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Late Holocene marine terraces of the Cartagena region, southern Caribbean: The product of neotectonism or a former high stand in sea-level?

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ABSTRACT

The detailed stratigraphic survey and paleontological study (mollusks, corals, foraminifera and ostracods) of four low-level, ~3 m, marine terrace sections: Punta Canoas, Manzanillo del Mar, Playa de Oro, and Tierra Bomba Island, from the Cartagena region, southern Caribbean, supplemented with 22 radiocarbon dates, reveals that the northern terraces were deposited as parasequences in a clastic depositional system compared to the Tierra Bomba Island succession that was deposited in a carbonate depositional system between ~3600 and ~1700 cal yrs BP. Drier conditions and the southern location of the ITCZ at about 3 ka triggered stronger easterly Trades and more dynamic southwestward sediment drift fed by the Magdalena River mouth, thus promoting the formation of sand spits that ultimately isolated the Cienaga de Tesca coastal lagoon from the Caribbean Sea. Our estimates support the hypothesis that the present position of the terraces is the product of neotectonism rather than a higher 3 ka, sea-level. Upheaval of the terraces varies between ~3.8 mmyr^{-1} at Punta Canoas and ~2.2 mmyr^{-1} at Tierra Bomba to ~1.5 mmyr^{-1} at Manzanillo del Mar and Playa de Oro terraces. Our study corroborates previous contentions on the role of mud diapirism and the dynamics of the Dique Fault as late Holocene upheaval mechanisms.

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RESUMEN

La descripción estratigráfica detallada y el estudio paleontológico (moluscos, corales, foraminíferos y ostrácodos) de cuatro niveles bajos, ~3 m, de las secciones de las terrazas marinas de: Punta Canoas, Manzanillo del Mar, Playa de Oro y Tierra Bomba en la región de Cartagena, sur del Caribe, suplementado con 22 dataciones radiocarbono, revela que las terrazas del norte fueron depositadas como parasecuencias en un sistema clástico comparadas con la sucesión de la isla de Tierra Bomba que fue depositada en un sistema carbonatado entre ~3600 y ~1700 años cal AP. Condiciones mas secas y la localización mas al sur de la ZCIT hace 3 ka resulto en vientos alisios del este mas fuertes y una deriva litoral hacia el suroeste mas dinámica alimentada por la desembocadura del Río Magdalena promoviendo así la formación de espigas de arena las cuales finalmente aislaron la Cienaga de Tesca del Mar Caribe. Nuestros estimativos apoyan la hipótesis que la posición presente de las terrazas es el producto de neotectonismo y no el de una posición del nivel del mar mas alta hace 3 ka. El levantamiento de las terrazas varia entre ~3.8 mmyr^{-1} en Punta Canoas y ~2.2 mmyr^{-1} en Tierra Bomba a ~1.5 mmyr^{-1} en Manzanillo del Mar y Playa de Oro. Nuestro estudio corrobora propuestas previas con respecto al papel del diapirismo de lodo y la dinámica de la Falla del Dique como mecanismos responsables del levantamiento de las terrazas bajas durante el Holoceno tardío.

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1. Introduction

Whether or not the marine terraces of the Cartagena region are the result of a former 3 m high stand in sea-level at ∼3 ka or recent tectonic upheaval, their depositional and paleo-bathymetric history should be interpreted first. This paper provides such a reconstruction and discuses neotectonic activity in a location that lies in the southern extreme of the Luruaco anticlinorium in the Sinu belt (Duque-Caro et al., 1983) where the Caribbean – South American plates converge (e.g. Taboada et al., 2000; Trenkamp et al., 2002; Flinch, 2003).

Sea-level changes in the Holocene respond to a complex balance between: (1) glacio-isostatic and hydro-isostátic effects, (2) subsidence and/or upheaval, and (3) sediment supply or erosion (e.g. Emery and Aubrey, 1991; Pirazzoli, 1996; Emery and Myers, 1996). Following deglaciation, the hydro-isostatic response of the continental margins was diverse and related to the distance to the polar ice caps of the northern hemisphere (e.g. Lambeck, 1993). Locations that where far away from former ice sheet, i.e. *far-field* regions such as Australia and Japan, have been studied for Holocene sea-level changes (Nakada and Lambeck, 1989; Chappell, 1987; Yokoyama et al., 1996; Lambeck, 2002). These studies reveal that most of the global ice sheets melting ceased ca. 7 ka when higher than present day sea-level indicators are observed at the *far-field* regions. The southern Caribbean is classified as *intermediate-field*, from the Laurentide ice sheets, where the ice loading component from the ice sheet is still considerable (Clark and Linge, 1979). Therefore, glacio-hydro-isostatic models predict continuous rise in sea-level throughout the Holocene including the present day highest sea-level (Lambeck et al., 2002).

Attempts to build a southern Caribbean Holocene sea-level curve include: (1) a palynological study, supported by radiocarbon dates, in eastern Venezuela (Rull et al., 1999), that in the absence of tectonic and glacio-hydro-isostatic considerations should be regarded as preliminary, (2) the dynamics of *Rhizophora mangle* and the precise radiocarbon dating of peat levels in Trinidad that suggest that sea-level rose from −9 m to −2 m between 7 and 2 ka (Ramcharan, 2004), and (3) a compilation of relative sea-level data and glacio-hydro-isostatic model (Milne et al., 2005) that allowed them to predict a relative sea-level curve for Curacao, i.e. a relative sea-level rise from the last glacial maximum (LGM), level to *ca.* 3 m at about 7 ka and the steady rise of ca. 1 m at about 5 ka.

The origin of the lower, i.e. *ca.* 3 m high, coastal terraces of the Colombian Caribbean remains controversial with regard to either a former high sea-level position at *ca.* 3 ka or recent tectonic upheaval. Historically, research on the low-level terraces (see Fig. 1 for location) has gone through: (1) stratigraphic and paleontological surveys of the *ca.* 3 m high Tierra Bomba Island terraces which were dated as 2850 ± 150 ^{14}C yrs BP (De Porta and De Porta, 1960; Richards and Broecker, 1963; De Porta et al., 1963), and 2800 and 3690^{14}C yrs BP, and interpreted as the result of a higher sea-level position (Burel et al., 1981; Vernette, 1989a), (2) ∼2500 and 8900 ^{14}C yrs BP dates on corals and mollusks from south of the Morrosquillo Gulf (Fig. 1c), that were compared with the hydro-isostatic curve for Brazil as a reference to estimate upheaval rates of ∼2–5 mmyr^{-1} and subsidence rates of ∼0.7 mmyr^{-1} along the coast (Page, 1983), (3) radiocarbon dates on peats, calcareous nodules, mollusks and corals collected from 11 samples from the continental shelf offshore Cartagena, that were used to construct a sea-level change curve, whose pattern is more alike type V than IV; therefore appearing to be more of a *far-field* type than an *intermediate-field* type (cf. Clark and Linge, 1979), where the effect of neotectonísm apparently was minimum (Javelaud, 1987) and, (4) a micropaleontological (foraminifera) study of 6 cores from the Barú Island (Fig. 1c) coastal lagoons and 18 cores from the continental shelf to reconstruct paleobathymetry (Parada, 1996).

Major pitfalls on these studies are the absence of stratigraphic columns, the dating of only few fossils without any control on their position in the terraces, taphonomy, and transport, uncalibrated ages or the complete absence of radiocarbon dates as is the case of Parada's (1996) study. Furthermore, interpretations of either a +3 m high sea-level stand at 3 ka or neotectonic upheaval, in

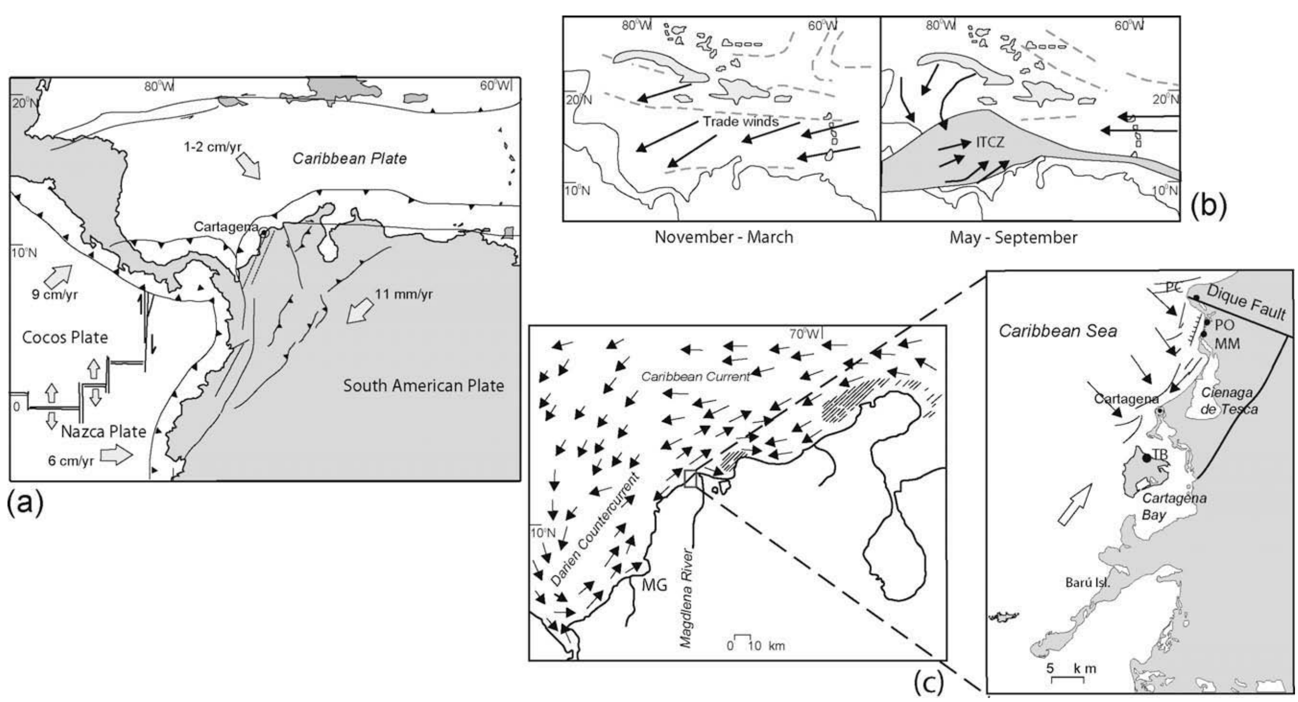

Fig. 1. The Cartagena region: (a) tectonic setting (based on Taboada et al., 2000), (b) atmospheric circulation and seasonal variations of the ITCZ (Pujos et al., 1984), (c) oceanic currents and coastal sediment drift (Pujos et al., 1984). Note the location of the stratigraphic columns (i.e. at the low-level terraces): Punta Canoas (PC), Playa de Oro (PO), and Manzanillo del Mar (MM), north of the Cartagena Bay, and Tierra Bomba (TB) south of it. Note also the Bocagrande spit south of Cartagena. MG = Morrosquillo Gulf.

those studies, were unsupported by a geophysical or tectonic study.

This paper documents the detailed survey of ten stratigraphic columns from four terrace sections with a sequence biostratigraphy and taphonomy approach plus a paleo-bathymetric reconstruction, supported by 22 radiocarbon dates. From this information we estimate sediment accumulation and upheaval rates, and explore the role of the southward migration of the intertropical convergence zone (ITCZ; Haug et al., 2001) in the construction of the depositional sequences, and evaluate the role of local faults. Herein we present data from four stratigraphic columns only. For full details of the other columns and cores see Gomez (2005) and Delgado (2004). Details of the taphonomic study will be published elsewhere.

1.1. The Cartagena region: tectonics, climate and oceanographic setting

The Cartagena region is located in an active tectonic zone where the Caribbean and South American plates interact. The Caribbean plate moves southeastward, colliding with the South American plate at a speed of 1–2 cmyr^{-1} (e.g. Taboada et al., 2000; Fig. 1a). Oblique convergence initiated in the Tertiary and shaped the poly-history Lower Magdalena Basin, where two provinces are recognized, the western Sinú belt and the eastern San Jacinto belt, separated by the Sinú lineament (Duque-Caro, 1980). Oblique plate convergence, together with high accumulation of terrigenous sediments on the continental margin results in the extensive formation of mud diapirs and volcanoes, which are characteristic of the Sinú belt and the present continental margin (e.g. Vernette, 1989b; Ordoñez, 2008). Mud diapirism in the Sinú belt apparently is responsible of most of the upheaval of the coastal terraces and subsidence in the Morrosquillo Gulf area (e.g. Page, 1983; Duque-Caro, 1984; Vernette, 1989b). The Sinú belt is composed of folded Miocene to Pliocene marine rocks affected by east-dipping thrusts, mud diapirism and NW-SE faults and lineaments, e.g. the Dique Fault (Fig. 1; Duque-Caro, 1980; Vernette, 1989b) or Canoas Fault of others (e.g. Ruiz et al., 2000). The La Popa Formation, a Pleistocene reef, caps most of the hills on the Tierra Bomba and Baru islands and north of Cartagena (La Popa hill) and constitutes the ~20 m high level terraces. By contrast, there is a low Holocene marine terrace level, which occurs at ~3 m all over the region, and is the object of this study.

Sediment yield over the Caribbean coast is controlled by the seasonal (latitudinal) migration of the ITCZ which controls precipitation in northern South America (Fig. 1b), i.e. a dry season (November to March), a transition season (April to August), and a rainy season (August to November). Similarly, northeast Trade Winds are stronger during the dry season, when the southwesterly Caribbean Current is stronger and the wave front hit the shore obliquely thus resulting in a southwestward longshore current and sediment drift (Fig. 1c). During the rainy season, when the northeasterly Darien Counter-Current is stronger, drifting of sediments is reduced (e.g. Pujos et al., 1984). However, during this season, hurricanes that originate as tropical depressions, occasionally hit the area thus transporting sediments from the northeast, e.g. hurricane Joan that reached the Cartagena region on October 1988 (Lawrence and Gross, 1989).

Therefore, the interaction between tectonism, climate and oceanographic dynamics has resulted in a coastal setting where a number of geomorphologic units can be recognized. Among them: (1) coastal plains associated to fluvio-marine sedimentary processes, (2) coastal lagoons partially or completely isolated from the sea by coastal bars (Gayet and Vernette, 1989), (3) beaches and coastal barrier islands, (4) coral reefs and, (5) marine terraces. The predominant supply of terrigenous sediments from the northeast, i.e. the Magdalena River, has resulted in two ecosystem and depositional settings, clastic and carbonate, north and south of the Cartagena Bay (Fig. 1c; Diaz and Puyana, 1994), respectively. These different depositional systems are reflected in the composition and spatial heterogeneity of the sedimentary marine terraces, i.e. the northern Punta Canoas, Manzanillo del Mar, and Playa de Oro terraces are mostly clastic, whereas the southern Tierra Bomba Island terraces are mostly calcareous (Burel and Vernette, 1981). In this paper we reconstruct the evolution of these depositional systems for the late Holocene.

2. Methods

To capture lateral variations we surveyed ten stratigraphic successions on four terrace sections (Fig. 1c), one in Punta Canoas (10°33′23.3″N, 75°30′20″W), three in Manzanillo del Mar (10°30′44.6″N, 75°30′2.8″W), three in Playa de Oro (10°30′19.1″N, 75°30′3″W), and three in Tierra Bomba Island (10°22.39′N, 75°34. 20′W). The altitude of the terraces was measured by drawing beach profiles, connecting the base of each stratigraphic column with the highest swash mark, with the aid of a Look level fixed to a PVC pipe, a compass and GPS, a metric tape, and a second PVC pipe that was used as a reading ruler. The base of the stratigraphic sections was complemented, when possible, by digging a trench in the beach in front of the terrace outcrop (grey bars in Fig. 2).

Sediment, and paleontological, samples were collected at intervals that varied between 20 and 100 cm. About 50 g of sediment were sieved in wet and their granulometry determined by weight, whereas their mineralogical content was examined with the aid of a microscope. The invertebrate content was studied from 75 samples. Together with the general appearance of the invertebrate assemblage, taphonomic patterns were established by assessing the degree of abrasion, fragmentation, corrosion, and bioerosion. Taxonomic determinations were done on specimens preserved in at least 25%, whereas invertebrate assemblages were determined for each stratigraphic section by means of Cluster analysis (R and Q modes) with the aid of *MVSP* 3.0[1] (Kovach, 2000). For radiocarbon analysis, 38 well-preserved, invertebrate bivalved specimens, found in life position, were selected. Analyses were performed at the University of Tokyo. Preparation methods are described elsewhere (Yokoyama et al., 2000). The calibration of calendar years from radiocarbon dates was performed with the aid of the CALIB 4.4 program, with the average reservoir effect value for the Caribbean of -19 ± 23 (Stuiver and Reimer, 2005). Therefore, all through the paper dates are given in calendar years BP. Then, sediment accumulation and upheaval rates were estimated. Errors include uncertainties with surveying of the sections and GPS measurements, the assessment of the paleobathymetry of the fossils dated, and the radiocarbon measurements. Micropaleontological samples were collected at Tierra Bomba and Playa de Oro terraces. Around 50 g of sediment sample were immersed in hydrogen peroxide (5%) until reaction stopped and then were wet sieved through 75, 150 and 250 μm mesh sizes. Samples were then dried at low temperature (<50 °C) and ~300 specimens of foraminifera and ostracoda were picked from the >150 μm size fraction.

3. Results

Our topographic survey shows the varying altitudes of the Cartagena terraces (Fig. 2). The top of Punta Canoas, the highest terrace, lies at ~680 cm above sea-level (cmasl), whereas the top of Playa de Oro, the lowest terrace, lies at ~212 cmasl. The terraces

[1] MVSP: Multivariate Statistical Package.

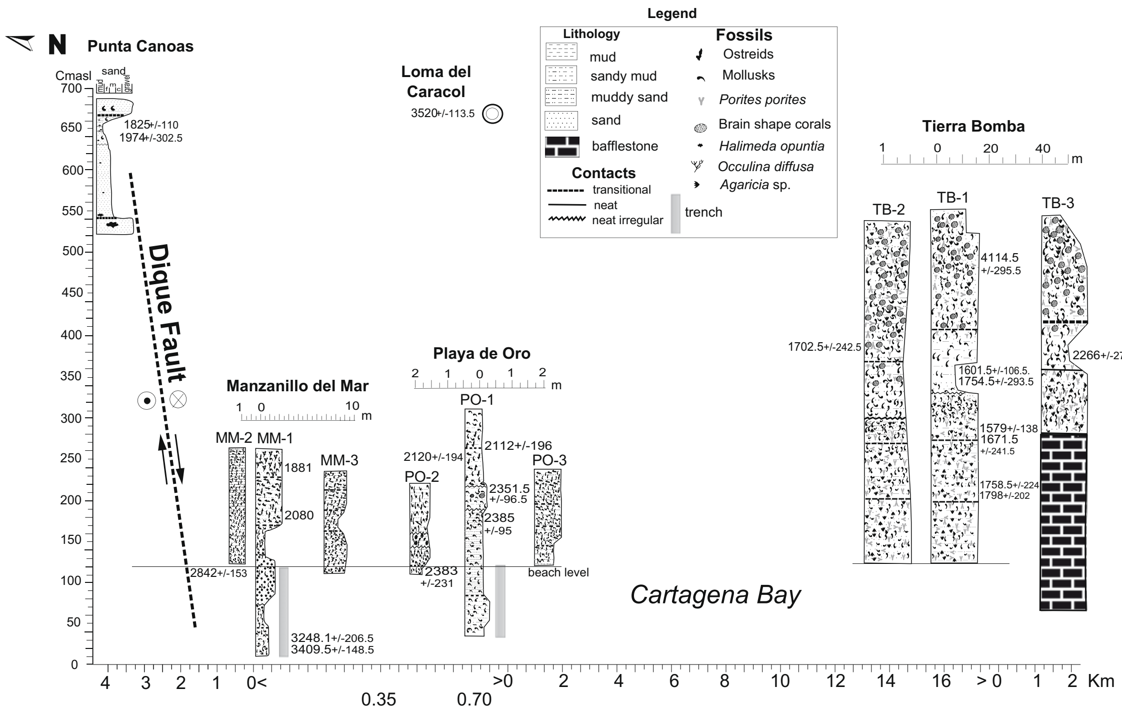

Fig. 2. Cartagena terraces cross-section. Note the position of the stratigraphic columns with respect to the present beach level, and their relative distance from the Manzanillo del Mar (MM) and Playa de Oro (PO) sections. Depositional systems: (1) clastic: Punta Canoas (PC), MM and PO terraces, (2) Carbonate: Tierra Bomba (TB). Radiocarbon dates (in calendar years) are indicated on each column. Note the location of the Loma del Caracol archeological midden east of the PO at ~670 cmasl and the relative displacement of the Dique Fault.

Table 1
Cartagena low-level terraces. Radiocarbon analyses on mollusk shells.

Stratigraphic section	Code lab.	Material analysed	Height (cmasl)	14C age BP (1σ)	Calibrated age BP (2σ)
PC	9	*Lucina* sp.	637	2230 ± 40	1825 ± 110
PC	8	*Anomalocardia* sp.	629	2320 ± 120	1974.5 ± 302.5
MM-1	15	*Oculina* sp.	248	2260 ± 80	1881 ± 203
MM-1	16	*Codakia* sp.	173	2420 ± 70	2080 ± 191
MM-1	11	*Brachiodontes* sp.	8	3400 ± 80	3248.5 ± 206.5
MM-1	12	*Tagelus* sp.	8	3520 ± 60	3409.5 ± 148.5
MM-2	25	*Chione* sp.	140	3040 ± 70	2842 ± 153
PO-1	20	*Chione* sp.	246	2460 ± 80	2112 ± 196
PO-1	19	*Chione* sp.	246	2470 ± 80	2120 ± 194
PO-1	18	*Chione* sp.	218	2645 ± 30	2351.5 ± 96.5
PO-1	17	*Chione* sp.	179	2675 ± 35	2385 ± 95
PO-2	29	*Corbula caribbea*	109	2670 ± 80	2383 ± 231
LC	22	*Anomalocardia* sp.	~670	3625 ± 40	3520 ± 113.5
TB-1	7	*Strombus* sp.	489	4070 ± 110	4114.5 ± 295.5
TB-1	6	*Codakia* sp.	344	2030 ± 40	1601.5 ± 106.5
TB-1	5	*Tellina* sp.	344	2160 ± 120	1754.5 ± 293.5
TB-1	3	*Anodontia* sp.	279	2020 ± 50	1579 ± 138
TB-1	2	*Macoma* sp.	279	2100 ± 100	1671.5 ± 241.5
TB-1	4	*Anodontia* sp.	199	2180 ± 90	1758.5 ± 224.5
TB-1	1	*Trachycardium* sp.	199	2210 ± 80	1798 ± 202
TB-2	33	*Codakia* sp.	359	2120 ± 100	1702.5 ± 242.5
TB-3	34	*Macoma* sp.	357	2260 ± 110	2266 ± 276

TB = Tierra Bomba, PC = Punta Canoas, MM = Manzanillo del Mar, PO = Playa de Oro, LC = Loma del Caracol. Reservoir effect (ΔR) is -19 ± 23 (average value for the Caribbean, Stuiver and Reimer, 2005).

were deposited between ~3400 and ~1600 yrs BP (Table 1). Two dates, codes 7 and 22, were excluded from our upheaval estimates. Sample code 7, collected in the Tierra Bomba terrace (TB-1 section), is considered as a reworked specimen because of its poor preservation and date out of sequence. Conversely, sample code 22, collected at Loma del Caracol archeological midden, that lies inland around 100 m from the Playa de Oro sections, is not in situ because of human transport.

3.1. Clastic depositional system north of Cartagena Bay for the Late Holocene

3.1.1. The Punta Canoas terrace

The base of the Punta Canoas terrace (Fig. 2) is located 369.5 m away from the present coastline at 514 cmasl. The stratigraphic succession (166 cm thick) consists, from base to top, of a loose clast-supported sandy gravel layer, rich in quartz and micas, followed by a fine-sand layer rich in quartz, chert and mica and some volcanic minerals (Fig. 3). This fining upward tendency continues to ~640 cmasl. However, at ~630 cmasl the first bioclasts (mollusks) appear. They consist of venerids (e.g. *Anomalocardia brasiliana*, *Chione cancellata*), corbulids (e.g. *Corbula caribaea*), lucinids (e.g. *Lucina pectinata*), arcids (e.g. *Anadara notabilis*), ostreids (e.g. *Crassostrea rhizophorae*), bullids (e.g. *Bulla striata*), neritids (e.g. *Neritina virginea*) and ceritids (e.g. *Cerithium lutosum*). Bivalves lie horizontally and some of them still bear their two valves. Their fragmentation is low, though corrosion is high. The beginning of a coarsening upward tendency is marked by an organic-rich mud layer (layer 4) that contains *Lucina* spp. specimens which lie horizontally and bear their two valves. Towards the top of the terrace, a loose clast-supported sandy gravel, rich in *A. brasiliana*, occurs. Here bivalve fragmentation is high, though the development of soil and modern human influence prevented us from assessing the timing of this fragmentation. Two radiocarbon dates (Table 1 and Fig. 2) suggest that the section was deposited during the latest Holocene, at least from 640 cmasl upward, and is younger than ~1970 ka. Both radiocarbon ages are stratigraphically consistent.

3.1.2. The Manzanillo del Mar terrace

The base of Manzanillo del Mar terrace (MM1) is located ~39 m away from the present coastline at 8 cmasl. The total thickness of the section, and presumably its height, results from the addition of 123 cm of section described from a trench dug in the beach, at the base of the outcrop (Fig. 2). The stratigraphic succession begins with a muddy fine-grained sand containing pockets of mollusks (most of them fragmented) which changes to a 53 cm thick sandy mud layer containing *Halimeda opuntia* plates and benthonic foraminifera (Fig. 4). A second layer is texturally composed of coarse-grain sand particles made mostly of *H. opuntia* with few corroded molluscan fragments. The top of the terrace is a sandy mud containing a varied molluscan assemblage and coral fragments (*Occulina diffusa*), with evidence of bioerosion and corrosion. Diversity, as expressed by the Shannon diversity index, is fairly constant throughout the section and is represented by 39 species of molluscans from 2918 specimens. Four assemblages are recognized by Cluster analysis in section MM1: (1) *A. brasiliana* that dominates in layer 1, (2) *Brachidontes modiolus* – *Diodora cayennensis* that dominate in layer 2, i.e. the *H. opuntia* layer, (3) *A. notabilis* – *Cerithium* sp. 1 that dominate in layer 3 and (4) *C. rhizophorae* – *Ostrea* sp. 1 that dominate in layers 4 and 5. Similar assemblages are found in sections MM2 and MM3, though ostreids are more common in the upper part of the latter section. Five radiocarbon dates (Table 1 and Figs. 2 and 4) suggest that the terrace was deposited during the latest Holocene and is younger than ~3500 yr BP. Radiocarbon ages are stratigraphically consistent.

3.1.3. The Playa de Oro terrace

The base of the Playa de Oro terrace (PO1) is located ~30 m away from the present coastline at ~36 cmasl. The total thickness of the section, and presumably its height, results from the addition of 110 cm of section that was surveyed in a trench dug on the beach at the base of the outcrop (Fig. 2). The stratigraphic succession consists of sandy and gravely muds with varying amounts of sand, containing *H. opuntia* plates, molluscan fragments, foraminifera, ostracoda and volcanic minerals (Fig. 5). Sandy gravels were observed as lateral variations north and south of the main column. In both columns (PO2 and PO3) there is a conspicuous coarsening upward tendency. Diversity of molluscan assemblages are analogous to those observed in the Manzanillo del Mar terrace, though in the Playa de Oro terrace a larger number of species, i.e. 73 species in 2856 specimens, were identified. Similarly, four molluscan assemblages are recognized in the PO1 section. From bottom to

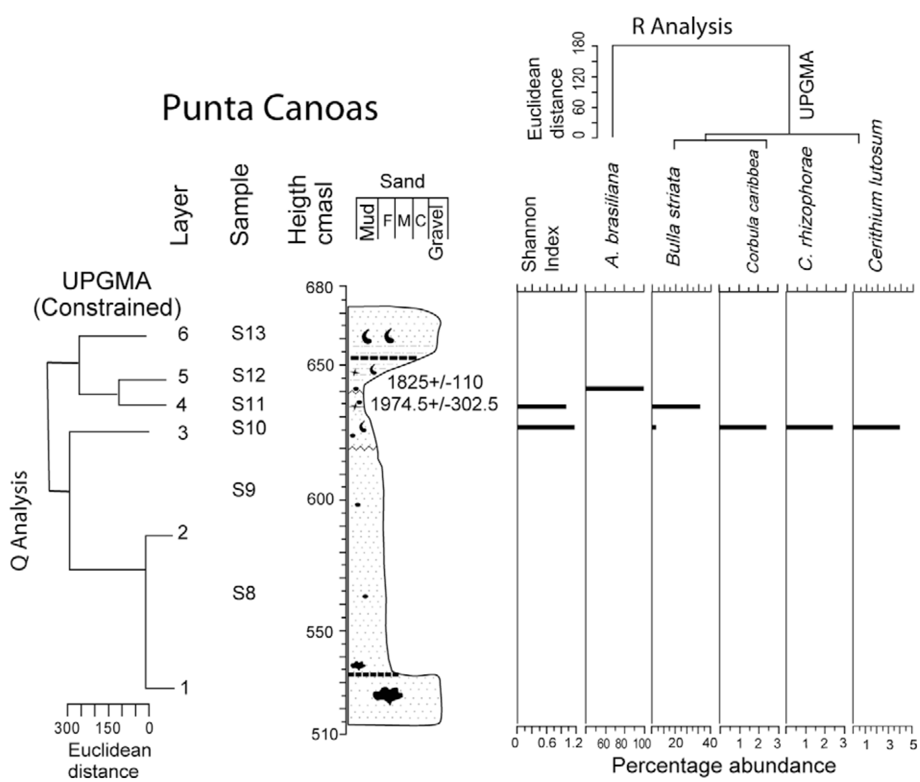

Fig. 3. Punta Canoas terrace (PC column): constrained (Q mode) cluster analysis, stratigraphy, Shannon diversity index, molluskan (percentage abundance) and assemblages as defined by unweighted (UPGMA) cluster analysis. Radiocarbon dates, as in Table 1, are indicated.

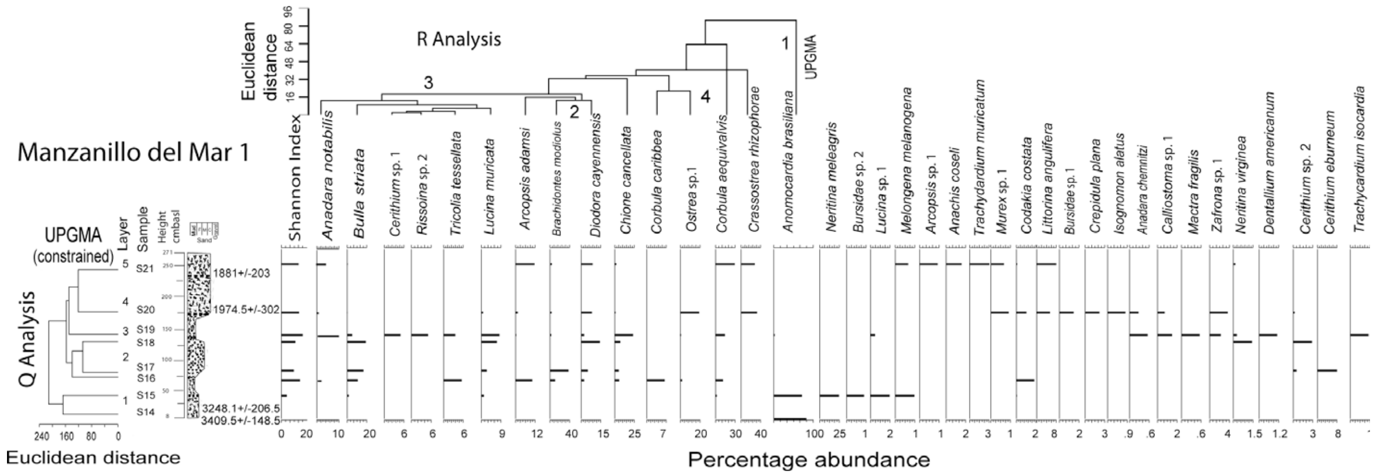

Fig. 4. Manzanillo del Mar terrace (MM-1 column): constrained (Q mode) cluster analysis, stratigraphy, Shannon diversity index, molluskan (percentage abundance) and assemblages as defined by unweighted (UPGMA) cluster analysis. Radiocarbon dates, as in Table 1, are indicated.

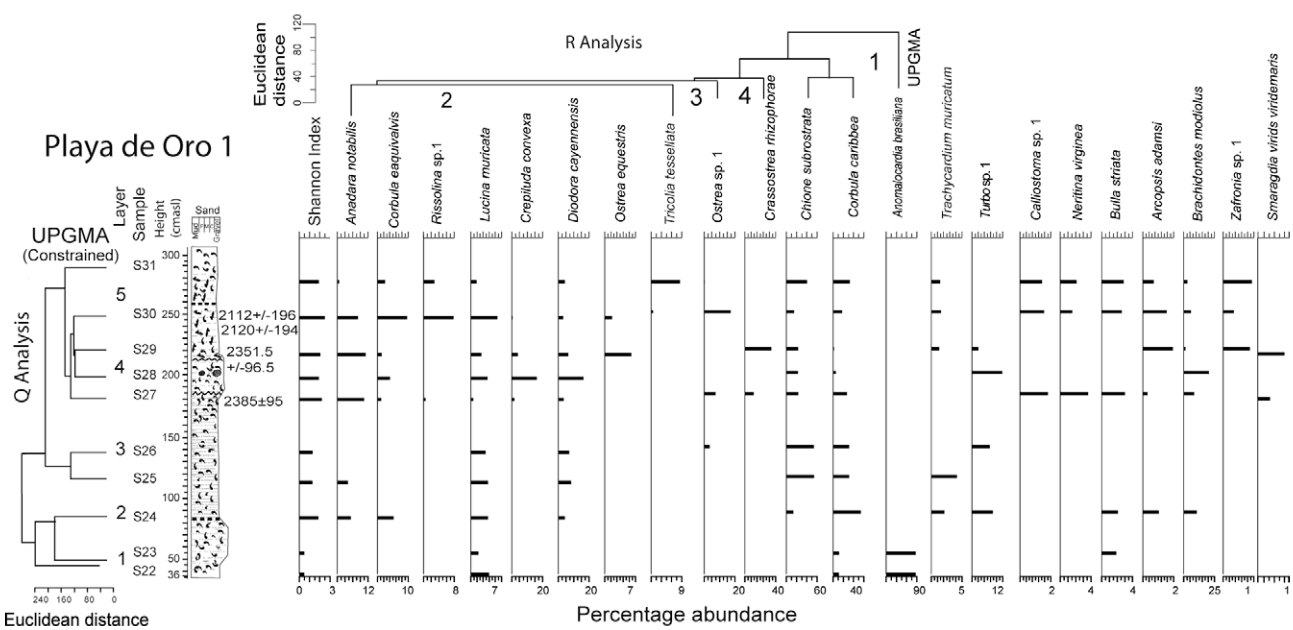

Fig. 5. Playa de Oro terrace (PO-1 column): constrained (Q mode) cluster analysis, stratigraphy, Shannon diversity index, molluskan (percentage abundance) and assemblages as defined by unweighted (UPGMA) cluster analysis. Radiocarbon dates, as in Table 1, are indicated.

top they are: (1) *A. brasiliana* – *L. muricata* that dominates layer 1, (2) *C. subrostrata* – *C. caribaea* that dominates layers 2 and 3, (3) *C. convexa* – *D. cayennensis* that dominates layer 4, (4) *C. rhizophorae* – *Ostrea* sp. 1 that dominates layer 5 (Fig. 5). Despite lateral variations in the PO2 and PO3 sections, molluscan assemblage variations are analogous to those reported for Manzanillo del Mar. Towards the top of the section, fragments of *Porites porites* and *Siderastrea* are common. Radiocarbon ages are stratigraphically consistent.

3.2. Carbonate depositional system south of Cartagena Bay for the Late Holocene

3.2.1. The Tierra Bomba terrace

The base of the Tierra Bomba terrace is located ~3 m away from the present coastline at ~60 cmasl (Fig. 2). The lowest recorded stratigraphic unit is a coral, *Porites porites* bafflestone. This unit varies, laterally and vertically, to sandy and muddy rudstones and sands, where coral (*P. porites, Siderastrea* spp., and *Agaricia* spp.) and molluscan fragments, *H. opuntia* plates, foraminifera and ostracoda are common.

From the three sections surveyed, 90 molluscan species were identified from 575 specimens. Section TB2 (Fig. 6) contains, among others, *Arcopsis adamsi*, *Modulus modulus*, and *Corbula caribaea* in layer 2, *C. orbicularis*, *Trachycardium muricatum*, and *Bulla striata* in layer 3, and *C. eburneum* in layer 4. Similar assemblages are recorded in sections TB-2 and TB-3 (Gomez, 2005). The benthonic foraminifera *A. beccarii*, *Cymbaloporetta squammossa* and *Brizalina subaenariensis*, among others, are common at the base of the section, whereas *Brizalina subaenariensis* y *Quinqueloculina seminulum* are common at the top. The ostracods *Loxoconcha*, *Cypris* and *Xestoleberis* are common (Liano, 1982; Delgado, 2004). Eight radiocarbon dates (Table 1 and Fig. 2) suggest that the terrace was deposited during the latest Holocene and is younger than ~2200 yr BP. Different to the other terraces, there are some stratigraphic inconsistencies, like the 4416 ka in section TB1.

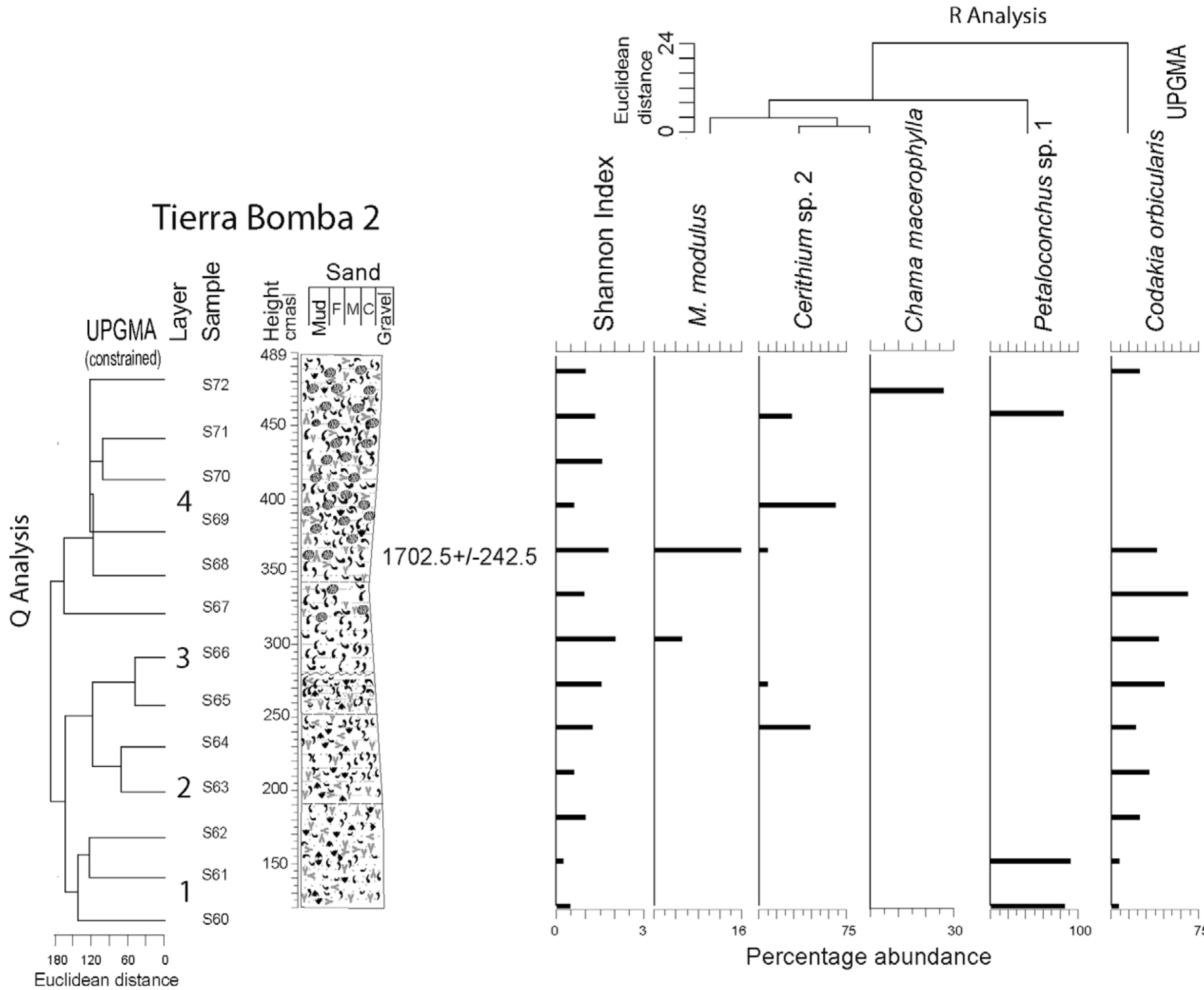

Fig. 6. Tierra Bomba terrace (TB-2 column): constrained (Q mode) cluster analysis, stratigraphy, Shannon diversity index, molluskan (percentage abundance) and assemblages as defined by unweighted (UPGMA) cluster analysis. Radiocarbon dates, as in Table 1, are indicated.

4. Discussion

4.1. Depositional environments

The above-mentioned faunal, taphonomic, and radiocarbon features for the Punta Canoas section suggest very low sedimentation rates and deposition in a shallow water environment, except for layer 4. Facial variations on the Punta Canoas stratigraphic section suggest a change from a fluvial dominated deltaic system to an estuarine and/or lagoon system (cf. Walker, 1984; Walker and James, 1992); interpretation that is supported by the molluscan assemblages, e.g. the presence of *C. cancellata*, *C. rhizophorae*, and *N. virginea* which are typical of lagoons and/or estuarine environments where salinity is low and variable. *Crassostrea rhizophorae* is an epiphytal species that either adheres to *Rhizophora mangle* or forms shell mounds in shallow water lagoons (e.g. Reyes and Campos, 1992; Diaz and Puyana, 1994). In no case the reported species live deeper than 6 m water depth, though they are commonly associated to seagrasses (*Thalassia testudinum*). We interpret the high corrosion of molluscan specimens in the section to low pH values common in coastal lagoons rather than to recent dissolution by meteoric waters.

At Manzanillo del Mar section, there is an environmental change from upper shoreface to estuarine conditions. At the base of the terrace the presence of *A. brasiliana*, that is an infaunal and detritivorous species that inhabits high energy estuarine systems at 3–5 m water depth (e.g. Diaz et al., 1990; Diaz and Puyana, 1994), together with the green algae *H. opuntia* and its associated molluscan species such as *T. nigrocincta*, that inhabits hypersaline (>25 psu) carbonate settings (e.g. Wray, 1980), suggests an upper shoreface environment. This shallowing tendency continues as suggested by the occurrence of *B. modiolus* that is associated to sandy and rocky upper shoreface environments covered by seagrasses (Diaz and Puyana, 1994). Then, a clear estuarine environment is suggested by the dominance of ostreids such as *C. rhizophorae*, *Neritina meleagris* and *Ostrea* sp. 1 that inhabit at water depths between 0 and 2 m and salinities between 0 and 5 psu (e.g. Diaz and Puyana, 1994). Finally, the MM1 section ends with a varied molluscan assemblage that suggest a mangrove populated lagoon occasionally disturbed by overwash deposits that eventually ended with its drying out by subareal exposure. This interpretation is supported by the occurrence of *L. angulifera* who lives commonly attached to *Rhizophora* roots and other intertidal molluscans such as *Melongena melongena* that inhabits shallow muddy mangrove waters and preys on epifaunal bivalves in coastal lagoons and associated environments (e.g. Von Cosel, 1986). Overwash and/or the return to shallow marine conditions are suggested by the occurrence of *A. adamsi*, and *A. coseli*, among others (Diaz and Puyana, 1994).

Similar to the Manzanillo del Mar section, at the base of the Playa de Oro section, the molluscan specis *A. brasiliana* and *B. striata*, and the benthonic foraminifera *Ammonia beccarii* and *Cypris* occur. This assemblage suggests mud and sand substrates populated by seagrasses (Diaz and Puyana, 1994) and water depths that did not exceed the 10 m (Parada and Pinto, 1985). The succession is followed by muddy sands with molluscan species such as *C. subrostrata*, *B. striata*, and *T. muricatum* that suggest shallow water to estuarine conditions (cf. Diaz and Puyana, 1994). The presence of the ostracod taxa *Cypris* and *Perissocytheridea* seem to support this interpretation. Later on, still some shallow taxa such as *A. adamsi* and *B. striate* co-occur with *C. rhizophorae*, *Neritina virginea*, and *Ostrea* sp. 1, thus suggesting a shallowing tendency and estuarine conditions, and occasional overwash deposits. This paleobathimetric reconstruction is similar to that interpreted for Manzanillo del Mar.

The Tierra Bomba section, was deposited in a carbonate environment. Its basal *Porites porites* bafflestone probably accumulated in a period of 100–400 yrs. This figure is estimated from coral growth rates of the order of 5–15 mm/yr for the Holocene in the Caribbean (Macintyre and Glynn, 1976; Bosscher, 1992) and is in accord to out data. Molluscan species such as *C. orbicularis* and *M. modulus*, and foraminifera such as *A. beccarii*, *C. squammossa* suggest a coral reef setting and its associated calcareous algae and seagrass patches at middle shoreface, i.e. 6–10 m water depth. This setting was followed, apparently, by seagrasses as suggested by the occurrence of *C. orbicularis* that is commonly associated to *Thalassia testudinium* (e.g. Diaz et al., 1990; Diaz and Puyana, 1994), and the decrease in foraminifera species at the expense of ostracods, particularly *Cypris* (Delgado, 2004). Similarly to the present distribution of coral reefs and seagrasses (Diaz, 2000), this succession apparently represents a shallowing tendency within a 0–15 m water depth range as suggested by the occurrence of *P. porites* that at present is dominant in low energy environments leeward of the reef crest (Diaz, 2000). The shallowing upward tendency continues up to layer 4 where species such as *A. adamsi*, that at present inhabits a coralline gravely substrate (e.g. Diaz and Puyana, 1994), and the taphonomic state of *Siderastrea* sp. 1, suggest intense reworking in a high energy setting (cf. Martin, 1999). Similarly, the replacement of the benthonic foraminifera *A. beccarii*, *C. squammossa* and *B. subaenariensis*, among others, by the ostracods *Loxoconcha*, *Cypris* and *Xestoleberis* supports the shallowing upward interpretation. *A. beccarii*, a euryhaline marginal marine species (e.g. Sen Gupta, 1999), co-occurs with *C. squammossa* and *B. subaenariensis* which are characteristic of the middle shoreface of the Colombian Caribbean (e.g. Parada and Pinto, 1985), whereas *Loxoconcha* and *Xestoleberis* are marginal marine species and *Cypris* is generally restricted to brackish lagoons (e.g. Van Morkhoven, 1963; Frenzel and Boomer, 2005).

4.2. Geomorphologic evolution

The late Holocene shallow water to estuarine and reefal environments and the contrasting dates in relation to the altitude of the Punta Canoas, Manzanillo del Mar – Plata de Oro, and Tierra Bomba terraces, suggest that a former ∼3 m high sea-level stand is very unlikely. By contrast, evidences presented herein suggest a late Holocene geomorphologic evolution that resulted from coastal dynamics and climate processes and the continuous and/or late upheaval of the region. Importantly, the spatial sedimentary heterogeneity of the region that is observed today, was present since the late Holocene.

The lowest sediment accumulation rate, ∼0.05 cmyr^{-1}, was found at the Punta Canoas and Manzanillo del Mar sections (Table 2). Sediment accumulation rates for the other terraces, vary from ∼1.7–5.0 cmyr^{-1} at Tierra Bomba (TB-1 section) to ∼0.05 cmyr^{-1} at Playa de Oro (PO-1 section). The upward increase in sediment accumulation rates in the terraces evidences the dynamics of deposition as clastic and carbonate progradational parasequences. Palaeobathymetry and palaeosalinty changes, as inferred from the mollusk and microfossil assemblages, and the history of deposition, as supported by the radiocarbon dates, are summarized in Fig. 7.

Sedimentary conditions remained analogous to the present for the past ∼3.5 ka. At Punta Canoas a high energy deltaic system started to develop ∼3 ka. This, together with intensified coastal drift from the northeast, i.e. the Magdalena River, might have fostered the growth of a spit and a coastal bar, i.e. the Manzanillo and Playa de Oro parasequences, and the development of the Tesca lagoon (cf. Martínez, 1993). The change in the sedimentary regime and construction of the coastal bar system occurred between 3 and 2.5 ka. By that time the ITCZ apparently migrated to the south,

Table 2
Cartagena low-level terraces. Estimates of sedimentation and upheaval rates.

Stratigraphic section	Code lab.	Age (yr. BP)	Height (cmasl)	Sedimentation rate (mmyr^{-1})	Estimated depth (cmbsl)	Uplift (cmasl)	Hydro-isostatic factor (cm)	Corrected uplift (cmasl)	Upheaval rate (mmyr^{-1})
PC	9	1825 ± 110	637	∼0.5	∼200	∼837	100	∼737	∼4.0
PC	8	1974.5 ± 302.5	629		∼180	∼809	90	∼719	∼3.6
MM-1	15	1881 ± 203	248	∼4.7	∼200	∼448	100	∼348	∼1.9
MM-1	16	2080 ± 191	173	∼1.4	∼300	∼473	90	∼373	∼1.8
MM-1	11	3248.5 ± 206.5	8		∼20	∼28	58	∼−30	–
MM-1	12	3409.5 ± 148.5	8		∼200	∼208	150	∼58	∼0.2
MM-2	25	2842 ± 153	140		∼300	∼440	100	∼340	∼1.2
PO-1	20	2112 ± 196	246		∼250	∼496	90	∼406	∼1.9
PO-1	19	2120 ± 194	246	∼1.2	∼250	∼496	90	∼406	∼0.2
PO-1	18	2351.5 ± 96.5	218		∼250	∼468	90	∼378	∼1.6
PO-1	17	2385 ± 95	179		∼250	∼429	90	∼339	∼1.4
PO-2	29	2383 ± 231	109		∼150	∼259	90	∼169	∼0.7
TB-1	6	1601.5 ± 106.5	344		∼100	∼444	50	∼394	∼2.5
TB-1	5	1754.5 ± 293.5	344		∼100	∼444	100	∼344	∼2.0
TB-1	3	1579 ± 138	279		∼300	∼579	150	∼429	∼2.7
TB-1	2	1671.5 ± 241.5	279	∼1.4	∼300	∼579	150	∼429	∼2.6
TB-1	4	1758.5 ± 224.5	199		∼300	∼499	100	∼399	∼2.3
TB-1	1	1798 ± 202	199	∼3.6	∼250	∼449	100	∼349	∼1.9
TB-2	33	1702.5 ± 242.5	359		∼100	∼459	100	∼359	∼2.1
TB-3	34	2266 ± 276	357		∼100	∼457	90	∼367	∼1.6

TB = Tierra Bomba, PC = Punta Canoas, MM = Manzanillo del Mar, PO = Playa de Oro, LC = Loma del Caracol. Reservoir effect (ΔR) is −19 ± 23 (average value for the Caribbean, Stuiver and Reimer, 2005).

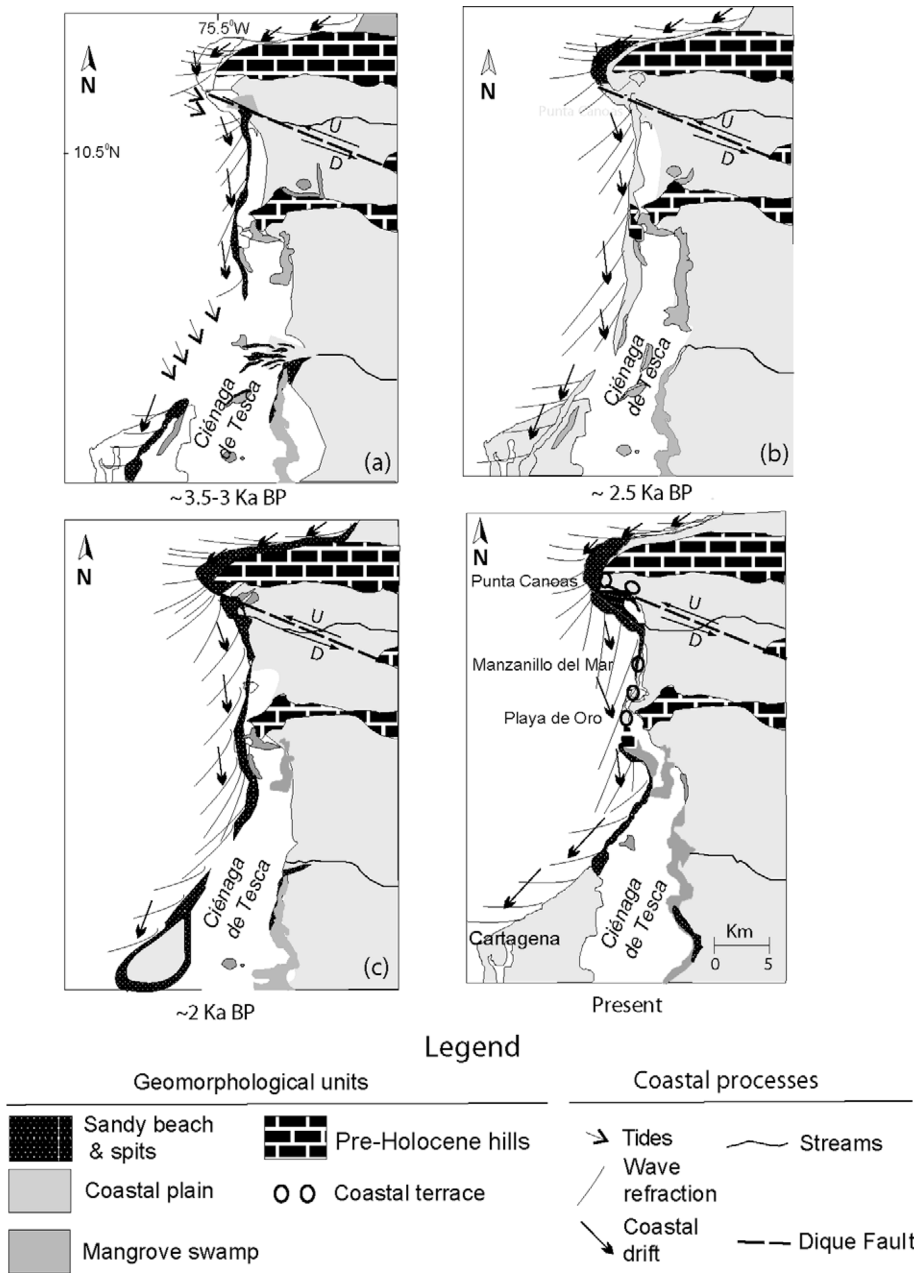

Fig. 7. Schematic late Holocene geomorphologic coastal evolution north of the Cartagena bay. (a) 3.5–3 ka, (b) ~2.5 ka, (c) ~2 ka, and (d) at present. Note the progressive closure of the Cienaga de Tesca coastal lagoon and the Dique Fault (dashed line).

thus resulting in a negative precipitation minus evaporation ($P - E$) balance and therefore, drier conditions and presumably strong El Niño phases (Haug et al., 2001). More dynamic Trade Winds would have forced longshore currents and a more efficient coastal drift of sediments (cf. Correa, 1990), though discharge and sediment load from the Magdalena River might have been reduced as is observed today during El Niño phase, when precipitation is low and the river transports <200 $\times$ 10^3 t day^{-1} (Restrepo and Kjerfve, 2000). Conversely, during La Niña phase the river transports three times more sediments, i.e. >600 $\times$ 10^3 t day^{-1} (Restrepo and Kjerfve, 2000) that apparently are episodically delivered to the sea (Restrepo et al., 2006). Expectedly, sediment drift would have been significantly reduced during the 3–2.5 ka interval. However, as it is observed today, the coastline between the Magdalena River mouth and Cartagena is highly dynamic in response to the accretion and erosion of sediments during La Niña and El Niño phases, respectively, e.g. for the 1942 and 1990 interval accretion of sediments on the bays was of the order of 27 myr^{-1}, whereas erosion on the heads reached 19 myr^{-1} (Correa, 1990). At a longer timescale, these same processes would have operated on the 3–2.5 ka interval, thus resulting in the accumulation of the terrace sediments and a net accretion of the coastline.

At Tierra Bomba Island, sample code 7 (Table 1) that lies out of sequence and is ~4000 yrs old, evidences the accumulation of a former terrace apparently reworked (by a hurricane?) within the <4 to >2.2 ka interval. This event is not recorded in the Punta Canoas – Manzanillo del Mar section because of their limited outcrops. By the end of the erosion interval, some reef patches grew on the area (section TB3, Fig. 2). This scenario remained until ~2.2 ka when clastic progradation covered the reefs, responding to a more dynamic Bocagrande spit (Fig. 1c) that even during historic times has episodically connected Tierra Bomba Island with the continent.

4.3. Sediment accumulation rates and tectonic upheaval

Sediment accumulation rates were estimated for each stratigraphic column from the difference in high (cm) between two consecutive calibrated radiocarbon dates over the difference in age (Table 2). Despite the apparent differences in the estimates, the large ranges of error and uncertainties, sediment accumulation rates were found to vary between ~0.02 to ~3.4 mmyr^{-1}.

Active diapirism and mud volcanism are common in the Colombian Caribbean (e.g. Duque-Caro, 1984; Vernette, 1989b), whereas the Dique Fault is an important component of the neotectonic activity in the Cartagena region (e.g. Ordoñez, 2008). A number of studies have documented the different tectonic settings, i.e. compressional and transpressional, north and south of the Dique Fault, respectively (e.g. Ruiz et al., 2000). However, it is the detailed neotectonic and geophysical study of Ordoñez (2008) that demonstrates that the Dique Fault is sinistral, rather than dextral, and fully documents the presence of mud diapirs north of it.

Evidences from Punta Canoas section, despite the fact that the Colombian Caribbean coast would lie within a IV zone (cf. Clark and Linge's, 1979 model), is in agreement with the neotectonic scenario presented by Ordoñez (2008).

We estimate upheaval rates using the maximum calendar year date and Eq. (1) (Page, 1983), previous correction for the hydro-isostatic effect for each date from the "*far-field*", tectonically stable, Brazilian curve (cf. Pirazzoli, 1991).

$$R = \frac{U - hi}{t} = \frac{(H + di) - hi}{t} \tag{1}$$

where R is the tectonic upheaval rate (mmyr^{-1}), U is the uplift difference as estimated between the present habitat of the mollusk and the height above sea-level. H is the terrace altitude above present sea-level, di is depth habitat of the fossil organism, hi is the hydro-isostatic factor from Clark and Linge (1979) model, and t is the age of the fossil. Errors involved in calculations are due to uncertainties in the depth habitats of fossil organisms and radiocarbon errors. Except for some taxa of benthonic foraminifera, the depth range of fossil invertebrates in the Cartagena region normally is so large that introduces a considerable error when estimating upheaval rates. In other words dt is larger than H and therefore our estimates should be considered only as semiquantitative approximations. Table 2 summarizes the sediment accumulation and upheaval rates for the Cartagena terraces. The highest upheaval rates were found in the Punta Canoas (3.78 mmyr^{-1}) and Tierra Bomba (3.11 mmyr^{-1}) terraces, compared to much lower rates at Manzanillo del Mar and Playa de Oro terraces (~1.5 mmyr^{-1}). Even bearing in mind uncertainties in upheaval estimates the former terraces were tectonically uplifted. Conversely, a coastal lagoon might have occupied the Manzanillo del Mar and Playa de Oro sector. Analogous late Holocene upheaval rates have been reported elsewhere, e.g. Portugal (Granja and De Groot, 1996), Sicily (Antonioli et al., 2003).

5. Conclusions

Evidence presented herein suggests that:

(1) The Punta Canoas, Manzanillo del Mar, and Playa de Oro successions (parasequences) were deposited in a clastic depositional system compared to the Tierra Bomba Island succession that was deposited in a carbonate depositional system during the late Holocene, i.e. between ~3.6 and ~1.7 ka.
(2) Drier conditions and the southern location of the ITCZ ~3 ka triggered stronger easterly Trades and more dynamic sediment southwest drift fed by sediment yield from the Magdalena River, thus promoting the formation of sand spits that ultimately isolated the Cienaga de Tesca coastal lagoon from the Caribbean Sea.
(3) Recent tectonism is responsible of the upheaval of the terraces, from 3.78 mmyr^{-1} at Punta Canoas and 3.11 mmyr^{-1} at Tierra Bomba to ~1.5 mmyr^{-1} at Manzanillo del Mar and Playa de Oro terraces.
(4) Our results are in agreement with the contention that the Dique Fault and the extensive mud volcanic activity are the mechanisms responsible of the upheaval of the low-level terraces.

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