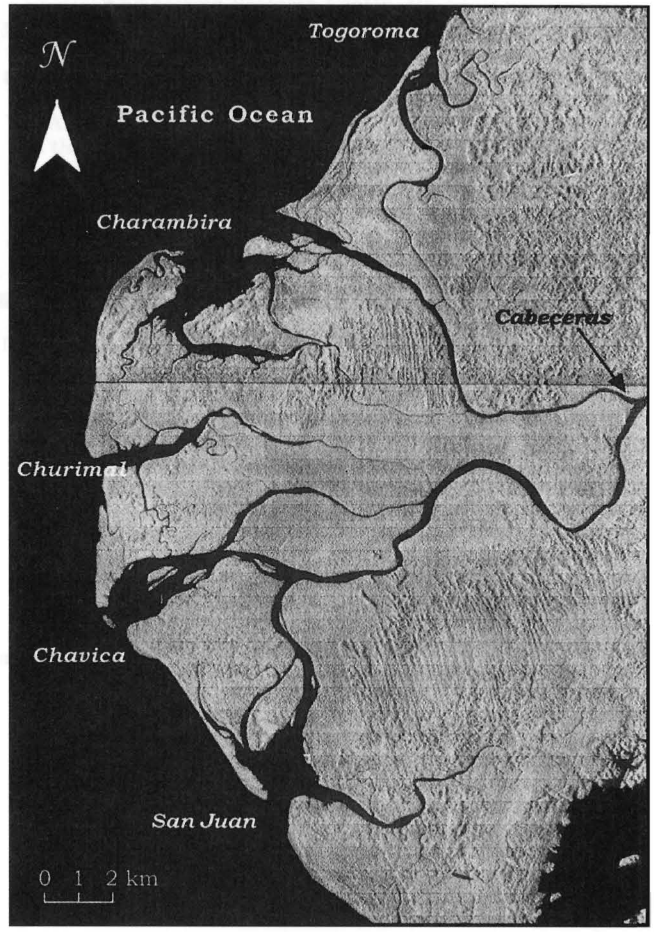

Figure 2. High resolution radar image of the San Juan River delta. The main river mouths are indicated. Note the high relief defined by Tertiary rocks. INTERA image from 1992. Courtesy of INGEOMINAS.

tervals were sampled for pollen analysis, but only two had enough pollen content to allow inferences on vegetation changes along the sequences. Grain size and mineralogy analysis were done on some sandy cores. X rays were taken from short segments of muddy facies. Thirteen samples were radiocarbon age dated at Geochron Laboratories in Massachusetts, and are reported as calendar years before present. Due to the lack of bench marks on the delta, it was not possible to reference the elevation of each core site to a known datum or to mean sea level. However, field observations allowed an estimate of the elevation of each site as compared to the level of Spring High Tides (SHT). Elevations were then referred to this level.

GENERAL SETTING

Geologic setting

The tectonic framework of the Pacific margin of Colombia is influenced primarily by the subduction of the Nazca plate beneath the South American plate (Figure 4), thus large magnitude, shallow-focus earthquakes are common along this coast (LONDSDALE, 1978; GOMEZ, 1980; PENNINGTON, 1981; GONZALEZ *et al.*, 1988; KELLOGG *et al.*, 1989; INGEOMINAS, 2000), (Figure 5). The two most intense Colombian earthquakes of the 20th century (1906 and 1979) caused both regional and local land subsidence of 0.6–1.6 m, and 2–3 m high tsunami waves that severely impacted the coastal fringe (RAMIREZ and GOBERNA, 1980; HERD *et al.*, 1981; MEYER *et al.*, 1992). The last important seismic event that impacted the study area occurred in November 1991; it was a shallow, 21 km depth, magnitude 7.0, earthquake whose epicenter was located 40 km offshore N of the delta (MEYER *et al.*, 1992), (Figure 6). The event caused severe damage to the small villages on the delta plain. Intense erosion of the delta fringe, and an increased number of annual overwash events on the barrier islands following the earthquake suggested that some subsidence might have occurred along the delta's coastline (CORREA *et al.*, 1995 and MORTON *et al.*, 2000).

The geologic framework of the central part of the Colombian Pacific coast has a complicated tectonic-stratigraphic history. The Buenaventura-San Juan delta area is located on the "Istmina Deformation Zone" (IDZ), a highly deformed zone extending in a N60°E direction from the Panama Basin to the western flank of the Western Cordillera, a branch of the Northern Andes. The IDZ has been interpreted as the southern limit of the "Choco Block", an exotic Centro-American terrain accreted to the northwestern South American continent during the Middle Miocene (DUQUE-CARO, 1990). Geophysical structural data for the Buenaventura-San Juan

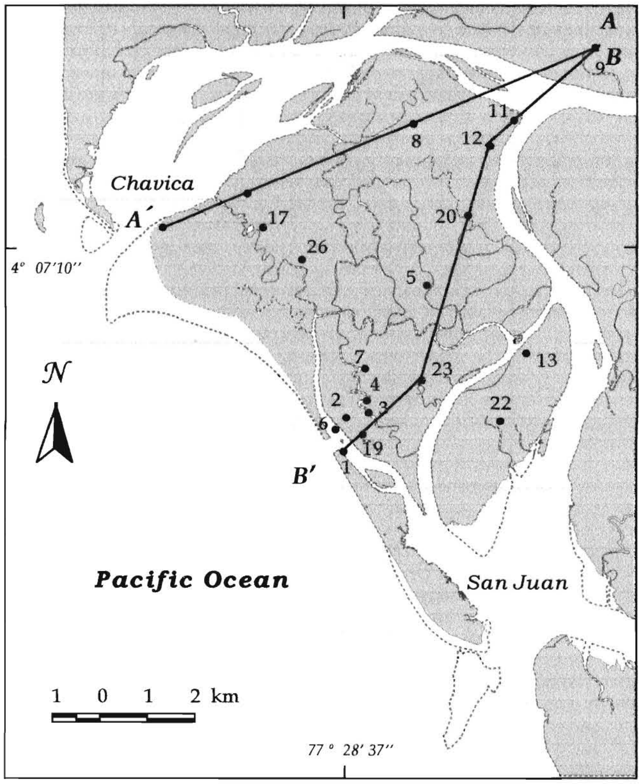

Figure 3. Map of SW island of the San Juan delta showing the location of cores, and the orientation of cross sections A—A' and B—B'.

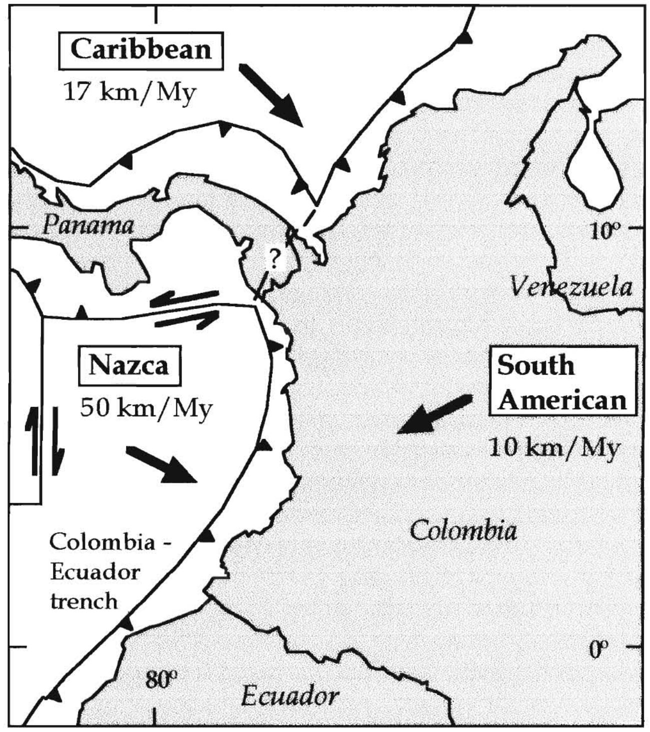

Figure 4. Plate boundaries in the NW South American region. Arrows indicated relative direction of plate motion. Barbs show direction of dip of the Nazca and Caribbean plates. Rates of plate motion after MOUNTNEY and WESTBROOK, (1997).

delta area shows a compressive pattern, with a volcanic-oceanic ridge-basement, the "Buenaventura Paleohigh" blocked by the Western Cordillera (PEREZ, 1980; DUQUE-CARO, 1990). Possible active transcurrent faulting in the area has been associated with several transverse Cretaceous paleofracture zones, the northernmost of which coincides with a large submarine canyon at Charambirá (PEREZ, 1980) (Figure 2), a major active mouth of the delta.

The low-relief San Juan delta contrasts with the hilly, structurally controlled high coastal relief north of Bahía Málaga that appears to be a tectonic depression associated with the activity of transverse faulting. To the north, the delta plain is limited by Pre-Miocene, sub-horizontal to 60°E dipping successions of marine calcareous mudstones and sandstones, *i.e.* the Mungido Formation (COSSIO, 1993). To the south, the delta is confined by sub-horizontal to sub-vertical Pliocene successions of marine sandstones and mudstones, *i.e.* the Mayorquin Formation (ASPDEN and NIVIA, 1984). These rocks also outcrop as isolated remnants on the central and southern deltaic plain.

Coastal Processes

Tides on the Pacific coast of Colombia are semidiurnal; on the San Juan delta, the highest spring tides reach 4.2 m (IDEAM, 1999). Along the delta front, strong ebb tidal currents dominate over longshore drift as is indicated by the presence of large ebb tidal deltas at the mouth of each distributary.

Around the delta, dominant wave directions are from the west and southwest and average wave heights vary from 0.5 to 1.5 m. Storm waves range from 1.5 to 2.5 m (MARTINEZ *et al.*, 1995). As evidenced by the morphology of spits on barrier islands, wave refraction is divergent at the axis of the delta and net longshore drift along the delta is both south and north away from the axis.

Climate and Vegetation

The San Juan catchment receives an average annual rainfall of 7,277 mm, (RESTREPO and KJERFVE, 2000). Southerly and westerly winds predominate around Buenaventura and the San Juan River delta, except for the period from February to April when they blow northerly and northeasterly (U.S. HYDORGRAPHIC OFFICE, 1948).

The sub-aerial delta and the adjacent coastal plain are covered by a dense tropical rain forest. A vegetation zonation is evident and is mainly due to differences in soil types and to the degree to which the land surface is affected by salt, brackish or fresh water. On the landward side of the islands, mangrove swamps form a continuous but irregular belt with zonations, grading from fully marine to fresh water. (WEST, 1957, PRAHL, 1989 and PRAHL *et al.*, 1990).

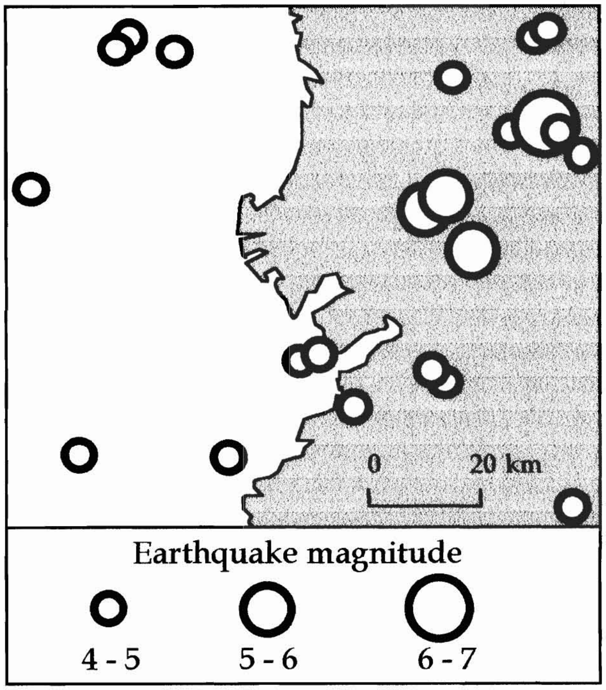

Figure 5. Sketch map showing the distribution of earthquake epicenters located within 100 km of the San Juan Delta in the period June 1993–Dec 1999. Only M > 4.0 earthquakes, are shown. Modified from INGEOMINAS, (2000).

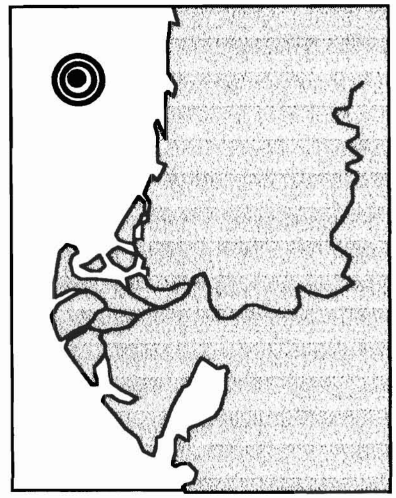

Figure 6. Sketch map indicating the epicenter of the November 19 1991, earthquake that apparently caused subsidence on the SW island of the delta. This was a shallow, 21 km, M 7.0 earthquake. After MEYER *et al.*, (1992).

Drainage Basin and River Discharge

The San Juan's drainage basin is ~16,645 km^2 in extent and the river course is ~352 km long. (RESTREPO and CORREA, 1995). River discharge is highest in October and November with an average of 3,600 m^3 sec^{-1}. The lowest discharge occurs in the months of February and March with an average of 1,800 m^3 sec^{-1}, (HIMAT, 1990).

The San Juan has the highest water (3,600 m^3 sec^{-1}) and sediment discharge (16.42 × 10^6 t yr^{-1}) of all rivers along the west-coast of South America (RESTREPO and KJERFVE, 2000).

THE DELTA PLAIN

The delta has a smooth protruding arcuate shape with an emergent area of ~800 km^2 and a shoreline length of 51 km. According to GALLOWAY'S (1975) morphological classification, the San Juan delta is influenced about equally by fluvial discharge, wave energy and tidal action.

Two main distributaries radiate from the delta apex. These primary distributaries bifurcate into third and fourth order distributaries, and at the coast, the flow is discharged through 6 active river mouths (Figure 2). Several small inlets between the main mouths act predominantly as tidal channels.

The San Juan Delta plain extends 28 km seaward from the apex. The fluvial delta plain covers 17 to 20 km seaward from the vertex; it is characterized by a relatively high (supratidal) compacted, and well-drained surface, with well-developed soils supporting a dense tropical rain forest. The tidal delta plain covers the seawardmost 8 to 11 km, it is incised by distributaries and tidal channels. Its surface is inundated during high tides and is covered by mangroves and salt tolerant plants. Four sandy barrier islands rim the delta's shoreline, and are 7 to 12 km in length and 80 to 500 m in width; their elevation is about one meter above the highest spring tide (MARTINEZ *et al.*, 1995).

Flooding on the fluvial influenced upper delta plain is rare observed only during a combination of high river discharge and the highest spring tides. The tidally influenced lower delta plain, in contrast, is subjected to inundation during each high tide. Flooding anywhere on the delta plain is of short duration; once flooding occurs the water rapidly returns to the channels with the next low tide.

SEDIMENTARY FACIES

Five major sedimentary facies were defined by their lithology, mineralogy, organic matter content, color and stratigraphic position from cores on these island. A summary of these deltaic facies is given in Table 1. Two cross sections, A—A′ and B—B′ on the northern and southern margins of the island (Figures 7 and 8), illustrate facies relations.

EVIDENCE FOR RAPID SUBSIDENCE

The presence of buried soils within the Barrier island and stranded ridge sand facies constitutes strong evidence for rapid subsidence. Two types of buried soils were found: (1) thick peaty soils and (2) a faint B soil horizon. Both are mantled by 1.2 to 1.5 m of sand.

Peaty Soil

The cores recovered two types of buried peat: (1) peat without a significant mud content, in cores 18 and 28, composed

Table 1. *Summary of major deltaic facies encountered in shallow cores of the SW island of the San Juan Delta.*

Facies	Lithology	Environment Interpretation	Diagnostic Features	Statigraphic Relationship	Approximate Thickness (m)
Flood plain mud F pm	Dark brown to blueish-grey clayey mud with abundant disseminated organic detritus and thin layers of peat	Flood plain	High clay content	Transitional lower contact with Fluvial sands	1–5
Intertidal mangrove mud Imm	Dark brown to black mud with coarse organics and thin to thick layers of peat	Intertidal mangrove	High organic content. Large mat of roots	Support mangrove forest today	2–3
Barrier Beach ridge sand Brs	Fine to medium clean sand, with abundant rock fragments, includes laminations of dark minerals and mica flakes	Beach	Clean sand, moderately well sorted evenly laminated	Interfingering lateral contact with flood plain mud	>5 ?
Fluvial sands F s	Poorly sorted coarse to conglomeratic sand with large wood fragments	River channel	Coarse to conglomeratic sand	Upper contact is transitional to flood plain mud	?

of detrital fragments of wood, twigs, leafs, bark, and forest floor litter, compressed to a layer 25 cm thick, (Figure 9) and (2) a muddy peat with abundant large wood fragments, in cores 7 and 9.

Faint B Soil Horizon

A faint, but easily recognizable B soil-horizon, 60–90 cm thick was found at a depth of 1.3 m, in cores 12 and 23. It lacks an overlying organic rich A horizon, and shows no traces of roots. In both cores the oxidized horizon is sharply bounded by fresh sands of similar texture.

Interpretation

The mud free peat soils document a high marsh environment adjacent to a forested surface that suddenly became submerged into the intertidal zone. The same is valid for the

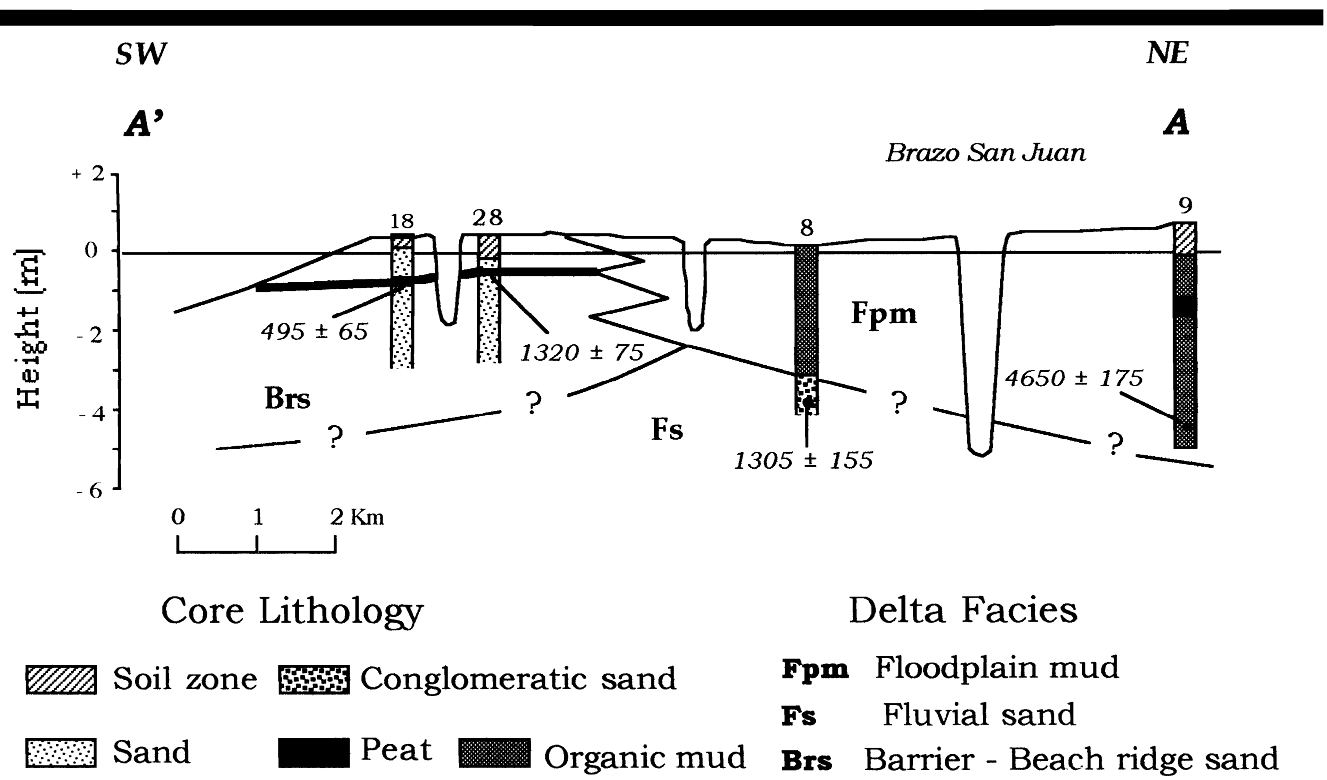

Figure 7. Stratigraphic cross section A—A′ through the northern side of island, showing facies relations and C14 dates. Elevations are approximately referred to Spring High Tide (SHT). For location of section see figure 3.

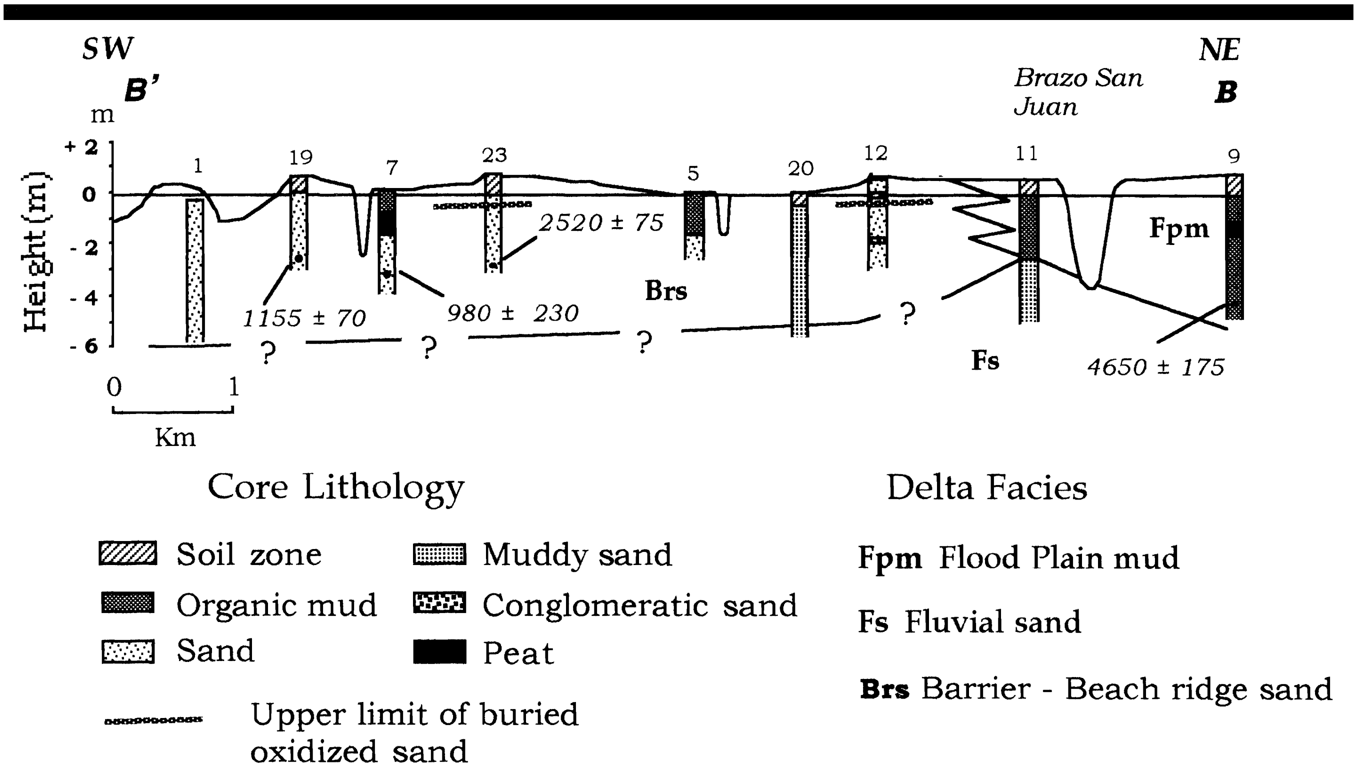

Figure 8. Stratigraphic cross section B—B′ through the southern side of island, showing facies relations and C14 dates. Elevations are approximately referred to Spring High Tide (SHT). For location of section see figure 3.

muddy peat, interpreted as being deposited below the upper part of a high marsh, and for the faint B soil horizon that formed as an exposed surface on which no vegetation was growing and no organic material was deposited. The intertidal deposits rest in sharp contact with the underlying soils, such a contact implies large (> 1 m), sudden submergence, which in an area adjacent to a plate boundary, characterized by a high seismicity, is most simply explained as being coseismic, associated to the occurrence of a large magnitude earthquake.

The timing of submergence could not be precisely defined; the only two radiocarbon ages of the same peaty soil are discordant, 495 ± 65 years BP for core 18 and 1320 ± 75 years BP for core 28 (Figures 7 and 10), in addition no datable material was found on the overlying deposit that covers the soils. However, a date of 980 ± 230 years BP from core 7 at 1 m below the equivalent peat, suggests that subsidence probably occurred closer to 500 years BP.

Discordant C14 ages of up to several hundred years of intertidal peats, are explained by NELSON (1992) as arising from: (1) a mixture of different types of organic material within the peat containing carbon of different ages and (2) from all the factors involved in the development of peats namely: burial and decay, type of marsh vegetation, amount of woody detrital material deposited, extent and rate of mixing of the soils by animals and plants, and the rate of peat accumulation.

Buried soils in the delta imply the presence of two major depositional events separated by a period of soil formation.

Alternative Explanations for Buried Soils

Submergence can result either from lowering of land surface (subsidence) or from a eustatic rise of sea level. Two arguments favor subsidence as the preferred interpretation of the buried soils in the San Juan delta. (1) Submergence of the soils probably happened too suddenly to have been produced by a gradual eustatic rise. This is indicated by the sharp nature of the contact between the soil and the mantling intertidal deposit, and (2) Submergence in this part of the delta amounted to at least 1.2 m in the last few hundred years, as suggested by the minimum depth of buried soils and by the radiocarbon dates. These do not correspond with the curve of eustatic rise of sea level for the late Holocene.

The possibility of the soils being buried by a non tectonic process such as slow gradual subsidence due to sediment loading, dewatering of sediments or oxidation of peats, can also be ruled out. The rates at which those processes act do not amount to more than a few cm/century (JELGERSMA, 1996), and subsidence under these rates would either be compensated by the rate of peat or sediment accumulation, or leave a transitional contact between the soils and the overlying deposit. Also burial of 1.2 m of a soil at these rates would required several thousand years.

Consequently, the rapid submergence inferred from the

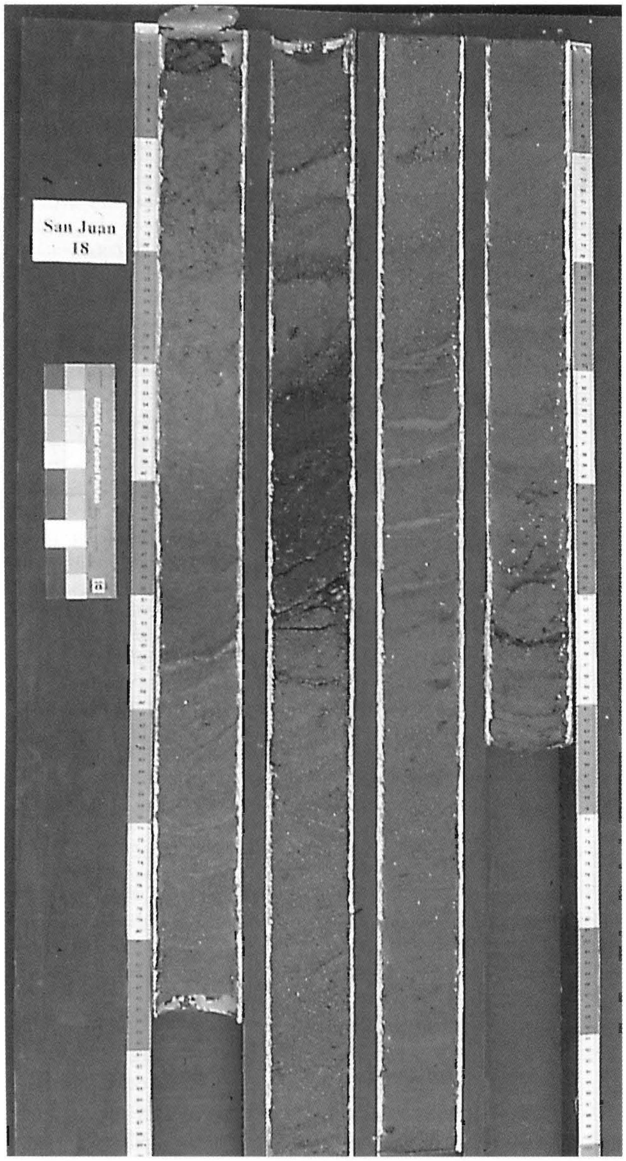

Figure 9. Picture of core 18 showing a buried peaty soil at a depth of 1.3 m. Peat is composed of detrital fragments of litter forest material and is free of mud. It is interpreted to have formed in a high marsh environment adjacent to a forested area. Note sharp upper contact with overlying sand deposit.

buried soils more likely resulted from a sudden lowering of the land than from a gradual rise of sea level or from a slow gentle compaction.

DISCUSSION

The buried soils found in the SW island of the San Juan delta are likely analogs of the sedimentary sequences found in several bays and estuaries along the coast of Washington, (ATWATER, 1992), Oregon (DARIENZO, 1989; GRANT *et al.*, 1989) and northern California (SAMUEL and CARVER, 1992), where coseismic subsidence, associated to large magnitude (M > 8) plate boundary earthquakes has been extensively documented.

Along the 1300 km long Pacific coast of Colombia, coseismic subsidence has been previously reported associated to two recent earthquakes. The magnitude 6.5, 8 km depth focus earthquake of 26 September 1970 caused 20 to 30 cm of subsidence at the town of Bahia Solano based on the level reached by the high tides after the earthquake (RESTREPO 1971). PAGE and JAMES (1981), in a study of subsidence in the area 10 years after the quake, showed that the coast has subsided three times in the last 800 years, as suggested by the presence of three levels of buried tree stumps in growth position and paleosols, indicating past Bahia Solano type earthquakes. The December 12, 1979, magnitude 7.9, 33 km depth focus, Tumaco earthquake-caused sudden subsidence of as much as 1.6 m along a 200 km stretch of the coast between Buenaventura and Tumaco. This coseismic subsidence also resulted in an apparent rise of sea level (HERD *et al.* 1981). Following the shock, trees and shrubs were drowned, and rows of palm trees planted above high tide were partly submerged. Streets and houses in San Juan de la Costa, which subsided about 1.2 to 1.6 m, were inundated by more than a meter at high tide.

Based on barrier island morphology and stratigraphy, MARTINEZ *et al.*, (in press) suggest that episodic subsidence of a meter or two has played a major role in the evolution of barrier islands along the central pacific coast of Colombia. The most conspicuous evidence they encountered pointing to subsidence of some of these islands are: (1) 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. (2) The overwash sediment column extends 2 m below the spring high-tide line. (3) The shallow platform, more than 2 km wide, seaward of some islands may reflect an immature shoreface which has not yet caught up with some of these islands long-term migration related to subsidence. Although MARTINEZ *et al.*, (in press) made no specific mention of coseismic subsidence, the evidence they present suggest rapid lowering of the land.

As implied above, segments of the barrier islands that front the San Juan delta may have subsided rapidly as result of the November 1991 magnitude 7.0 earthquake with epicenter 40 km NW of the delta (Figure 6). Perhaps the most reliable indicator of local land subsidence after the earthquake is the frequency of washover and flooding, which local residents stated increased from about 3 to 17 times per year (CORREA *et al.*, 1995 and MORTON *et al.*, 2000).

Historical evidence from earthquakes along this coast and results form comparable studies on the Pacific Northwest of North America, lead us to propose that the occurrence of large (> 1 m) sudden subsidence, such as the one we report here, requires a shallow focus earthquake of M 7.9 or greater.

CONCLUSIONS

The high seismicity originating at the convergence of the Nazca and the South American plates is the most important physical process that controlled the late Holocene development of the San Juan delta. This study provides strong evi-

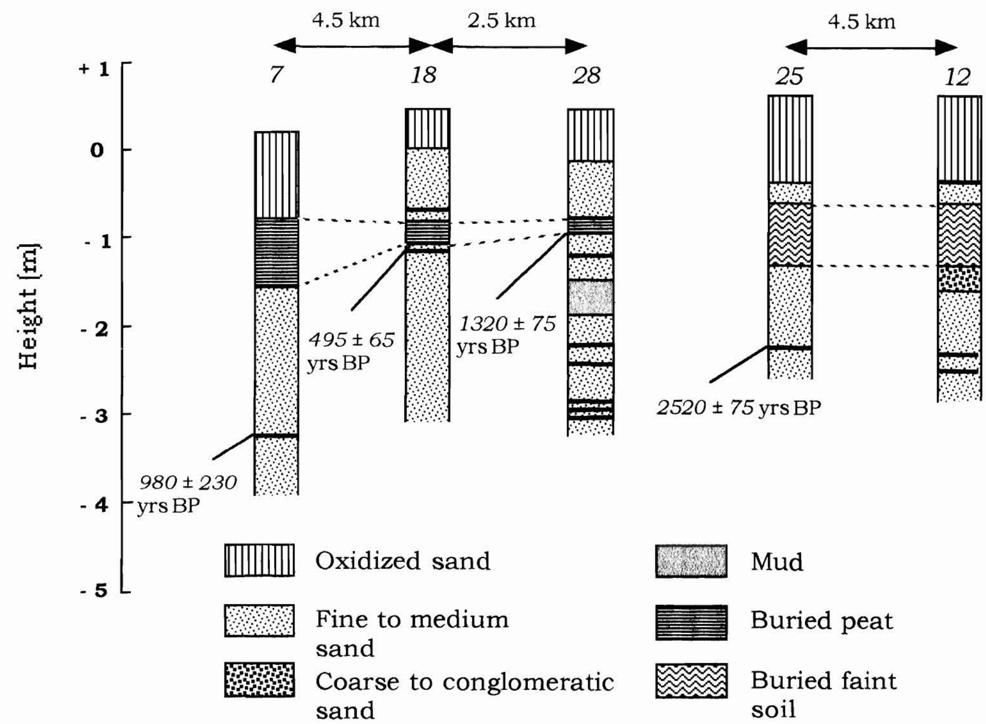

Figure 10. Columnar sections indicating, depth of buried peat or oxidized sand, distance between cores, C14 dates, and elevation with reference to the level of Spring High Tide (SHT).

dence for the occurrence of sudden submergence of 1.2 to 1.5 m around 500 years BP on the southwestern island of the delta, and possibly on the rest of the delta plain and the adjacent coastal areas.

Soils buried by intertidal deposits within the sedimentary sequence of the San Juan delta, can most simply be explained by coseismic subsidence. Evidence that favors this interpretation are the abrupt upper contact between the soil and the overlying deposit and the fact that the area is within the influence of an active subduction zone where large magnitude and shallow focus earthquakes are not rare. Alternative explanations for the buried soils include eustatic sea level rise and deltaic compaction, but they both can be readily ruled out.

Historical evidence has shown that along this collision coast coseismic subsidence can be expected associated with > M 7.9, shallow focus earthquake.

Earthquake induced subsidence should be considered as a geologic hazard when evaluating hazard zoning and land-use planning on this largely undeveloped and unpopulated coast. The evidence for a large prehistoric earthquake presented here gives paleoseismology a new element in defining the region's seismic hazard.

New studies are required along the central Pacific coast of Colombia to provide answers to three specific questions: (1) how extensive was the subsidence event reported here? (2) what is the precise date of the earthquake that caused the rapid submergence? and (3) have there been other late Quaternary earthquakes that caused subsidence on this low alluvial coast?

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□ RESUMEN □

El delta del Río San Juan se formo bajo unas condiciones físicas complejas, entre las que se encuentran: estar ubicado en una área con una de las mayores tasas de precipitación del mundo, presentar descargas altamente variables y altos niveles del mar de corta duración ambos, asociados a la perturbación climática del Fenómeno de El Niño—La Niña, tener un rango mesomareal combinado con un clima de olas moderado. De todos los aspectos que hacen el marco físico complejo, tal ves el que mas ha influenciado el desarrollo del delta durante el Holoceno Tardío ha sido la alta sismicidad del área originada de la subducción de la Placa de Nazca bajo la Placa Sur Americana. Perforaciones someras en la isla SW del delta revelaron la existencia de suelos enterrados entre 1.2 y 1.5 m, cubiertos por depósitos intermareales; el contacto abrupto entre los suelos y el deposito que los cubre, implica que estos quedaron sumergidos súbitamente, lo cual se puede explicar de la manera mas simple como habiendose originado por subsidencia cosismica, asociada a la alta sismicidad del área. Con los datos disponibles se sugiere la ocurrencia de este evento alrededor de 500 años AP. Evidencia de sismos recientes a lo largo del sector sur-central de la costa Pacifica Colombiana, indica que la ocurrencia de subsidencia cosismica mayor de un metro requiere de un sismo de magnitud mayor de 7.9.