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Deficit of sand in a sediment transport model favors coral reef development in Brazil

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ABSTRACT

This paper shows that the location of the shoreface bank reefs along the northeastern and eastern coasts of Brazil, in a first order approximation, seem to be controlled by the deficit of sediment in the coastal system. The sediment transport pattern defined by a numerical modeling of wave refraction diagrams, representing circa 2000 km of the northeastern and eastern coasts of Brazil, permitted the regional-scale reproduction of several drift cells of net longshore sediment transport. Those drift cells can reasonably explain the coastal sections that present sediment surplus or sediment deficit, which correspond, respectively, to regions where there is deposition and erosion or little/no deposition of sand. The sediment deficit allows the exposure and maintenance of rocky substrates to be free of sediment, a favorable condition for the fixation and development of coral larvae.

Key words: sediment deficit, longshore drift, coral reefs, Northeast Brazil.

INTRODUCTION

In general, coral larvae need a hard and stable substrate onto which they can attach themselves (Woolfe and Larcombe 1999). Thus, input of sediments, which cover hard substrates, can be a limiting factor for recruitment (Hubbard 1986, Buddemeier and Hopley 1988, Macintyre 1988, Grigg and Dollar 1990, Rogers 1990, Potts and Jacobs 2002, Babcock and Smith 2002). In this way, the accumulation of sediment covers rocky substrates, which under other conditions, would be adequate for colonization by corals (Larcombe and Woolfe 1999). Where sandy sediments are abundant it is the hydrodynamic conditions that determine areas of reduced sediment accumulation that can preserve hard substrates and favor coral colonization and reef development.

Along the northeastern and the eastern coasts of Brazil, between Mucuri and Três Irmãos Point (Fig. 1), a region characterized by the presence of sandy beaches, are the largest and most developed coral reefs of the South Atlantic Ocean (Laborel 1969, Maida and Ferreira 1997, Castro and Pires 2001, Leão et al. 2003). Figure 1 illustrates the location of the reefs and an average percentage of the shoreface reefs in each study region. Some of these reefs form one or two lines of elongate banks parallel to the coastline and, in some cases, occur adjacent to the sandy beaches (Fig. 2). Others, like the Abrolhos and Parcel das Paredes reefs, in the south part of the study area, are isolated banks and coral pinnacles located from about 10 to 60 km off the coast (Fig. 1) (Leão et al. 2003).

The shoreface bank reefs, which are the focus of this study, are surrounded by sediment predominantly composed by terrigenous components derived from inland (Leão and Ginsburg 1997, Leão et al. 2003). These reefs are located in depths less than 10 m (Castro and Pires 2001, Leão et al. 2003), and their distribution and

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morphology are controlled by the underlying substrate, such as older reefs, Precambrian bedrock and lines of Quaternary beachrock (Leão et al. 1985, 2003).

The regional sandy sediment dispersion patterns along this coastline are described by Bittencourt et al. (2005). In general, these patterns can explain, to a first order approximation, the relationship between the wave climate and the locations of accumulation and erosion or little/no deposition of sediment along the study area.

The objective of the present paper is to find out if there is any relationship between the distribution of the shoreface coral reefs and the sandy sediment dispersion patterns along the coastline.

GEOLOGICAL-PHYSIOGRAPHICAL SCENARIO

In addition to the coral reefs, a marked characteristic of the study area is the nearly continuous occurrence of Tertiary deposits of the Barreiras Formation (Mabesoone et al. 1972, Bigarella 1975a, Suguio and Nogueira 1999), which form extensive tablelands. These tablelands composed of unconsolidated sediments present a more or less planar top, with heights between 10 and 100 m that gently dip into the sea and are dissected by small local streams. Active sea cliffs in the Barreiras Formation occur along the coast, locally exposing at their base abrasion terraces with a ferruginous laterite veneer (Fig. 1). Another characteristic of this region is the presence of marine terraces of Pleistocene and Holocene ages (Bittencourt et al. 1979, 1983, Martin et al. 1980, 1996, Barbosa et al. 1986, Dominguez et al. 1990, 1992) and by the existence of important Quaternary dune fields, both active and stabilized by vegetation (Dominguez and Bittencourt 1996). Still, another very common characteristic along the coast is the presence of beachrock lines (Fig. 1) (Mabesoone 1964, Bigarella 1975b, Flexor and Martin 1979, Dominguez et al. 1990, Oliveira et al. 1990). Sparse outcrops of Precambrian basement metamorphic rock and Cretaceous and Tertiary sedimentary rocks occur along some of the coastal sections (Fig. 1).

Among the rivers that empty along the coastline, only the São Francisco and the Jequitinhonha rivers stand out by their capacity to contribute sediments to the coastal system, thereby constructing significant delta characteristics (Dominguez et al. 1987) (Fig. 1). On the regional scale of this paper the other rivers can be considered insignificant. The São Francisco River is significant with an average flow of 2,850 m^3/sec., while the Jequitinhonha River has an average flow of 354 m^3/sec. The São Francisco River was considered by Laborel (1969) and Maida and Ferreira (1997) as being responsible for the notable absence of reef structures along vast stretches of the coast to the south of its mouth.

In general, the continental shelf in the study area is relatively flat, presenting few irregularities between Mangue Seco and Miaí and between Mucuri and Belmonte (Fig. 1). The most marked physiographic characteristics of the shelf are found in the latter section in the Royal Charlotte and the Abrolhos banks. The shelf is very narrow (average 50 km width), extending up to 200 km in the banks mentioned above. The shelf break occurs between 60 and 80 m and, with the exception of the section between Mucuri and Belmonte, generally follows the coast.

Tide variation ranges from micro- to meso-tides. The spring tides of the study area vary from 1.7 at the extreme south to 3.0 m at the extreme north.

According to Bittencourt et al. (2005), the most significant directions of wave fronts are from: NE, E, SE and SSE with periods of 5 sec. and height of 1.0 m for NE and E directions, and 6.5 sec. and 1.5 m height for the SE and SSE directions.

SEA LEVEL OSCILLATIONS

Two important transgressive episodes affected the study area during the Quaternary. The older one, known as the Penultimate Transgression, reached its maximum at 120 ky B.P., when the sea level was 8 ± 2 m above the present position (Martin et al. 1982, Bernat et al. 1983). The more recent episode, known as the Last Transgression, reached its maximum approximately 5.1 ky B.P., when sea level reached approximately 5 m above the present-day level (Martin et al. 1979, 2003, Suguio et al. 1985).

Using various types of indicators (vermetid gastropod incrustations, beach-ridge terraces, beach-rocks, corals, calcareous algae, shell middens and lagoonal sediments), it was possible to draw curves or sketches of curves of relative variations of sea level starting from the age when present average sea level was first reached –

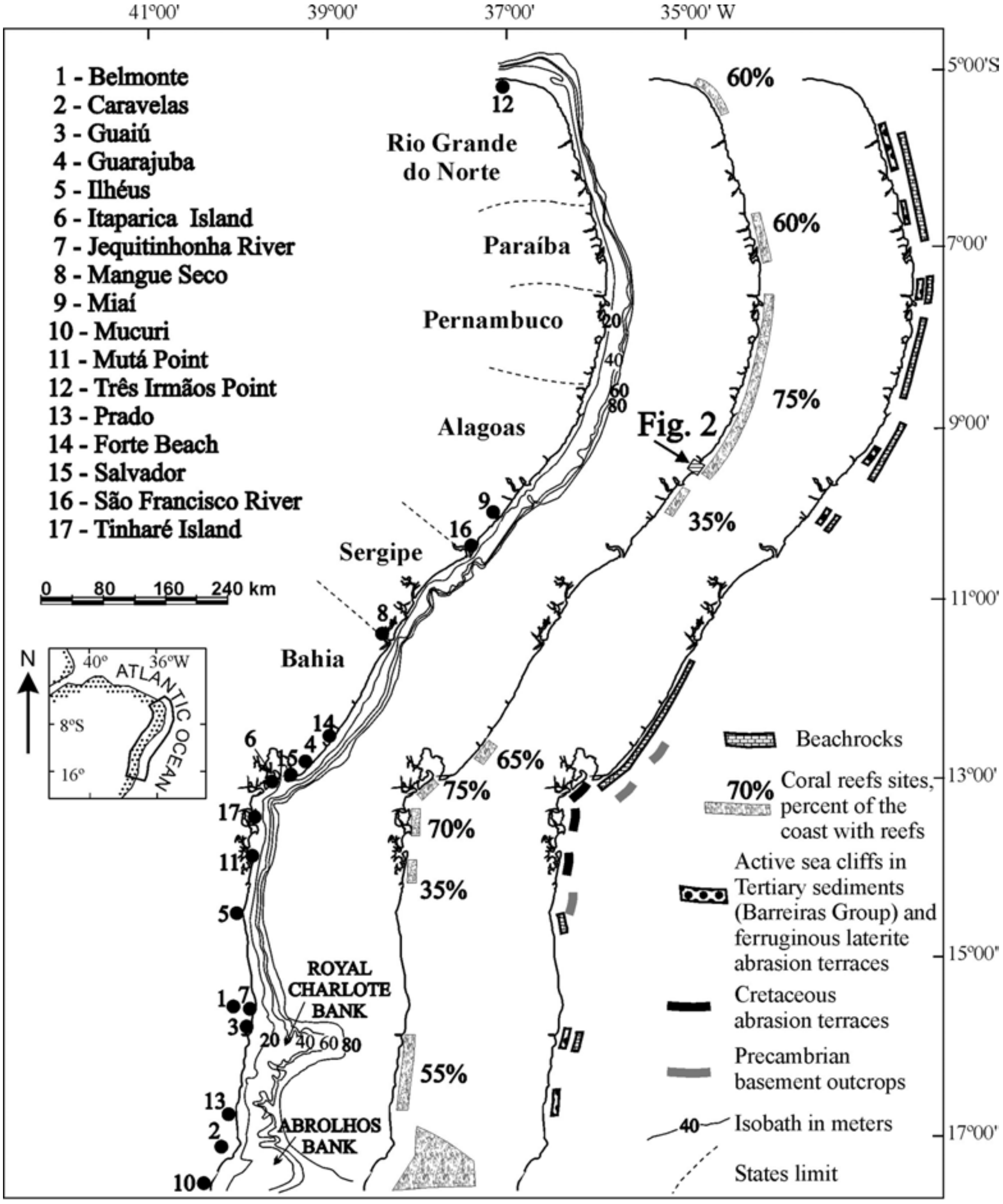

Fig. 1 – Location of major coral reef areas along northeastern and eastern Brazil illustrating the average percentage of reefs in each study area; the location of different types of rocky substrate outcrops along the coast; and the location of active sea cliffs.

approximately 7 ky B.P. – to the present, for different sections of the study area (Fig. 1): Salvador, Ilhéus and Caravelas (Martin et al. 1979, 1996, 2003, Suguio et al. 1985); State of Pernambuco (Dominguez et al. 1990); State of Rio Grande do Norte (Bezerra et al. 2003). The most detailed of these curves was drawn for the region of Salvador (Martin et al. 1979, 2003) (Fig. 3). In spite of small discrepancies, taking the curve for the city of Salvador as reference, these curves show that the drop in the ocean level beginning 5.1 ky B.P. was not regular, but interrupted by high frequency oscillations of the order of 2-3 m, occurring in the time scale of not more than 200-300 years. Angulo et al. (2006) have questioned the interpretation of these oscillations.

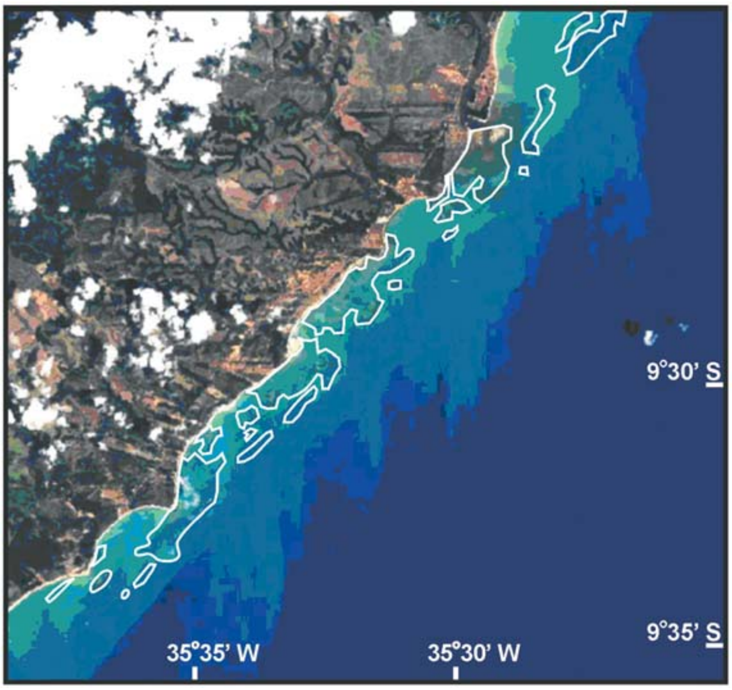

Fig. 2 – Landsat 7 ETM image illustrating two lines of shoreface bank reefs (highlighted in white line) parallel to the north coast of the state of Alagoas, 60 km north of Miaí (for location see Fig. 1).

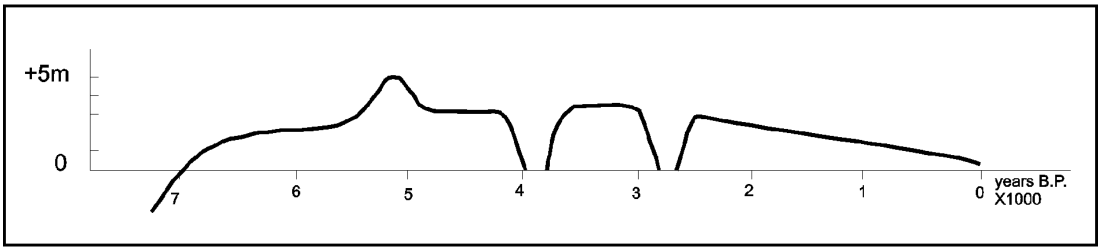

Fig. 3 – The Holocene sea level curve for the coast of Salvador City during the last 7 ky (according to Martin et al. 1979, 2003).

THE EVOLUTION OF SHOREFACE REEFS

The oldest Holocene reef in Brazil initiated growth between 7 and 8 ky B.P. after flooding of the continental shelf, an ecological phenomenon widespread in the tropics (Leão and Kikuchi 1999). Following the late Holocene history of seal level (Martin et al. 1979, 2003, Suguio et al. 1985), four well-marked stages of reef growth are recognizable along the coast of Brazil: 1) reef initiation and establishment; 2) rapid upward reef accretion; 3) lateral growth of the reef framework; and 4) reef degradation. The first two stages developed during the transgressive sea, and the last two stages developed during the sea level regression (Leão et al. 2003).

The data obtained from two cores of the Guarajuba reef located at the north coast of the state of Bahia, described by Nolasco and Leão (1986) and Leão et al. (1988) (Fig. 1), can be considered as representative for interpreting the evolution of coral reefs from the northeastern and eastern regions of Brazil (Leão et al. 2003).

Based on C^{14} dates and seismic refraction profiles, the initiation of shoreface reefs of Guarajuba was between 6 and 5.5 ky B.P., in depths of about 10 m below present-day sea level. During the maximum of the Last Transgression, when sea level was at about 5 m above today's level, reefs attained heights above the present

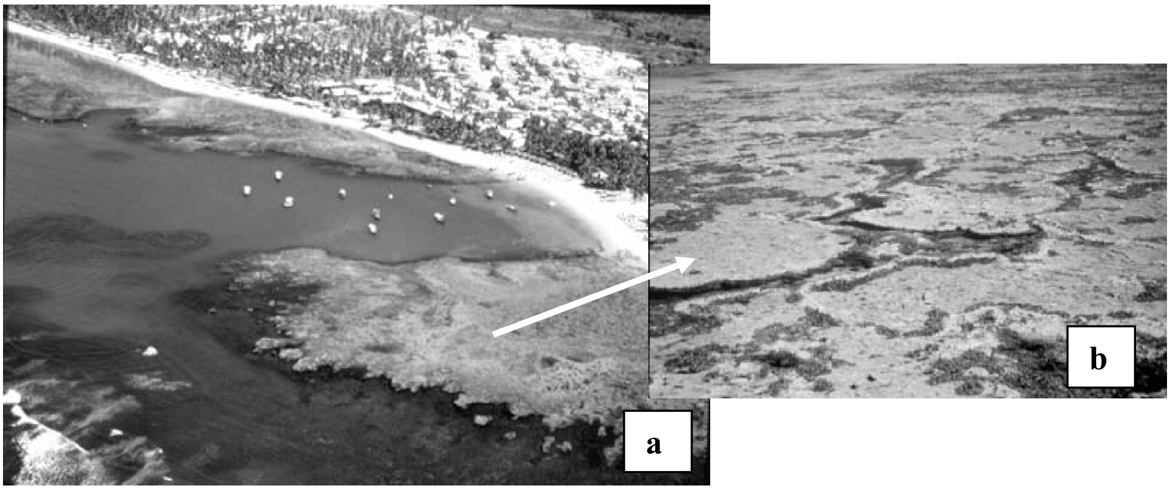

Fig. 4 – a) The emergent top of Forte Beach Reef at the north coast of the State of Bahia. b) Detail illustrating truncated colonies of endemic coral *Mussismilia braziliensis* Verrill 1868, up to 1 m diameter. Photographs taken at low spring tide (for location see Fig. 1).

day reef surface, and during the regressive phase the reefs became emergent and their frameworks were exposed to erosion (Fig. 4) (Kikuchi and Leão 1998). As part of that process, the lowering of sea level moved the coastline closer to the reefs. This period characterizes a passage from a phase of vertical reef accretion to a predominance of lateral growth which was evidenced by C^{14} dates of several reef tops along the northeastern coast of Brazil (Barbosa et al. 1986, Nolasco and Leão 1986, Dominguez et al. 1990, Leão et al. 2003, Leão and Kikuchi 2005).

SEDIMENT DISPERSION PATTERNS

Figure 5 shows the long-term regional patterns of sand dispersion along the coastline defined by a numerical modeling of wave climate in the study region (Bittencourt et al. 2005). These patterns are expressed by coastal cell drifts (from I to XI, Fig. 5), identified through alterations in the direction and potential intensity of net littoral sediment drift. The absence of data for the coastal section between Salvador and Mutá Point is because the scale of observation used for modeling did not permit an appropriate representation of the highly segmented coastline in which sections are under accumulation, erosion or little/no deposition.

The coastal sections that present accumulation and erosion or little/no deposition, as mentioned previously, are explained by Bittencourt et al. (2005) based on drift cells (Fig. 5). The coastal sections under accumulation are related to: a) convergence in the direction of the drift cells, and b) decrease of drift intensity in the downdrift direction. Convergence is what happens regarding the cuspate Quaternary plains of Caravelas and Corumbau Point and in the coastal section near Mangue Seco. Drift cells converge also to between Salvador and Mutá Point, resulting in the accumulation of sediments in this coastal section. It should be emphasized that in relation to the Corumbau Point, that has a shape of a tombolo, its formation likely originated after the development of the reefs existing in front of it (Bittencourt et al. 2000). In fact, in the region between Guaiú and Caravelas (Fig. 1), close to the maximum of the Last Transgression (5.1 ky B.P.) (Fig. 3), there existed a sediment deficit caused by a divergence in the direction of the net littoral sediment drift (L.A. Ferraz et al., unpublished data). This divergence in the direction of sediment transport could have impeded the development of the Corumbau tombolo, and instead favored the establishment of the reefs. If so, the formation of the Corumbau Point should have initiated after the reefs reached sea level, a situation similar to the formation of the cuspate shape of the Caravelas Quaternary coastal plain in relation to the reefs of Abrolhos and Paredes (Bittencourt et al. 2000). Regarding the region between Mutá Point and Salvador, it is significant that it is a coastal section

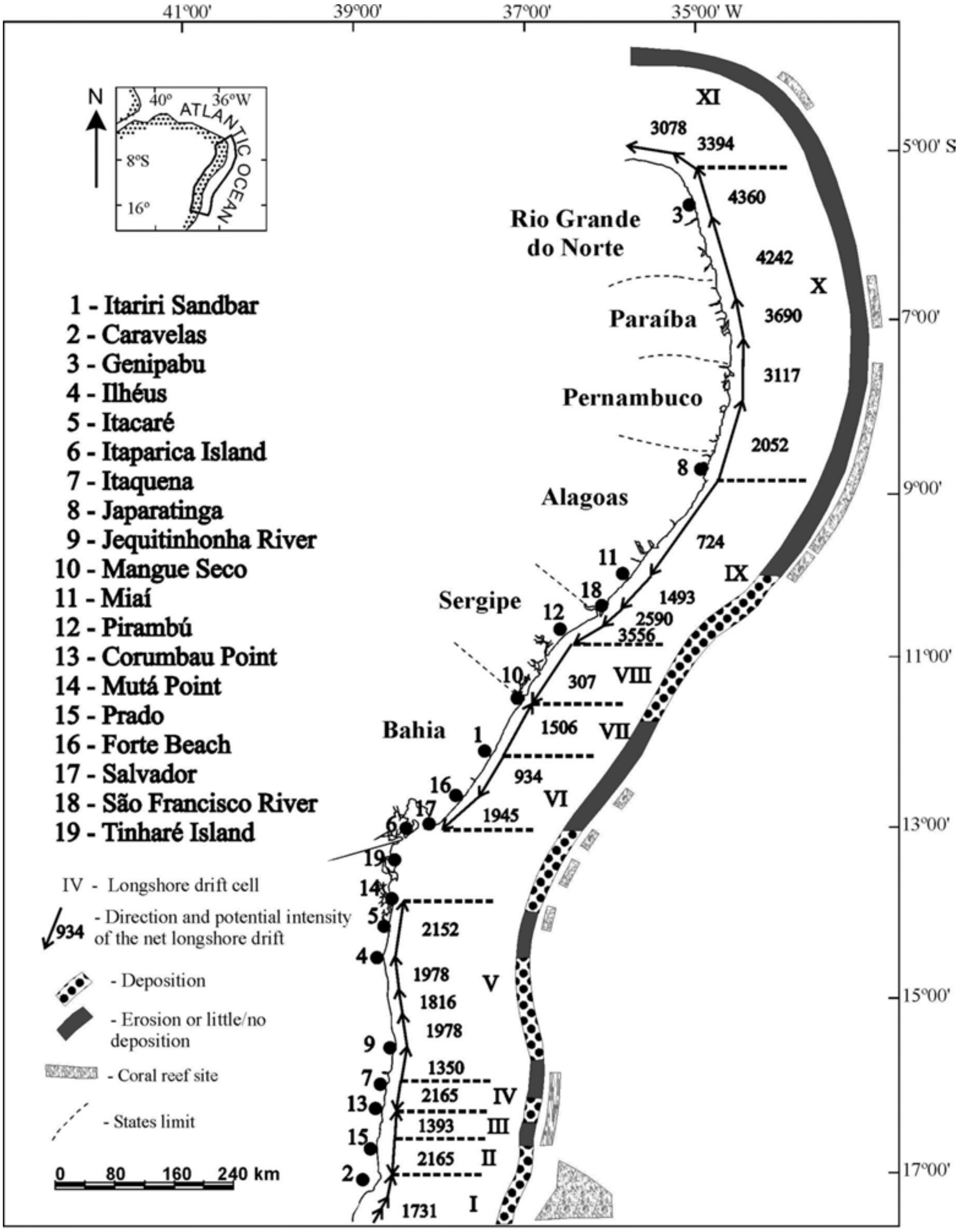

Fig. 5 – Map of northeastern and eastern Brazilian coasts showing coral reef location and longshore drift cells, and the direction and potential intensities of net longshore drift (according to Bittencourt et al. 2005).

with impeded littoral drift due to the existence of the islands and tidal inlets. Therefore, it is reasonable to think that the islands of Tinharé and Itaparica are receiving little/no sediment from the drift cells V and VI (Fig. 5). Furthermore, J.S. Alfaya Filho et al. (unpublished data), based on wave refraction diagram analyses, mention the existence of two net drift cells with divergent directions along the coastline of Itaparica Island facing the ocean in front of the coral reefs. Downdrift decrease of sediment is what happens on the Quaternary plains between Pirambu and Mangue Seco. The fact that the drift cell XI corresponds to a coastal section under erosion or little/no deposition, in spite of the existence of a reduction in the intensity of effective drift may be related to the removal of sand from the beach face to feed the extensive dune fields there. In addition strong coastal currents generated by the joint action of winds and tides may also contribute (Testa and Bosence 1999).

The relationships between the sandy sediment dispersion patterns and the coastal sections that present evidences of erosion or little/no deposition are linked to (Fig. 5): a) divergence in the direction of the drift cells, and b) increase in the downdrift direction of drift intensity. Divergence of drift cells is what happens in the regions of Itaquena and adjacent areas, between Prado and Corumbau Point, Itariri Sandbar and adjacent areas, and Japaratinga and adjacent areas. The first two and the last coastal section present large extensions of active sea cliffs excavated in the tablelands of the Barreiras Formation and, in Japaratinga, the Quaternary plain is very narrow and nearly absent in some locations. Downdrift increase in intensity is what happens in the coastal sections between Itariri Sandbar and Salvador, Japaratinga and Miaí, and Japaratinga and Genipabu. Between Miaí and Genipabu, the Quaternary plains are poorly developed, or even absent, with long stretches of active sea cliffs in the Barreiras Formation. Between Itariri Sandbar and Salvador, the evidence of sediment deficit is marked by the poor development of Quaternary plains. In cell V, in spite of a general tendency for an increase in drift intensity in the downdrift direction, only in the section between Ilhéus and Itacaré there seems to be a correspondence between this gradient and an insipient development of Quaternary coastal accumulations. In the remainder of the coastal section corresponding to cell V, this relationship is not observed, which may be attributed, according to Bittencourt et al. (2005), to the influx of sediments carried by the Jequitinhonha River. The same situation may be occurring in the section of cell IX between Miaí and Pirambu due to the presence of the São Francisco River.

TYPES OF ROCK SUBSTRATE

The coastal sections with reduced sediment have a variety of different rock substrates. Information of these rock substrates comes from cores from the north coast of Bahia (Nolasco and Leão 1986) and on the island of Itaparica (Leão et al. 1988) (Fig. 1). On the north coast of the State of Bahia (Guarajuba reef) Precambrian bedrocks were identified and, approximately 10 km south, beachrock served as reef substrate and on Itaparica Island, Cretaceous sedimentary rocks were recovered. In the other occurrences of coastal reefs, the indications of the composition and age of rock substrates were obtained from visual observations, during deep scuba diving, and geomorphologic interpretation. Thus, the coastal reefs in the States of Alagoas, Pernambuco, Paraíba and Rio Grande do Norte overlie on beachrock (Laborel 1969, Dominguez et al. 1990, Maida and Ferreira 1997, Castro and Pires 2001). The reefs bordering the Island of Tinharé and from Itacaré to Mutá Point, overlie on Cretaceous sedimentary rock (Z.M.A.N. Leão and R.K.P. Kikuchi, unpublished observations), and those of the region between Guaiú and Prado are on ferruginous laterite abrasion terraces of the Barreiras Formation (Z.M.A.N. Leão and R.K.P. Kikuchi, unpublished observations) (Fig. 1).

DISCUSSION AND CONCLUSIONS

Nearly all the shoreface coral reefs from the northeastern and eastern coasts of Brazil are located in areas "under erosion or little/no deposition". The reefs located in front of Corumbau Point and the islands of Itaparica and Tinharé, although designated today as sections "under deposition", were mostly likely developed under sediment deficit conditions, as previously discussed. At approximately 7 ky B.P., when zero (present-day sea level) was cut for the first time (Fig. 3) during the Last Transgression, the coastal sections with sediment deficit must have permitted the exposure of the different types of rock substrates mentioned previously, assuming that, in some locations, these exposures may have been in more elevated positions than the region of the surrounding bottom. In such a situation, these substrates could remain free from the accumulation of sediments, as well as from sediments in transit. In effect, it should be considered that the coastal sections indicated in figure 5 as under erosion or little/no deposition, although in the general computation are locations of sediment deficit, they are seasonally swept, in opposing directions, by sediment in transit by different wave fronts that reach them there (Bittencourt et al. 2005). Thus, the reef substrates remained free of a sediment cover and, with the rising of sea level, became more distant from the coastline due to the transgressive sea. This process continued, until these rocky substrates reached a depth of 10 to 11 m below today's sea level, between 5.5 and 6 ky B.P (taking as reference the Guarajuba Reef), allowing larvae attachment and the start up of the present reefs. The reefs developed until the subsequent regression of the sea level reached the reef structures, at which point they started to erode to the present level. Thereafter, they expanded laterally until finally, in some cases, the reefs became juxtaposed to the coastline, being partially covered by the regressing sands.

The present study shows that, on a large scale, the regions of reduced sandy sediment accumulation along the northeastern and eastern Brazilian coastal systems, in a first order approximation, seem to control the locations of the reefs because they allow the exposure and maintenance of rocky substrates, which favor the recruitment of coral larvae. The mouths of São Francisco and Jequitinhonha rivers impede the development of reefs because the sediment accumulations cover rock substrates.

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RESUMO

Este trabalho mostra que a localização dos recifes de coral ao longo dos litorais leste e nordeste do Brasil, em uma aproximação de primeira ordem, parece ser controlada pelo déficit de sedimentos no sistema costeiro. O padrão de transporte de sedimentos definido por modelagem numérica a partir de diagramas de refração de ondas, representando cerca de 2000 km dos litorais leste e nordeste do Brasil, permitiu a reprodução, em escala regional, de várias células de deriva litorânea efetiva de sedimentos. Essas células de deriva podem razoavelmente explicar os segmentos costeiros que representam superávit, ou deficit de sedimentos que correspondem, respectivamente, a regiões onde existe deposição e erosão ou pouca/nenhuma deposição de areia. O deficit de sedimentos propicia a exposição e manutenção de substratos rochosos livres de sedimento, uma condição favorável para a fixação e desenvolvimento das larvas de coral.

Palavras-chave: deficit de sedimento, deriva litorânea, recifes de coral, nordeste do Brasil.

REFERENCES

Angulo RJ, Lessa GC and Souza MC. 2006. A critical review of mid-to late-Holocene sea-level fluctuations on the eastern Brazilian coastline. Quaternary Sci Rev 25: 486–506.

Babcock R and Smith L. 2002. Effects of sedimentation on coral settlement and survivorship. Proc 9th Int Coral Reef Symp Bali, Indonesia 1: 245–248.

Barbosa LM, Bittencourt ACSP, Dominguez JML and Martin L. 1986. Quaternary coastal deposits of the state of Alagoas: influence of the relative sea-level changes. Quaternary South America and Antartic Peninsula 4: 269–290.

Bernat M, Martin L, Bittencourt ACSP and Vilas-Boas GS. 1983. Datation Io/U du plus haut niveau marin du dernier interglaciaire sur la côte du Brésil. Utilization du ^{229}Th comme traceur. Cr Acad Sci II A, T 296: 197–200.

Bezerra FHR, Barreto AMF and Suguio K. 2003. Holocene sea-level history on the Rio Grande do Norte State Coast, Brazil. Mar Geol 196: 73–89.

Bigarella JJ. 1975a. The Barreiras Group in northeastern Brazil. An Acad Bras Cienc 47: 365–393.

Bigarella JJ. 1975b. Reef sandstones from Northeastern Brazil (A survey on sedimentary structures). An Acad Bras Cienc 47: 395–409.

Bittencourt ACSP, Martin L, Vilas Boas GS and Flexor JM. 1979. The marine Quaternary formations of the coast of the State of Bahia (Brazil). In: Suguio K, Fairchild T, Martin L and Flexor JM (Eds), 1978 International Symposium on Coastal Evolution in the Quaternary. São Paulo, SP, Brazil, p. 232–253.

Bittencourt ACSP, Martin L, Dominguez JML, Flexor JM and Ferreira YA. 1983. Evolução paleogeográfica Quaternária da costa do Estado de Sergipe e da costa sul do Estado de Alagoas. Rev Bras Geocienc 13: 93–97.

Bittencourt ACSP, Dominguez JML, Martin L and Silva IR. 2000. Patterns of sediment dispersion coastwise the State of Bahia – Brazil. An Acad Bras Cienc 72: 271–287.

Bittencourt ACSP, Dominguez JML, Martins L and Silva IR. 2005. Longshore transport on the northeastern Brazilian coast and implications to the location of large-scale accumulative and erosive zones: An overview. Mar Geol 219: 219–234.

Buddemeier RW and Hopley D. 1988. Turn-ons and turn-offs: causes and mechanisms of the initiation and termination of coral reef growth. Proc 6th Int Coral Reef Symp, Townsville, Australia 1: 253–262.

Castro CB and Pires DO. 2001. Brazilian coral reefs: what we already known and what is still missing. B Mar Sci 69: 357–371.

Dominguez JML and Bittencourt ACSP. 1996. Regional Assessment of Long-term Trends of Coastal Erosion in Northeastern Brazil. An Acad Bras Cienc 68: 355–371.

Dominguez JML, Martin L and Bittencourt ACSP. 1987. Sea-level history and the Quaternary evolution of river mouth-associated beach-ridge plains along the east-southeast coast of Brazil: a summary. In: Nummedal D, Pilkey DH and Howard DJD (Eds), Sea-Level fluctuation and coastal evolution (special issue). Soc Econ Paleont Mineral 41: 115–127.

Dominguez JML, Bittencourt ACSP, Leão ZMAN and Azevedo AEG. 1990. Geologia do Quaternário Costeiro do Estado de Pernambuco. Rev Bras Geocienc 20: 208–215.

Dominguez JML, Bittencourt ACSP and Martin L. 1992. Controls on Quaternary coastal evolution of the east-northeastern coast of Brazil: roles of sea-level history, trade winds and climate. Sediment Geol 80: 213–232.

Flexor JM and Martin L. 1979. Sur l'utilisation des grès coquiliers de la región de Salvador (Brésil) dans la reconstrution des lignes de risage holocènes. In: Suguio K, Fairchild T, Martin L and Flexor JM (Eds), 1978 International Symposium on Coastal Evolution in the Quaternary. São Paulo, SP, Brazil, p. 346–357.

Grigg RW and Dollar SJ. 1990. Natural and anthropogenic disturbance on coral reefs. In: Dubinsky Z (Ed), Ecosystems of the World 25 – Coral Reefs. Elsevier, Amsterdam, p. 439–452.

Hubbard DK. 1986. Sedimentation as a control of reef development: St. Croix, U.S.V.I. Coral Reefs 5: 117–125.

Kikuchi RKP and Leão ZMAN. 1998. The effects of Holocene sea level fluctuation on reef development and coral community structure, Northern Bahia, Brazil. An Acad Bras Cienc 70: 159–171.

Laborel J. 1969. Les peuplements de Madréporaires des côtes tropicales du Brésil. Annales de l'Université d'Abidjan – Série E 2: 1–260.

Larcombe P and Woolfe KJ. 1999. Increased sediment supply to the great Barrier Reef will not increase sediment accumulation at most coral reefs. Coral Reefs 18: 163–169.

Leão ZMAN and Ginsburg RN. 1997. Living reefs surrounded by siliciclastic sediments: the Abrolhos coastal reefs, Bahia, Brazil. Proc 8th Int Coral Reef Symp, Panamá 2: 1767–1772.

Leão ZMAN and Kikuchi RKP. 1999. The Bahian coral reefs – from 7000 years BP to 2000 years AD. Ciência e Cultura 51: 262–273.

Leão ZMAN and Kikuchi RKP. 2005. A relic coral fauna threatened by global changes and human activities, Eastern Brazil. Mar Pollut Bull 51: 599–611.

Leão ZMAN, Bittencourt ACSP, Dominguez JML, Nolasco MC and Martin L. 1985. The effects of Holocene sea level fluctuations on the morphology of the Brazilian coral reefs. Rev Bras Geocienc 15: 154–157.

Leão ZMAN, Araújo TMF and Nolasco MC. 1988. The coral reefs off the coast of eastern Brazil. Proc 6th Inter Coral Reef Symp, Townsville, Australia 3: 339–347.

Leão ZMAN, Kikuchi RK and Testa V. 2003. Corals and coral reef of Brazil. In: Cortés J (Ed), Latin America Coral Reefs, Elsevier Science, p. 9–52.

Mabesoone JM. 1964. Origin and age of the sandstone reefs of Pernambuco (Northeastern Brazil). J Sediment Petrol 34: 715–726.

Mabesoone JM, Campos e Silva A and Beurlen K. 1972. Estratigrafia e origem do Grupo Barreiras em Pernambuco, Paraíba e Rio Grande do Norte. Rev Bras Geocienc 2: 173–188.

Macintyre I. 1988. Modern coral reefs of western Atlantic: New Geological perspective. Am Assoc Petr Geol B 72: 1360–1369.

Maida M and Ferreira B. 1997. Coral Reefs of Brazil: an overview. Proc 8th Int Coral Reef Symp, Panamá 1: 263–274.

Martin L, Flexor JM, Vilas-Boas GS, Bittencourt ACSP and Guimarães MMM. 1979. Courbe des Variations Relatif de la Mer au Cours des 7.000 Dernières Années sur un Secteur Homogène du Litoral Brésilien (Nord de Salvador, Ba, Brasil). In: Suguio K, Fairchild T, Martin L and Flexor JM (Eds), 1978 International Symposium on Coastal Evolution in the Quaternary, São Paulo, SP, Brazil, p. 264–274.

MARTIN L, BITTENCOURT ACSP, VILAS BOAS GS AND FLEXOR JM. 1980. Texto Explicativo para o Mapa Geológico do Quaternário Costeiro do Estado da Bahia. Companhia de Pesquisa Mineral, Secretaria de Minas e Energia, Bahia, Brasil, 57 p.

MARTIN L, BITTENCOURT ACSP AND VILAS-BOAS GS. 1982. Primeira ocorrência de corais pleistocênicos da costa brasileira – datação do máximo da penúltima transgressão. Rev Cienc Terra, SBG 3: 16–17.

MARTIN L, SUGUIO K, FLEXOR JM, DOMINGUEZ JML AND BITTENCOURT ACSP. 1996. Quaternary sea-level history along the central Part of the Brazilian Coast. Variations in coastal dynamics and their consequences on coastal plain construction. An Acad Bras Cienc 68: 304–354.

MARTIN L, DOMINGUEZ JML AND BITTENCOURT ACSP. 2003. Fluctuating Holocene sea levels in Eastern and Southeastern Brazil: evidence from multiple fossil and geometric indicators. J Coastal Res 19: 101–124.

NOLASCO MC AND LEÃO ZMAN. 1986. The carbonate buildups along the northern coast of the state of Bahia, Brazil. In: RABASSA J (Ed), Quaternary of South America and Antarctic Peninsula. Balkema Publication, Amsterdam, Netherlands 4: 159–190.

OLIVEIRA MIM, BAGNOLI E, FARIAS CC, NOGUEIRA AM AND SANTIAGO M. 1990. Considerações sobre a geometria, petrografia, sedimentologia, diagênese e idade dos beach-rocks do Rio Grande do Norte. Anais do 36º Congresso Brasileiro de Geologia, Natal, RN, Brasil 2: 621–634.

POTTS DC AND JACOBS JR. 2002. Evolution of reef-building scleractinian corals in turbid environments: a paleo-ecological hypothesis. Proc 9th Inter Coral Reef Symp, Bali, Indonesia 1: 249–254.

ROGERS CS. 1990. Responses of coral reefs and reef organisms to sedimentation. Mar Ecol Prog Ser 62: 185–202.

SUGUIO K AND NOGUEIRA ACR. 1999. Revisão crítica dos conhecimentos geológicos sobre a Formação (ou Grupo?) Barreiras do Neógeno e o seu possível significado como testemunho de alguns eventos geológicos mundiais. Geocienc 18: 461–479.

SUGUIO K, MARTIN L, BITTENCOURT ACSP, DOMINGUEZ JML AND FLEXOR JM. 1985. Flutuações do nível relativo do mar durante o Quaternário Superior ao longo do litoral brasileiro e suas implicações na sedimentação costeira. Rev Bras Geocienc 15: 273–286.

TESTA V AND BOSENCE DWJ. 1999. Physical and biological controls on the formation of carbonate and siliciclastic bedforms on the northeast Brazilian shelf. Sedimentology 46: 297–301.

WOOLFE KJ AND LARCOMBE P. 1999. Terrigenous sedimentation and coral reef growth: a conceptual framework. Mar Geol 155: 331–345.