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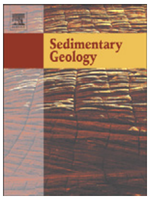

Development of a Pliocene mixed-carbonate siliciclastic reef (Limon, Costa Rica)

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ABSTRACT

The Miocene to Pleistocene Limon Group of Costa Rica is a mixed carbonate–siliciclastic succession that formed in association with the emergence of the Central American Isthmus. Our study focuses on a lower Late Pliocene reef unit, the newly excavated Contact Cut, which is located at the contact between the siliciclastic sediments of the Rio Banano Formation and the mixed reefal and coral bearing deposits and siliciclastic sediments of the Quebrada Chocolate Formation. The siliciclastic sediments were deposited in a thick, deltaic setting sourced by erosion of the Cordillera de Talamanca. Deposits of the Limon Group preserve a sequence of progressively shallowing, near-shore sediments that were exposed by uplift during the early to middle Pleistocene.

The Contact Cut outcrop shows the first reef sequence in the stratigraphic sequence and thus illustrates the reestablishment of Caribbean coral reef predominance in the Neogene. It shows extensive reef growth during a rise in sea level and a slight progradation during the succeeding sea-level highstand. Three stages of reef evolution are recognized based on faunal diversity. The Contact Cut reef complex is comparable to the time equivalent reef of the Las Islas roadcut, situated west of Limon, which shows a rapid burial of the corals by siliciclastics. Both reefs document a distinct facies diversification during the final stages of the closing of the Central American Seaway. The reefs developed in an environment stressed by siliciclastic input, which ultimately caused a decrease in coral diversity and abundance followed by a temporary demise of the reefs. The biotic composition of the patch reefs that occurred during the sea-level rise, Las Islas and Contact Cut, did not differ from the reefs that developed during the final highstand in sea level, the reefs of the overlying Moin formation (Limon Group). Differences in the position on the shelf relative to the source of the siliciclastics might have been the cause for the different response to the rise in sea level of the transgressive reefs, with a very fast give up scenario for Las Islas reef and a catch up followed by a give up phase for Contact Cut reef.

1. Introduction

1.1. Tectonics

In the literature two different models are discussed to explain the plate tectonic evolution of the Caribbean plate. The “Pacific Model” proposes a Late Mesozoic origin of the Caribbean ocean crust in the Pacific region and describes its drift into its present position between North- and South-America (Pindell and Dewey, 1982; Burke et al., 1984; Pindell, 1985, 1994). The “inter-American Model” proposes the formation of the Caribbean crust in a position in-between the two Americas but west of its present position (Klitgord and Schouten, 1986; Frisch et al., 1992; Meschede et al., 1997; Meschede and Frisch, 1998). In this study we follow the inter-American-position model as described in detail by Meschede and Frisch (1998). These authors proposed that during the Late Oligocene to Early Miocene, the Farallon plate split itself (Fig. 1) into a NNE moving Cocos plate and an eastward moving Nazca plate (Hey, 1977). The present day northward convexity of the Panama Arc is due to the westward drift of the South America plate and the collision of the Panama arc and the Western Cordillera (Meschede and Frisch, 1998). Coates et al. (2004) stated that the collision between the eastern part of the Central American Arc and the Western Cordillera took place between 12.8 and 9.5 Ma, and that the Central American arc gradually became emergent before the initial collision, as of ~16 Ma. This gradual shoaling process is shown by a shallowing from lower- and middle-to upper bathyal, and outer neritic waterdepth in the southern Limon and Bocas del Toro Basins. The first exchange of terrestrial faunas between North and South America, raccoons and ground sloths, occurred around 9.3 Ma to 8 Ma (Marshall et al., 1979; Marshall, 1985). Coates et al. (2004) showed that at 6 Ma the last definitive deep-water connection existed between the Pacific and Atlantic. This is also shown by the analyses of

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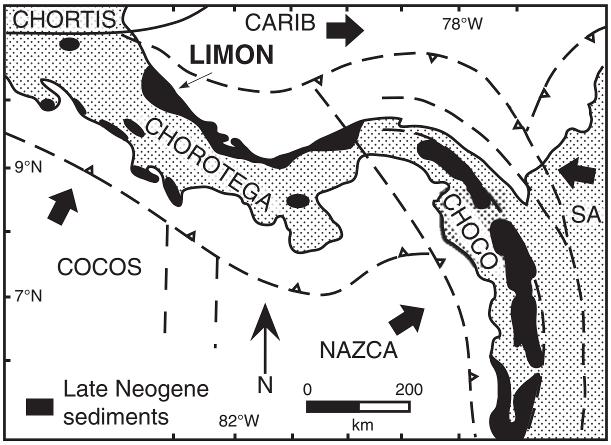

Fig. 1. Simplified regional tectonic and location map of the Central American Isthmus. The study area near Limon, Costa Rica, forms part of a major late Neogene sedimentary basin on the Caribbean side of the isthmus (modified from McNeill et al., 1997). Large black arrows indicate plate movement direction, after Duque-Caro (1990).

benthic foraminifer fauna (Collins et al., 1996), and by the deposition of inner neritic sediments that overly upper bathyal sediments in the Panama Canal Basin. These events correspond with a relative global rise in sea level (Haq et al., 1987). Coates et al. (2004) proposed that a eustatic rather than a tectonic event resulted in breaching the Isthmus of Panama that locally introduced Pacific faunas to the Caribbean. The Isthmus of Panama was the last part of the Central American Isthmus that became emergent (Coates and Obando, 1996). The last breach of the Isthmus occurred at 6 Ma, which was succeeded by the final closure of the Isthmus between 3.2 and 3.0 Ma (Keigwin, 1978, 1982; Haug and Tiedemann, 1998; Steph et al., 2006).

1.2. Paleoceanography

A series of studies have shown that the environmental conditions in the eastern Pacific and the Caribbean were fairly homogenous before the closure of the Central American Seaway (Collins et al., 1996; Terranes et al., 1996; Haug and Tiedemann, 1998; Jackson and Herrera-Cubilla, 2000; Kameo and Sato, 2000). The shallowing of the gateway resulted in an intensification of the Gulf Stream (Maier-Reimer et al., 1990) and led to increased North Atlantic Deep Water (NADW) formation around 2.8 Ma in the Labrador Sea and the Greenland–Norwegian Sea (Haug and Tiedemann, 1998). Coupling of the Northern Hemisphere glaciation (3.2 Ma) with the closure of the Isthmus of Panama led to reoccurring ice ages that interrupted the warm climate of the early to middle Pliocene (e.g. Maier-Reimer et al., 1990; Haug and Tiedemann, 1998). The closure of the seaway not only had an impact on the hydrography and the carbonate environments in the Pacific and Caribbean region around Costa Rica and Panama (Coates and Obando, 1996; Jackson and D`Croz, 1997; Haug and Tiedemann, 1998), but also influenced the entire Caribbean (Budd et al., 1996, 1998; Jackson, 1997; Reijmer et al., 2002).

At present oligotrophic conditions with accelerated reef growth prevail (D`Croz and Robertson, 1997; Ginsburg, 2001) in the tropical carbonate environments of the Caribbean. On the Pacific side warm-temperate carbonate production may prevail, as for example in the Gulf of California (Halfar et al., 2000, 2001, 2005) and the Gulf of Chiriqui and the Gulf of Panama (Reijmer et al., 2011). However, on the continental shelves of North, Central and South America carbonate environments are rare due to high terrigenous input associated with the tectonically active margins and regional upwelling effects (Halfar et al., 2000). It is the start of carbonate production after the full closure of the Central American Seaway that we want to assess in this manuscript. A comparison will be made with earlier studies on the reef development in Costa Rica (McNeill et al., 1997, 2000).

1.3. Regional setting

The Cordillera de Talamanca volcanic arc initiated in the late Cretaceous as a result of subduction between the Farallon, Cocos, and Nazca plates (Coates and Obando, 1996; Meschede and Frisch, 1998). Subduction of the aseismic Cocos Ridge has produced uplift of the basement and sedimentary basins on both flanks of the Costa Rica–Panama microplate (Collins et al., 1995). Neogene forearc (Pacific) and backarc (Caribbean) sedimentary basins formed on both sides of the volcanic arc (Fig. 1). Through the late Miocene, restricted marine connections existed between the marine basins on both sides of the arc (Coates et al., 1992; Coates and Obando, 1996). As volcanism and uplift continued, the Central American archipelago developed and the southern Limon back-arc basin became progressively shallower. The Neogene Limon Group of the southern Limon Basin contains the Uscari, Rio Banano, Quebrada Chocolate and Moin Formations (McNeill et al., 1997, 2000; Coates, 1999).

The sediments of the Limon Group reflect the regional emergence of the Isthmus of Panama in the transition from bathyal to middle-shelf depths in the lower and middle Miocene to marginal-marine and deltaic environments of the overlying lower Pliocene Rio Banano Formation. Major streams and marine deltas to the north and south of Limon and river mouth migration controlled the deposition of boulder conglomerates and well developed channel cut-and-fill structures. Variations in the river systems control the upper Neogene geologic history of Limon. The streams formed as a result of the uplift of the Cordillera de Talamanca and not only caused increasing shoaling of the depositional environments around Limon, but also resulted in the input of relative large amounts of sediment in the entire area (Taylor, 1975). Siliciclastic deposition alternated with coral reefs as fairly broad sheets of sediment periodically smothered existing reef trends. In the vicinity of Limon, marine deposition continued until the early Pleistocene, forming shallow-water, brackish and normal marine mudstone, sandstone and reef deposits that represent lagoonal, mangrove, and shallow shelf habitats, interfingering with a variety of tabular and patch reefs (Coates et al., 1992).

A detailed study by McNeill et al. (2000), combining litho- and biostratigraphy with paleomagnetic analysis, of the upper Neogene sediments of the region immediately west of Limon, confirmed the Moin Formation as the youngest unit of the Limon Group. These authors also added a new unit, the Quebrada Chocolate Formation to those defined by Taylor (1975) and Coates et al. (1992). The Quebrada Chocolate Formation conformably underlies the Moin Formation and contains the Buenos Aires Reef Member, the focus of this study. Outcrops in the Limon region and other tropical settings are often rare due to intense weathering and heavy vegetation. This study was made possible because of intense land clearing and excavation exposing the internal configuration of the investigated Quebrada Chocolate Formation reefs.

1.4. Quebrada chocolate formation

The Quebrada Chocolate Formation crops out and is exposed in excavations in the area west of Limon and south of Puerto Moin along Chocolate Creek and along Route 32 (Fig. 2). The sediments are latest early Pliocene to earliest late Pliocene in age and deposits of the Quebrada Chocolate Formation overlie the sediments of the Rio Banano Formation and underlie those of the Moin Formation.

McNeill et al. (2000) placed the contact between the Rio Banano Formation and the overlying Quebrada Chocolate Formation at the waterfall within Chocolate Creek and stated that the contact between the Buenos Aires Reef Member and the Rio Banano Formation may be diachronous. The newly discovered Contact Cut outcrop is situated in

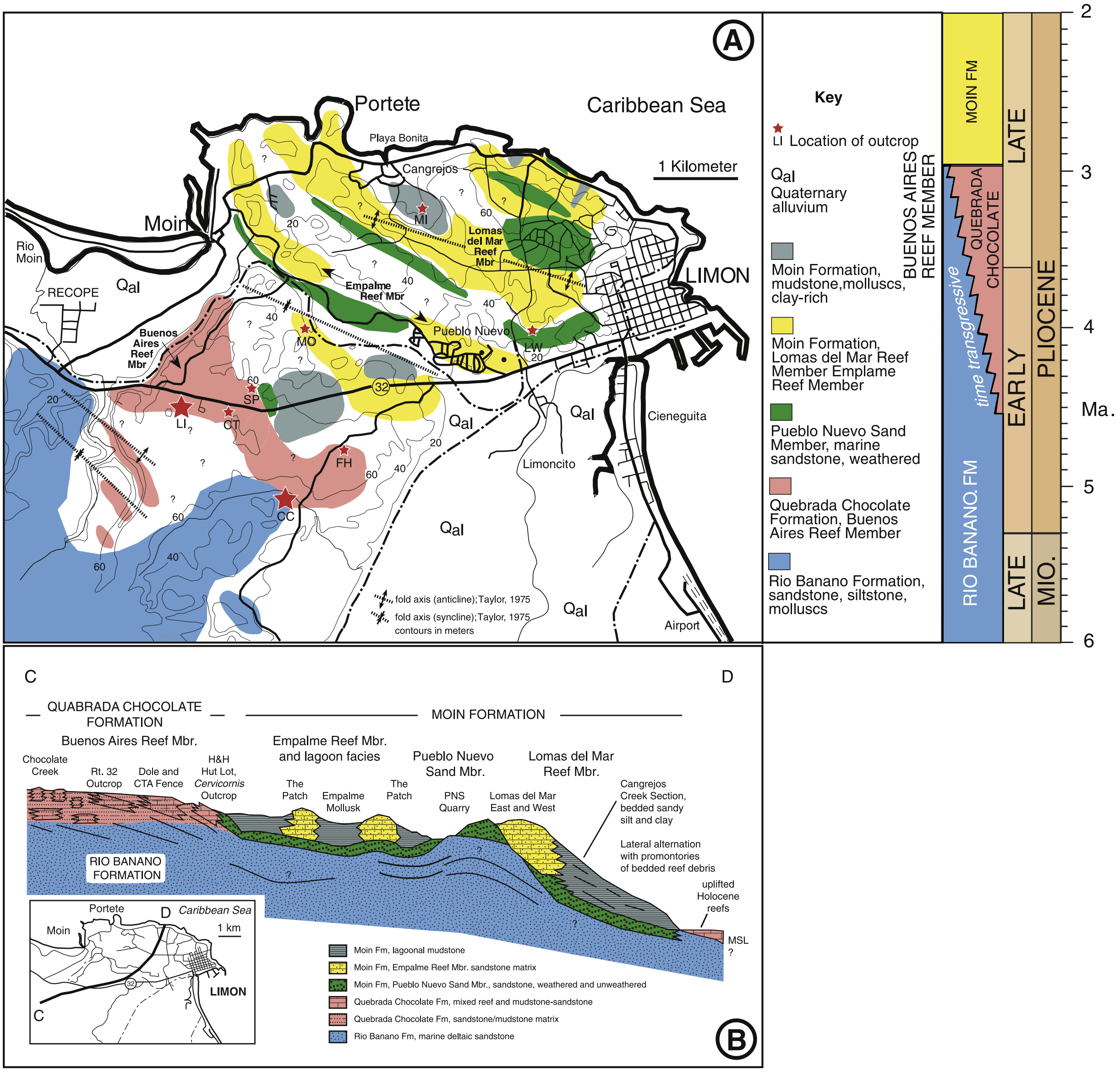

Fig. 2. (A) Geology in the Area of Limon, Costa Rica. Studies focused on two outcrops within the Quebrada Chocolate Formation. The Las Islas (LI) roadcut along Route 32 and the newly discovered Contact Cut (CC). Map modified from McNeill et al. (2000). (B) Schematic cross section of regional stratigraphic relationships after McNeill et al. (2000). The deltaic silt and sandstones of the Rio Banano Formation are overlain by the Buenos Aires Reef Member (Quebrada Chocolate Member) and the marine sandstones from the Pueblo Nuevo Sand Member (base Moin Formation). These are succeeded by the lagoonal mudstones and Lomas del Mar and Empalme Reef Members (Moin Formation).

the contact zone between the Rio Banano Formation and the Buenos Aires Reef Member of the Quebrada Chocolate Formation.

The Quebrada Chocolate Formation shows reef-derived carbonate debris ranging from branching corals to carbonate-reef build-ups with minor siliciclastics or reef patches with abundant siliciclastics (Fig. 2). A detailed description of the sediments within the Quebrada Chocolate Formation can be found in McNeill et al. (2000).

1.5. Buenos Aires reef member

The top of the Quebrada Chocolate Formation consists of a series of extensive tabular reefs and reef patches, as described in this study, which is defined as the Buenos Aires Reef Member. It is named after the village of Buenos Aires, on Route 32 six km west of Limon, where it forms a low but distinct topographic feature (Coates et al., 1992). The type section is located along Route 32 from Buenos Aires to about 1.2 km east of where the Old Moin road meets Route 32. The Buenos Aires Reef Member is about 140 m thick and consists of a series of coral thickets with a silt–clay matrix, dominated by *Porites* sp., *Acropora* sp., *Stylophora* sp., *Caulastrea* sp., and *Avaricious* sp. Interbedded within the reefs are coral- and mollusc-rich carbonate sandstone and siliciclastics (Coates et al., 1992; McNeill et al., 2000).

2. Methods

2.1. Studied outcrops

The two locations analyzed in this study are the newly discovered Contact Cut outcrop and the Las Isla roadcut outcrop along Route 32 (Fig. 2). Both sections are situated within the Buenos Aires Reef Member of the Quebrada Chocolate Formation.

The Contact Cut outcrop (CC) is located South-West of Limon, at 09° 58.553′N/83° 04.083′W, on a construction site next to the road from Santa Rosa to Pueblo Nuevo. The newly excavated site revealed an extensive reefal zone within the Buenos Aires Reef member immediately overlying the contact with the Rio Banano Formation.

The Las Isla roadcut (LI) is located at 09° 59.066′N/83° 05.306′W, west of Limon. Extensive land clearing and excavation has greatly improved the exposure of this outcrop that previously was described by McNeill et al. (1997, 2000). The analysis of this roadcut outcrop started at the base of the Quebrada Chocolate Formation through the Buenos Aires Reef member. The reef complex, as described by McNeill et al. (1997), shows a fringing reef with slope, reef-front and reef-crest and a transition to a barrier-reef morphology.

2.2. Sediment analysis

More than 250 sediment samples were taken during the field expedition in March 2004. In total 10 locations southwest of Limon were sampled. Over 120 samples originate from the newly discovered Contact Cut site and the Las Isla roadcut, previously described by McNeill et al. (1997, 2000) as Route 32 roadcut. Forty-nine thin sections were analyzed of the carbonate–siliciclastic mixed sediments. The grains within the thin sections were counted and quantified as the percentage out of the total amount of counted grains present within one thin section. In each thin section 300 points where counted and the biota was described after Scholle and Ulmer-Scholle (2003). The counted grains were divided into red algae, foraminifera, gastropods, bivalves, echinoderms, corals, siliciclastic grains and non-determinable grains. In addition, 200 fossil samples were collected, e.g. corals, gastropods to bivalves. Thin sections and fossil samples were used to obtain a detailed overview of the biotic contents of the individual sedimentary units. The morphologic characteristics of the collected fossils were examined to determine the different genera and communities within the reefs. The morphometric methods in species recognition were used as discussed in Budd and Coates (1992).

3. Results

3.1. Contact cut (CC)

The sediments of the Rio Banano Formation at the base of the outcrop consist of organic rich clayey siltstones that grade to siltstones, light gray to light brown at the base and blue-dark gray at the top. The siltstones contain abundant molluscs, shell fragments, and bryozoans with *Callianassa* sp. and *Thalassinnoides* burrows. The reef facies is time equivalent (Fig. 2) to sediments described from the siliciclastic Quitaria section (3.7–3.5 Ma) by McNeill et al. (2000) within the Rio Banano Formation. The Quitaria section, sampled and dated by Coates et al. (1992), was redated by McNeill et al. (2000) using microfossils, paleomagnetic and strontium-isotope measurements and the age date was revised to the timescale of Berggren et al. (1995). This age confirms the time transgressive nature of the Quebrada Chocolate Formation (Fig. 2).

3.2. Facies description

The Contact Cut patch reef complex at the base of the Quebrada Chocolate Formation shows different coral community zones through three different stages in the evolution of the patch reef. The CC outcrop excavation nicely reveals the interfingering of carbonates with siliciclastics. The coral community and matrix sediment changed through time and show three main diversity/abundance stages (Figs. 3, 4, 5). Stage 1 represents the first occurrence of corals as isolated patches with a siliciclastic matrix of mud and fine sand that is similar to the underlying Rio Banano Formation. Stage 2 is marked by a diversification in coral species as well as an increase in size of the reef build-ups. Stage 3 is marked by a decrease in coral diversification and reef size (Figs. 3, 4), as only a few coral patches remain in a siliciclastic-dominated setting.

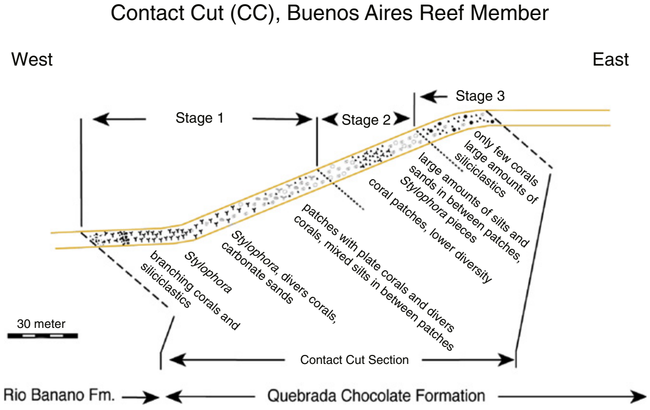

Fig. 3. Contact outcrop (CC), showing the three different stages, note diminishing of corals in amount and diversity and the increase in siliciclastics from stage 1 to 3.

Stage 1 shows the development of moderately diverse coral reefs admixed with siliciclastics. Three lateral facies (A-C) are recognized. Facies 1A marks the deeper forereef and is characterized by abundant branching corals, especially *Stylophora* sp. Siliciclastic mud forms the matrix sediment in Facies 1A. Facies 1B contains *Porites* sp., *Agaricia agaricites* (Fig. 5B), and *Dichocenia stokesi* (Fig. 5C). Facies 1C contains corals more suited for a back reef setting; these include *Dichocenia* sp., *Manicina areolata*, and *Siderastrea siderea*. Facies 1C is dominated by back-reef patches with a relatively high diversity of massive corals (Table 1). The patches measure 1 to 4 m high and 2 to 15 m wide as seen in the excavated outcrop. In between these patches fine-grained sediment is mixed with fragments of branching *Stylophora* sp (Fig. 5E). The matrix sediment between the patches consists of mostly carbonate mud with less than 30% siliciclastics. Thin sections of the sediment between the patches show a small percentage (<5%) of skeletal grains, mainly red algae, foraminifers, molluscs and echinoderms. The quantity of siliciclastics in this facies decreases upward toward the second stage in reef development. A mollusc horizon with up to 55% bivalves (in thin section) marks the end of this first reef stage (Fig. 4).

The second stage of reef accumulation is marked by a slight decrease in coral diversity and a change to a sand-dominated matrix. The placement of the boundary between Stage 1 and Stage 2 is based on the change in size (from mud to sand) of the siliciclastic grains.

Stage 2 contains reef front/reef crest and back reef facies. The forereef branching coral zone seen in Stage 1 is greatly diminished to absent. It appears that this Stylophora coral zone is considerably less well developed or absent altogether. Only a few fragments of Stylophora occur on the seaward side of the reef front facies. The reef front and back reef facies show a slight decrease (relative to Stage 1) in diversity of the corals, especially the head corals. Common in the reef front are the corals *Dichocoenia stokesi*, *Diploria labyrinthiformis* (Fig. 5D), *Montastrea cavernosa* and just a few *Stylophora* sp. fragments. The common gastropods found are Murexiella keenae, *Conus (Lithoconus) archon* and *Cerithicum (Thericium) nicaraguense*. The bivalves are mainly represented by *Chione compta* and *Ensis tropicalia*. *Dichocenia* sp. and *Porites* sp. dominate the reef crest facies. The back reef consists of small patches of coral. The patches are smaller than those in Stage 1, measured from 1 to 3 m high and 2 to 6 m wide. The most common corals are *Solenastrea bournoni*, *Siderastrea siderea*, and *Dichocoenia stokesi*. Between the back reef patches, the sediment is predominantly carbonate sand but the amount of siliciclastic sediment increases from ~10% at the base to ~40% at the top of the Stage 2 deposit. The inter-patch sediment also contains occasional pebble-sized volcanic clasts, often coated with carbonate. The carbonate skeletal components (as a percentage of the total in thin section) consist of red algae (20%), benthic foraminifers

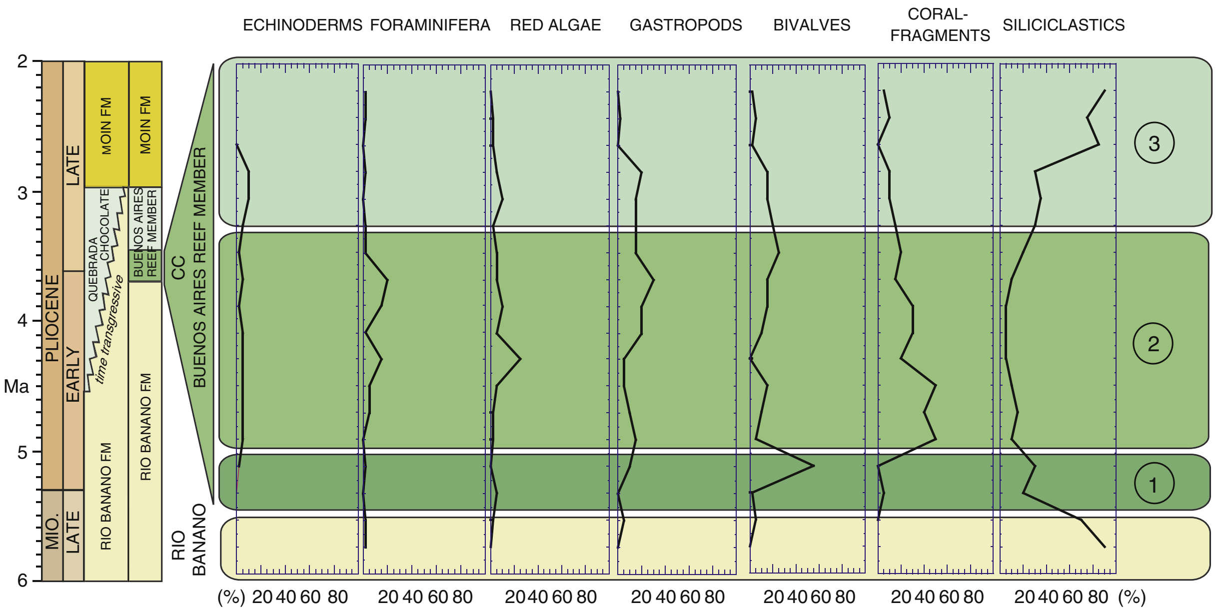

Fig. 4. Thin section point-count results from selected back reef samples of the Contact Cut outcrop. Stratigraphy and timetable based on McNeill et al., 2000. Stage 1: few siliciclastics and coral fragments, a mollusk horizon with higher abundance of siliciclastics at the top; Stage 2 shows an increase in siliciclastic input towards stage 3, high abundance of coral fragments. In stage 3 the reef becomes buried by siliciclastics, slight increase in echinoderms.

(10%), and mollusc or echinoderm fragments (up to 15%). Several molluscs were common in the back reef facies; they include the gastropods *Conus (Ximeniconus) perplexus* and *Strombus graceilior*, as well as the bivalve *Glycymeris delessertii*.

The third stage of the reef complex consists of a mixed carbonate–siliciclastic back reef coral patch facies. In this stage only a few remnants coral heads remain. Although relatively diverse (5 species) the quantity of coral in the outcrop is low. *Solenastrea bournoni*, *Manicia areolata*, *Siderastrea* siderea, *Dichocoenia eminensi* and *Diploria labyrinthiformis* are the species present. These species are typical of shallow, restricted conditions. Thin sections show an upward increase in siliciclastics (40% to 90%) and a decrease in skeletal allochems (Fig. 4).

3.3. Las Isla roadcut (LI)

The sediments at the base (Stage 1) of the Las Isla roadcut (Fig. 6) directly overlying the top of the Rio Banano Formation consist of siliciclastics (silt to sand) with abundant benthic foraminifers, predominantly *Amphistegina* sp. and *Bolivina* sp. Red algae are also

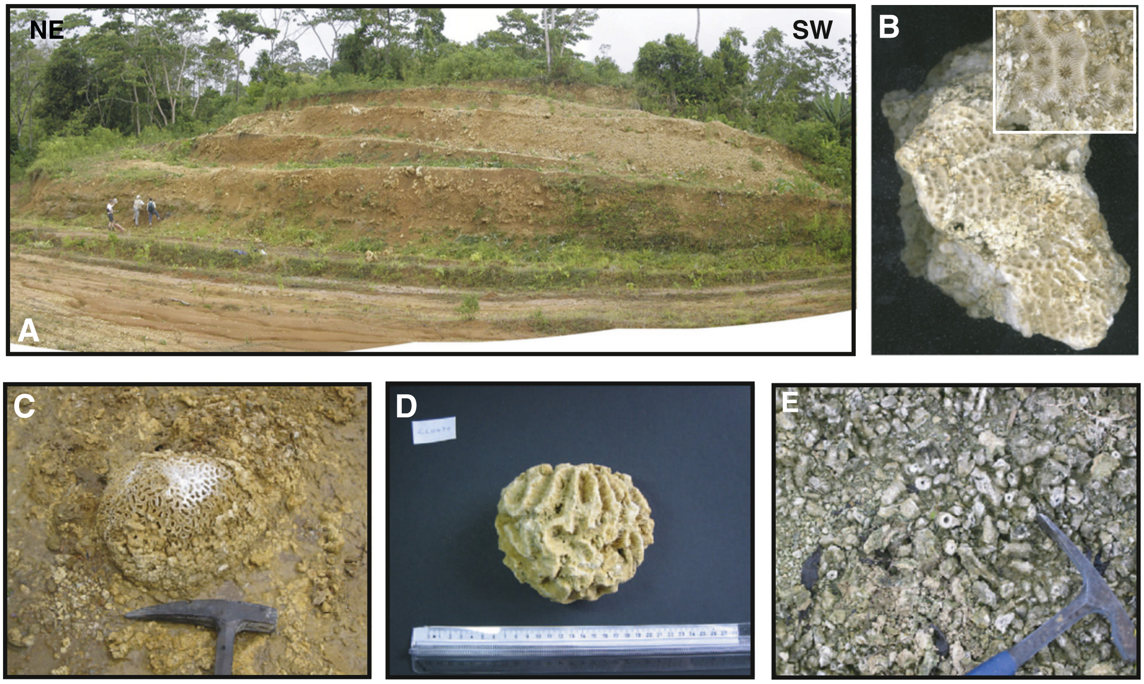

Fig. 5. Contact Cut outcrop (CC): Contact Zone between the Rio Banano Formation and the Buenos Aires Reef Member of the Quebrada Chocolate Formation: (A) Panorama view of CC outcrop; (B) *Agaricia agaricites;* (C) *Dichocoenia stokesi in situ*; (D) *Diploria labyrinthiformis*; and (E) *Stylophora* sp. within patch reef of stage 1 (CC).

Table 1
Contact cut.

	Slope / Reef front	Reef Crest	Outer back-reef
Stage 1			
Corals	*Diploria labyrinthiformis*	Agaricia agaricites	*Dichocoenia* sp.
	Diploria sarasotana	*Dichocoenia stokesi*	*Dichocoenia stokesi*
	Diploria zambensis	*Porites* ssp.	*Diploria labyrinthiformis*
	Montastraea cavernosa		*Manicina areolata*
	Stylophora ssp.		*Siderastrea siderea*
			Solenastrea bournoni
Gastropods	*Bulla punctulata*		
	Fossaridae		
	Semele junonia		
Bivalves	*Chione compta*	*Macoma siliqua*	
	Macoma siliqua		
Interpretation: shallow reef environment, slope with fringing reef, max. waterdepth 30 m.			
Stage 2			
Corals	Dichocoenia stokesi	*Dichocoenia stokesi*	Dichocoenia stokesi
	Diploria labyrinthiformis	*Dichocoenia eminens*	*Siederastrea siderea*
	Montastraea cavernosa	*Porites* ssp.	*Solenastrea bournoni*
	Stylophora ssp.		*Diploria clivosa*
Gastropods	*Cerithium nicaraguense*		*Conus perplexus*
	Conus archon		*Strombus graceilior*
	Murexiella keenae		
Bivalves	*Chione compta*		*Glycymeris delessertii*
	Ensis tropicalia		
Interpretation: shallow reef environment, beginning of siliciclastic input, transition fringing to barrier reef, close to coast, max. waterdepth 20 m.			
Stage 3			
Corals	n.a.	n.a.	*Dichocoenia stokesi*
			Diploria labyrinthiformis
			Manicina areolata
			Siderastrea siderea
			Solenastrea bournoni
Gastropods	n.a.		*Strombus graceilior*
			Conus perplexus
Bivalves	n.a.		*Glycymeris delessertii*
			Ensis tropicalia
			Vermetus sp.
Interpretation: shallow reef environment, strong siliciclastic input, transition fringing to barrier reef, close to coast, max. waterdepth 20 m. (n.a.: not applicable).			

common and only a few fragments of corals were found. The thin sections show up to 40% foraminifers, mainly *Amphistegina* sp. and up to 40% red algae. On top of this unit the first reefal unit occurs (Fig. 6), which is dominated by branching corals *Stylophora* sp. (McNeill et al., 1997). This interval is about 15 to 20 m thick.

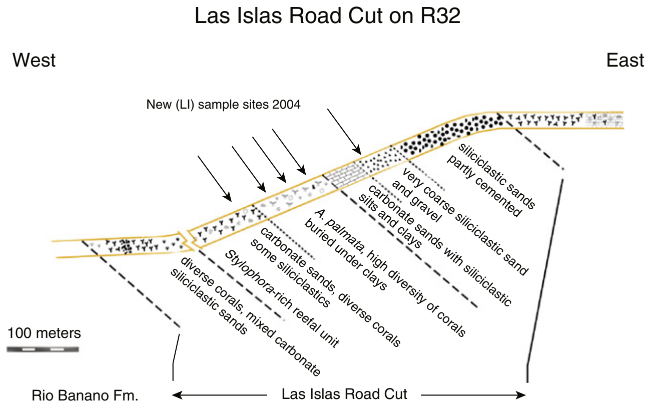

Fig. 6. The Las Islas (LI) Road Cut, showing location of *Stylophora* reefal unit and new sampling sites from 2004.
Modified after McNeill et al., 1997.

The succeeding main reef unit (Stage 2) shows a high diversity in corals, i.e. *Diploria* sp., *Porites* sp., *Isastrea* sp., *Mycetophyllia danaa*, *Montastrea* sp. and *Acropora palmata* on top of the reef-crest. McNeill et al. (2000)report a mixed coral unit with a high coral diversity (39 coral species, 61.5% extant). The corals grow in large closely spaced colonies. The sediments in between the colonies are fine to coarse siliciclastics with subordinate carbonate sand. The thin sections show only a few red algae and benthic foraminifers (5% to 25%). The gastropods show a diverse composition and common bivalves include are *Chione* sp. and *Trigoniocardia biangulata*.

Thin sections from the reef-crest showed abundant coral fragments embedded in a clay- to silt-sized siliciclastic sediment. The excellent preservation of the fronds and little to no micro or macro boring suggests that the corals were rapidly buried (McNeill et al., 1997). Red algae crusts occur frequently on these corals. One thin section showed up to 50% encrusting red algae.

On top of the crest only remnants of corals and coral fragments were found (Stage 3). During this stage the facies changed into mixed carbonate–siliciclastic sediment with minor corals, with increasing siliciclastic content to the top from very coarse siliciclastic sand to gravel.

4. Discussion

4.1. Paleodepth

The biotic community of corals, gastropods and molluscs suggests a maximum paleo-water depth of 30 m for the first stage of reef development (Tables 1 to 3). During the second stage of reef development, the biotic community shows a shallower environment with a maximum depth of 20 m for the branching coral zone on the reef front. The frequent occurrence of *Diploria* sp. on the reef front supports a depth <20 m. The comparison of the fossil coral community with recent reef communities (Zlatarski and Estalella, 1980) and the occurrence of the primary reef-builders *Agaricia agaricites* and *Porites* sp. on the modern reef crest suggest a paleo-water depth closer to 5–7 m for the reef crest facies (Riegl et al., 2003). This estimate agrees with the observations of a developing reef flat and back reef facies. The species occurring in Stages 2 and 3, *Diploria clivosa* and *Solenastrea* sp. are found today in backreef settings with a

Table 2
Living space of molluscs found at Contact outcrop and Las Isla roadcut.

Species	Habitat
Bulla punctulata	Offshore beyond low-tide limit, muddy ground
Cerithium nicaraguense	Intertidal and offshore to 37 m
Columbella major	Under rocks, tidal zone
Columbella strombiformis	Under rocks, tidal zone
Conus archon	Mostly offshore to 26 m; and 400 m
Conus perplexus	Mostly on sandbars, also offshore to 37 m
Fossaridae	
Murexiella keenae	Intertidal and offshore to 33 m
Oliva polpasta	Muddy environments
Semele junonia	Offshore to 70 m
Strombus granulatus	Muddy to sand in community with Thalassia
Strombus graceilior	Offshore to 45 m, more protected environment, Thalassia, on sand flats and lagoons
Trivia radians	Intertidal, muddy, soft sediment under rocks
Turitella ssp.	5 m to 130 m
Vermetidae	Mostly cemented to rocks, sand to gravel
Cardids biangulata	Intertidal and depths to 115 m
Chione compta	Mostly offshore 22–27 m
Chione mariae	Mostly offshore in depths to 110 m
Ensis tropicalia	Sandy bottom, 11 m to 25 m
Glycymeris delessertii	Muddy to sandy ground, most offshore to 30 m, occurrence of single shells very common in beach drift
Scaphopods	
Macoma siliqua	Depths up to 110 m

Table 3
Average living depths of corals, habitat and their fossil record.

Species	Average water depth[a]	Habitat	Tertiary to Quaternary fossil record of genus
Acropora palmata	2–14	Shallow outer reef slopes exposed to wave action	Eocene – to this day
Agaricia agaricites	6–15	Shallow reef environments	Miocene – to this day
Dichocoenia caloosahatcheensis		Most reef environments	Pliocene – Pleistocene
Dichocoenia eminens		Most reef environments	Pliocene – Pleistocene
Dichocoenia stokesi	6–23	Most reef environments	Eocene – to this day
Diploria clivosa	2–6	Most reef environments, especially shallow slopes and lagoons	Eocene – to this day
Diploria labyrinthiformis	8–14	Shallow reef environments	Eocene – to this day
Diploria sarasotana		Shallow reef environments	Pliocene
Diploria zambensis		Shallow reef environments	Miocene – Pliocene
Manicina areolata	8–19	Subtidal sea grass beds where colonies are small and free-living; also shallow reef environments where colonies are attached and become hemispherical; lagoons	Oligocene – to this day
Montastraea cavernosa	9–32	All reef environments, especially lower slopes	Eocene – to this day
Mycetophyllia reesi	17–20	Lower reef slopes protected from wave action	Oligocene – to this day
Porites ssp.[b]	2–15	Most reef environments	Eocene – to this day
Siederastrea siderea	7–24	Shallow reef environments	Cretaceous – to this day
Solenastrea bournoni	2–5	Shallow turbid environments including sea grass beds and reef lagoons	Oligocene – to this day
Stephanocoenia duncani		Shallow reef environments	Pliocene – Pleistocene
Stephanocoenia ssp.[b]	12–30	Shallow reef environments	Eocene – to this day
Stylophora ssp.		Most reef environments, sloping rock facies	Paleocene – to this day

[a] Average depth of recent corals ascertained after Zlatarski and Estalella (1980).

[b] Identified in outcrop, impossible to retrieve sample.

water depth ranging from 2 to 7 m (Zlatarski and Estalella, 1980; Table 3).

During the 1st and 2nd stages of reef development the main carbonate producers and reef-builders are the branching coral *Stylophora* sp. on the reef front, and *Porites* sp. and *Agaricia agaricites* (Fig. 5) on the reef crest. Towards the reef flat lagoon, the production rate decreases (McNeill, 2005). The increased reef growth accompanied by high carbonate production rates for the reef crest during the first reef phase led to a general shallowing of the reef.

4.2. Sea level and increased siliciclastic input

A rise in sea level is proposed for the early/late Pliocene (Haq et al., 1987) followed by a sea-level highstand observed in “highstand-reefs” of the Moin Formation (Limon Group) (McNeill et al., 2000). Stage 1 of the reef represents the catch-up phase of the reef (Schlager, 1981) in which reef growth likely exceeded sea-level rise. The succeeding slow rise in sea level gave the reef enough time to grow and during this time interval, carbonate production exceeded sea-level rise (Eberli and Ginsburg, 1989). As a result, the reef nearly caught-up with sea level (Fig. 7). The reef crest with the main carbonate-producing organisms accumulated faster relative to the reef-front and reef flat, so that a back reef environment developed behind the crest.

The 2nd reef stage is characterized by the development of an outer back reef facies with a large diversity of coral patches. It evolves directly after the mollusc horizon.

A high input of coral rubble from the reef front as well as an increase of siliciclastics with upwards-increasing grain size is observed towards the 3rd stage of reef development.

The 2nd and 3rd stages reflect a sea-level highstand and the progradational configuration in the outcrop suggests an overproduction of sediment that filled accommodation space. An increase in siliciclastic input starting in stage 2 and culminating during stage 3, deposits a blanket of sediment over the back reef facies and finally the reef crest, restricting coral growth more and more.

4.3. Coral depth zonation

A large variety of corals were present in the outcrops studied. In their study of 49 different recent reefs around Cuba, Zlatarski and Estalella (1980) very precisely described the depth zonations of a large series of coral species. Using the averaged depth values of the individual coral heads as indicated in that study (see their Table 2; our Table 3) allowed us to determine the individual growing zones of the coral communities in the Pliocene reefs of Costa Rica. The estimation of the precise paleodepth also helped to understand the evolution in time of the reef types encountered. Some differences exist between the species found in the Pliocene outcrop and the ones described in literature. For our depth analysis and environmental interpretation we assumed that the same genus of corals in the Pliocene and those that occur at present, grow in similar and comparable water depths. The Pliocene communities were primarily dominated by *Stylophora* sp. and *Goniophora* sp. with some agariciid and poritid species. This reflects rather a modern Indo-Pacific coral community than a Caribbean one. Modern Caribbean reefs are dominated by *Diploria* ssp., *Acropora* ssp, and *Montastrea* ssp.

After the late Cenozoic emergence of the Central American Isthmus several significant changes in the shallow-marine biotic communities around tropical America occurred (Coates et al., 1992) including increased speciation and extinction of molluscs (Allmon, 1992; Allmon et al., 1993; Jackson et al., 1996, 1999). In addition, changes in coral diversity and reef structure (Budd et al., 1996; Collins et al., 1996) are observed.

During the early Pliocene a faunal turnover event led to the extinction ~64% of all reef corals and a similar percentage of molluscs (Budd et al., 1994a, b). The timing of this turnover in molluscan fauna is dated to between 4 and 2 Ma, whereas the turnover of corals started about 1 my earlier (Goreau, 1959; Budd et al., 1994a, b).

Far field effects of this emergence, changes in platform morphology and biota, were seen within the carbonate platform deposits of the Bahamas (Reijmer et al., 2002). Even the Australian Queensland Plateau showed distinct sequence boundaries and facies shifts that could be related to the CAI emergence (Betzler et al., 2000).

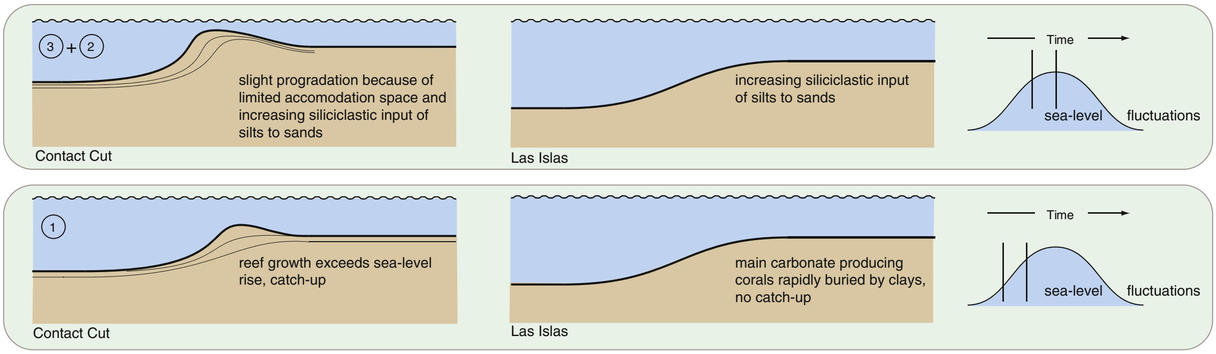

Fig. 7. Reef development correlated to sea level. During the transgressive phase (sea-level rise) reef growth at Contact Cut exceeds sea-level rise (catch-up). At Las Islas a first siliciclastic input of clays buried the main carbonate producing corals (no catch-up). During the highstand phase (sea-level stillstand) slight progradation occurs at Contact Cut due to limited accommodation space. In addition, increasing siliciclastic input at Contact Cut and Las Islas restricts reef growth, which finally results in the demise of both reefs.

4.4. Reef community

Scleractinian corals are very sensitive to changes in light, temperature, salinity and nutrients and thus their distribution is limited to special habitats (e.g. Smith and Buddemeier, 1992). Our analysis shows that the Pliocene Contact Cut reef has a reefal community similar to the modern reef systems around Cuba. This is surprising given the faunal turnovers that occurred in the Caribbean. In recent studies, it has been proposed that faunal change could start at different geographical locations at different times and in different ways (Budd et al., 1994a, b). The Contact Cut reef exhibits a clear growth zonation with a branching and a massive coral zone at the reef slope/front and the reef crest.

In between the coral patches, some *Strombus* sp. gastropods could be found. The combination of gastropods and corals suggests a lagoonal setting with stabilized sea grass meadows between the coral patches. In recent coral reef systems *Diploria clivosa*, *Solenastrea bournoni* and *Manicina areolata* preferentially occur in lagoonal settings. *Strombus* sp. gastropods usually occur in protected areas such as back reef flats and lagoons (Table 3), and often in settings with sea grass (Keen and McLean, 1971).

Silt-size grains dominate the siliciclastics sediments. Abundant silt admixed with skeletal components from molluscs and echinoderms are often an indicator for sea-grass-dominated habitats (Pomar, 2001). It is hard to find direct evidence for sea-grass meadows in the fossil record and we can only deduce such a setting from the sedimentology and paleontology (Brasier, 1973, 1975).

4.5. Reduced water clarity and its impact on reef diversity

The increased suspension of particles in the water through turbidity might have severely affected coral growth. As a source of the siliciclastics, we propose nearby river systems, which were already described by Taylor (1975). River systems affect the entire Neogene geologic history of the Limon area. Similar to today, the occurrence of rivers was likely prevalent in the Pliocene as suggested by the siliciclastic deposits of the Rio Banano Formation and the proximity of the Cordillera de Talamanca (Coates et al., 1992; McNeill et al., 2000). The migration of the streams and nearshore reworking of the siliciclastics results in a sheet-like deposit capable of smothering the reefs (Taylor, 1975). A precondition for increased turbidity is the availability of sufficient sediments that can be transported by suspension. The shallowing caused by the extensive reef growth and any associated increase in wave energy, along with the tidal effect, likely led to an increased suspended load. One of the commonly invoked influences on modern reef decline in the western Atlantic is increased turbidity (Lighty et al., 1978; Macintyre, 1988). Tidal currents can have sufficient velocity to suspend silt and fine sand and keep these particles in suspension (Kleypas, 1996). Some factors that control the generation and distribution of turbidity are resuspension by waves, particle settling and vertically mixing (Larcombe and Woolfe, 1999).

On Puerto Rican reefs that were affected by terrigenous input, Acevedo et al. (1989) have found a relation between reduced water clarity and a decrease in the drowning depth of reef corals. The amount of coral colonies, the decrease of the size of the corals as well as the absence of major framework-builders might indicate the impairment of the reef growing conditions. Increased turbidity is likely one of several contributors to this coral decline. During an increase in sedimentation and turbidity (an increase in sediment suspension concentration in the water) a shift to smaller coral species may occur because they are more efficient in sediment rejection relative to larger growth forms (Rogers, 1990). In addition, an accompanying decrease in diversity may occur (as in our stage 3). Under high turbidity stress fewer species exist that can tolerate such conditions (Kleypas, 1996). With increase in the amount of siliciclastics from 10% on the reef flat in the middle of stage 2 to up to 90% in stage 3 we note a decrease in the abundance of the main reef builder at the crest (*Porites* sp.) and on the reef front (*Stylophora* sp.). In addition, many fragments of *Porites* sp. and complete coral heads (not in-situ) were present on the reef flat of the 3rd stage.

Van Woesik (1992) and Kleypas (1996) described the effects of turbidity on major reef-builders on the Great Barrier Reef and the change to more turbidity-tolerant species. The same process could be observed in the Contact Cut reef.

4.6. Coral rubble transport and building of patches

The reef flat and outer back reef facies are characterized by enormous amounts of coral rubble in between the reef patches. The rubble mostly contains small fragments of *Stylophora* sp. and some rubble from other massive corals. Specifically, during stage 3 the amount of *Diploria* sp. fragments increases. Interpretation of these *Diploria* sp. fragments is problematic. Relatively few studies have focused on transport of coral fragments by wave-energy or tidal events. Most focused on episodic storm events (Baines et al., 1974; Ball et al., 1976; Dollar and Tribble, 1993; Scoffin, 1993; Bourrouilh-Le Jan, 1998). Hughes (1999) examined the generation and movement of coral rubble down the reef slope and showed that fragments of more than 100 g could be transported. Sixty-eight percent of the coral fragments of *Stylophora* sp. in our study area had a weight below 50 g. If we keep in mind that the fragments were perhaps lighter before secondary cements were added, a shoreward transport of coral fragments to the reef flat would be feasible. The paleo-slope angle of the reef front was relatively low (below 10°). The co-occurrence of gentle slopes with reef-flats in shallow waters may have resulted in shoreward transport of rubble (Woodley et al., 1981; Scoffin, 1993; Rasser and Riegl, 2002). In addition, the mollusc horizon that marks the end of stage 1 has abundant coral rubble (*Stylophora* sp.) from the reef front slope mixed within, which could be an indicator of a possible storm event that winnowed the matrix sediment and concentrated the larger mollusc shells. Stage 2 coral patches grow directly on top of this rubble or lag bed and may have provided a substrate for settlement of coral larvae as observed in modern reefs (Gilmore and Hall, 1976; Davies, 1983; Hughes, 1999; Rasser and Riegl, 2002).

4.7. Las Islas and stratigraphic correlation

The Las Islas roadcut shows a different sequence of reef development than that at Contact Cut. Three main stages are documented in this road cut. At the base, Stage 1 shows a pronounced *Stylophora* sp. branching zone that is interpreted as thickets of branching coral growing on the deeper part of the inclined shelf or delta front. Stage 2 consists of a distinct carbonate-rich interval with abundant coral species, the primary reef builders being *Porites* sp. and *Acropora palmata* (McNeill, et al., 1997). In contrast to Contact Cut reef, at Las Islas we first observe a clay-sized siliciclastic matrix (Stage 1) that grades into silts and sands (Stage 2) and led to a comparable carbonate–siliciclastic lithofacies like the one in stage 3 of the Contact Cut reef. Stage 3 shows an influx of coarse siliciclastics and burial of the shallow-water corals by these siliciclastics In thin section, point counts show a steady increase in siliciclastic grains from 15% in Stage 1 to 40% in Stage 3.

After a rapid sea-level rise in the transgressive stage, the Las Islas reef is buried by siliciclastics (mostly clays at first). In contrast to the Contact Cut reef the carbonate factory at the Las Islas reef was turned-off by the siliciclastics. The well-preserved coral heads in growth position as well as the lack of coral rubble on the slope or the inner reef suggest a fast burial and time-equivalent turn-off of carbonate production.

4.8. Geological record and timing of contact cut and Las Islas reefs

The Buenos Aires reef member as well as the Las Islas reef is well-dated using microfossils, magnetostratigraphy, and strontium-isotope stratigraphy (McNeill et al., 2000). The age of the Quitaria section of the Rio Banano Formation is dated between 3.7 and 3.5 Ma. The Las Islas Reef of the Buenos Aires Reef Member ranges from 3.7 to 3.6 Ma. The similar stratigraphic position of the Contact Cut reef to these well-dated sections suggests a comparable age of the Las Islas and Contact Cut reefs. Furthermore, a similar coral community and process of the reef development, and the similarity of the reef burial by coarse siliciclastics supports this interpretation.

McNeill, et al. (1997) portrayed the Las Islas reef of the Buenos Aires Formation as an *in-situ* mixed transgressive reef with stacked reefal build-ups. This interpretation is supported by our new samples. McNeill et al. (1997) further describes the Moin Formation reefs as highstand reefs with their lateral mixing of small patch reefs (2–7 m high and 5–30 m wide) and alternation of corals and siliciclastics. The newly described Contact Cut outcrop shows such a lateral mixing of small patch reefs (1–4 m high and 2 to 15 m wide) with an alternation of coral and siliciclastics and hence would fit into the classification as a highstand reef of the Moin Formation. The stratigraphic position, time-equivalent to that of the Las Islas reef, however, shows that the reef complex also evolved during the transgressive phase.

5. Conclusions

The early to late Pliocene reefal facies around Limon were strongly influence by a nearshore setting that was rich in siliciclastics that eroded off the volcanics of the nearly closed Central American Seaway. The uplift of the Cordillera de Talamanca led to the migration of the riverbeds and the shedding of siliciclastics onto the shallow fringing reefs of the marginal shelf. Examination of two reef sections in this dynamic setting has shown that reefs developing at about the same time, in close proximity and with similar coral communities, can respond very differently to siliciclastic input and thus prodice different stratigraphic profiles in the geologic record. Both reefs were the first reef sequences encountered in the stratigraphy and are interpreted to illustrate the reestablishment of coral reefs in the Neogene of the Caribbean.

It was shown that during a rapid sea-level rise, the transgressive phase, followed by a slow rise of sea-level leading to a highstand in sea level, locally varying input of siliciclastics resulted in the early demise of the carbonate factory at the Las Islas outcrop, while within the time-equivalent Contact Cut a slowdown in reef growth was observed followed by a “catch up” phase of the reef. The latter phase included progradation of the reef and the development of distinct reef flats. Later in time the continuing input of siliciclastics also resulted in the demise of the Contact Cut reef community.

The biotic content of the Las Islas and Contact Cut patch reefs, which both developed during a transgression, however, did not differ significantly from the reefs of the overlying Moin formation that developed during a sea-level highstand. Hence, slightly dissimilar positions on the shelf relative to the source of the siliciclastics might have caused the differences in response of the Las Islas and Contact Cut patch reefs to the environmental changes associated with the overall transition in sea level.

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