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Sedimentation in the coastal reefs of Abrolhos over the last decades

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ABSTRACT

Coral reefs of the coastal area of Abrolhos are located in an environment with a high influx of terrigenous sediments that are carried out to the sea, either as a result of natural processes (river output, coastal erosion, and torrents) or due to anthropogenic influences (deforestation, coastal development, and dredging). Excessive terrigenous sediment in coastal areas has been identified as one of the major threats to coral reefs, leading to their worldwide decline. The present study assessed the evolution of sedimentation in the Abrolhos coastal reefs during the past decades by analyzing samples from sediment cores collected near the reefs of Coroa Vermelha (located 15 km from the coast), Pedra de Leste (located 12 km from the coast) and Popa Verde (located 35 km from the coast). The purpose of this assessment was to observe whether the previously described pattern of surficial bottom sediment distribution in Abrolhos, which consisted of terrigenous mud in the nearshore reefs, to carbonate-dominant sediments towards the offshore reefs, is still a prevalent feature. Sediment color, texture, $CaCO_3$ percentage, biogenic compounds and clay minerals, as well as the sedimentation rate and the geochronology of the sediment cores were analyzed. The results showed indications of an increase in the deposition of terrigenous mud, over the last decade, in the vicinity of the reefs nearest to the coast, though this does not yet constitute a definitive evidence of such a change. However, this observation therefore suggests that local processes resulting from anthropogenic actions are most likely causing an increase of the sedimentation rate of continent-derived sediment runoff in the Abrolhos coastal areas. To minimize this situation, there is an urgent need for the development of new management strategies to protect the already disturbed Abrolhos coastal reefs, especially during times of global changes.

1. Introduction

Extremely high rates of sediment and elevated turbidity are considered great threats to coral reef health because they affect the structure and functioning of the reef ecosystem influencing for example, reef distribution, community structure, growth rates and coral recruitment (Rogers, 1990). Sediment influx in coastal areas is caused by natural and human-induced processes, including fluvial discharge, terrigenous runoff, coastline erosion, resuspension of bottom sediment after storms and the impacts that result from nearshore unplanned human occupation and the associated dredging activity (Dodge and Vaisny, 1977; Hodgson, 1993; Dutra et al., 2006).

Several of the potentially negative effects of sedimentation and turbidity on corals have been documented, such as the smothering of filter-feeding organisms with an excess of suspended fine-grained sediment; the abrasion of coral colonies by the movement of the sediment deposited on their surfaces; changes in coral morphology due to light attenuation; reduction in the rate of coral larvae settlement and the consequent reduction of coral survival due to the lack of a suitable substrate and the failure of coral recruitment and coral growth, including the consequent loss of living coral cover, reef biodiversity and reef surface covered by reef-building corals (Dodge et al., 1974; Loya, 1976; Cortés and Risk, 1985; Brown and Howard, 1985; Hodgson, 1993; Edinger et al., 1998; Babcock and Smith, 2000; Hughes and Tanner, 2000; Miller and Kosmynin, 2008).

Despite all the examples indicating that high sedimentation inputs to coastal reef areas are negatively affecting reef species, many corals thrive in these supposedly inhospitable environments. There are many examples worldwide of coastal reefs that are exposed to turbid conditions in which light intensity is reduced by substantial amounts of suspended particulate or dissolved materials and episodic sediment runoff from continental areas (Dodge and Vaisny, 1977; Woolfe and Larcombe, 1999; Potts and Jacobs, 2000; Anthony and Larcombe, 2000; Larcombe et al., 2001; Ogston et al., 2004; Otero and Carbery, 2005; Perry et al., 2009).

In several reef areas where coral adaptation has occurred to cope with intense sediment regimes, experiments have tested the hypothesis that corals from turbid conditions have a greater capacity to use suspended sediment as a food source (Anthony and Fabricius, 2000).

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In these turbid zones, heterotrophic processes could potentially be enhanced by increasing the availability of particulate food (Anthony, 2000). This may occur when there are longer periods of relatively clear conditions between shorter periods of heavy sedimentation, which allow corals to recover, because they either expend less energy to clean the sediment and use their ability to mix nutritional modes (increasing heterotrophy) or compensate for the reduced light levels to resist the marginal conditions of the turbid zones and consequently may be adapted or acclimated to such events (Anthony and Larcombe, 2000).

The Abrolhos coastal reefs are amongst all those numerous examples of coral reefs exposed to a high input of terrigenous sediments. Previous studies by Leão (1982), Leão and Ginsburg (1997) and Leão et al. (2006) about the Abrolhos reefs, showed that the continent-derived sediment in the nearshore reef surroundings constitutes up to 70% of the surficial bottom sediment and has two major sources: the reworked sediment from the erosion of hinterland outcrops and the river loads transported to the reef area by longshore currents. Dutra et al. (2006) analyzing variations in the rate of sediment accumulated in sediment traps in several reefs of this region confirmed that the sediment rates and the amount of terrigenous mud were higher in the reefs located closer to the coastline than in the offshore reefs, and that these higher values had a negative effect on several parameters of reef vitality.

In the present study the evolution of sedimentation was evaluated through the use of sediment cores collected in the vicinities of three reefs in the coastal zone of Abrolhos, considering that, over the past decades, the continental region bordering the reefs has been subjected to urban and industrial developmental projects mainly related to tourism, fisheries and logging. More recently, in 2003, in the area facing the reefs, a harbor facility was built to export *Eucalyptus* logs (Lessa et al., 2005).

The main objective of this assessment was to acquire data on the sedimentation process that has occurred over the past decades in order to understand if the previously described pattern of surficial bottom sediment distribution in Abrolhos, which consisted of terrigenous mud in the nearshore reefs, to carbonate-dominant sediments towards the offshore reefs (Leão, 1982; Leão and Ginsburg, 1997; Leão et al., 2006; Dutra et al., 2006, Segal and Castro, 2011) is still a prevalent feature. The Abrolhos corals have been coexisting with high land-sourced sedimentation and consequent water turbidity for a long time. The response of these already threatened corals to global changes is still unknown.

2. Material and methods

2.1. The studied reefs

The Abrolhos reefs are the southernmost coral reefs of the Western Atlantic. They are located between 17°20′–18°00′S and 38°30′–39°30′W in an area approximately 200 km wide on the eastern Brazilian continental shelf – the Abrolhos Bank (Leão, 1996; Leão and Kikuchi, 2001). The region is shallow (no deeper than 30 m), and the shelf edge is only approximately 70 m deep. Between the coastal reefs and the coastline, depths are less than 15 m. The Abrolhos channel, which is up to 30 m deep, separates the coastal reefs from the Abrolhos islands and the outer reefs (Fig. 1).

Three reefs were selected to be studied. Two of them, Coroa Vermelha and Pedra de Leste, are located less than 15 km offshore at depths less than 10 m; and the Popa Verde Reef lies approximately 35 km from the coast at a depth of up to 20 m. The Coroa Vermelha reef is located approximately 15 km from the coastline (at 17°56′S and 39°11′W), it has an elongated form with irregular contours and is surrounded by small isolated coral pinnacles. The reef top, which emerges during low water levels, is flat and covered with patches of several shallow water reef organisms, such as zoanthids and turf and macro algae. In the windward border of the reef top there are thick crust layers of coralline algae and gastropod vermetids. There is a small carbonate sandy island in the southern part of the reef top. The Pedra de Leste reef is part of the Parcel das Paredes reefs, which is a group of shallow bank reefs and isolated coral pinnacles occupying an extension that is approximately 30 km long. This small bank reef, which is

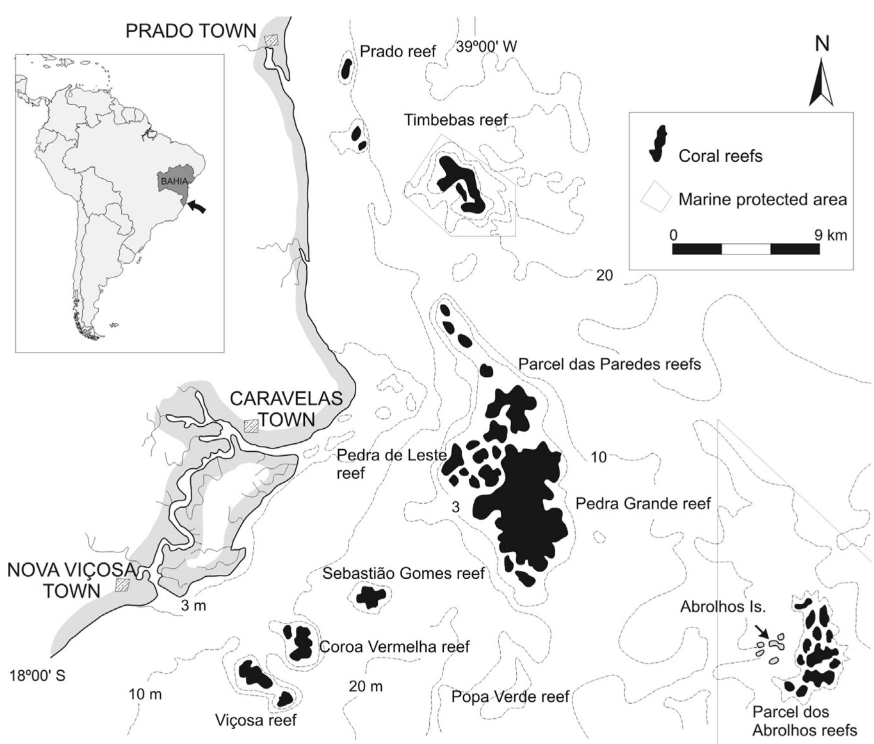

Fig. 1. Location of Abrolhos coral reefs, Bahia, Brazil.

approximately 3 km long, is located 12 km from the coast (at 17°46′S and 39°20W). The reef is parallel to the coastline and forms a small barrier between the leeward side of the larger reefs of Parcel das Paredes and the coast. Similarly to the Coroa Vermelha reef, its flat top emerges during low tides. The Popa Verde reef is located 35 km from the mainland. It is formed by isolated coral pinnacles at a depth of approximately 20 m from their base (see Fig. 1 for the approximate location). The morphology of these isolated coral pinnacles and the deep channels between them create an environment that functions as a trap for the accumulation of fine-grained sediment. These isolated coral pinnacles do not emerge during low water levels, and their tops are at depths of approximately 5 m (Leão et al., 2008).

The climate characteristics and the oceanographic parameters of the Southwestern Atlantic Ocean, where the Abrolhos Bank is located, are described in several articles in this issue such as Arruda et al., (2013), Soutelino et al. (2013); Teixeira et al. (2013).

2.2. Core collection and treatment

The coring sites were situated in the vicinity of the reef bases, where oceanographic conditions allowed for the best conditions of the coring operation. The cores of the recent sediments were taken by gently pushing 6 cm diameter PVC tubes into the bottom sediment surface. The coring operation occurred in September 2008 with scuba diving equipment. The length of the cores varied from 45 to 75 cm. The cores were sealed, frozen and stored in the Nuclear Physics Laboratory of the Federal University of Bahia (UFBA). Each core was sub-sampled in 1 cm sequences, and each sub-sample was prepared for the sediment analyses. The sub-samples were weighed before and after drying in an oven at 45 °C. Each sediment core had a different number of sub-samples. The Coroa Vermelha core was sub-sampled 45 times, the Pedra de Leste core had 73 sub-samples, and the Popa Verde core had 61 sub-samples.

2.3. Sediment analyses

The color of the sediment was determined in all the samples from the three cores using the Rock Color Chart (Goddard et al., 1963). Sediment grain-size was also determined for all samples from the three cores. This analysis was performed with a laser particle size analyzer that reported the cumulative frequencies of sand, silt and clay grain types. The calcium carbonate content was determined in five samples from each sediment core that were regularly distributed from the base to the top of the cores. This analysis followed a method that was developed for soil determination and adapted for marine sediments (EMBRAPA, 1997). The calcium carbonate content was calculated by digestion with HCl and titration of the excess of acid with NaOH. The composition of the muddy fraction of the sediment was determined by X-ray diffractometry in three sub-samples from each core. One sub-sample was taken from the base of the core, one was taken from the middle portion, and the third was taken from the top of the core. The constituent components of the sandy fraction were obtained by identifying 50 grains under a binocular microscope from five samples collected along the length of the cores.

2.4. ^{210}Pb dating

The ^{210}Pb activity was determined using gamma-spectrometry. The excess ^{210}Pb activity was measured based on the distribution of total ^{210}Pb minus the value of the supported ^{210}Pb. In the Coroa Vermelha core, ^{210}Pb was detectable down to sample 23, which corresponded to a 23 cm core depth. The ^{210}Pb activity in the Popa Verde core was detected until sample 22, which was at a 22.5 cm core depth. To determine the ^{210}Pb dating of the Pedra de Leste reef, a fourth core was used and the ^{210}Pb activity reached a depth of 27 cm.

3. Results and discussion

3.1. Sediment characteristics

3.1.1. Sediment color and the mineralogy of the fine-grained fractions

Olive gray hues predominated in the three cores, with a slight variation between the cores and along their lengths. Darker hues predominated in the sediments from the cores of the reefs located closer to the coast, the Coroa Vermelha and Pedra de Leste reefs, which are located 12 km and 15 km respectively from mainland. Lighter colors were seen in the sediment from the Popa Verde reef, which is located 35 km offshore.

Dark gray hues are commonly present in sediments with higher amounts of organic matter in the fine-grained fractions (silt and clay

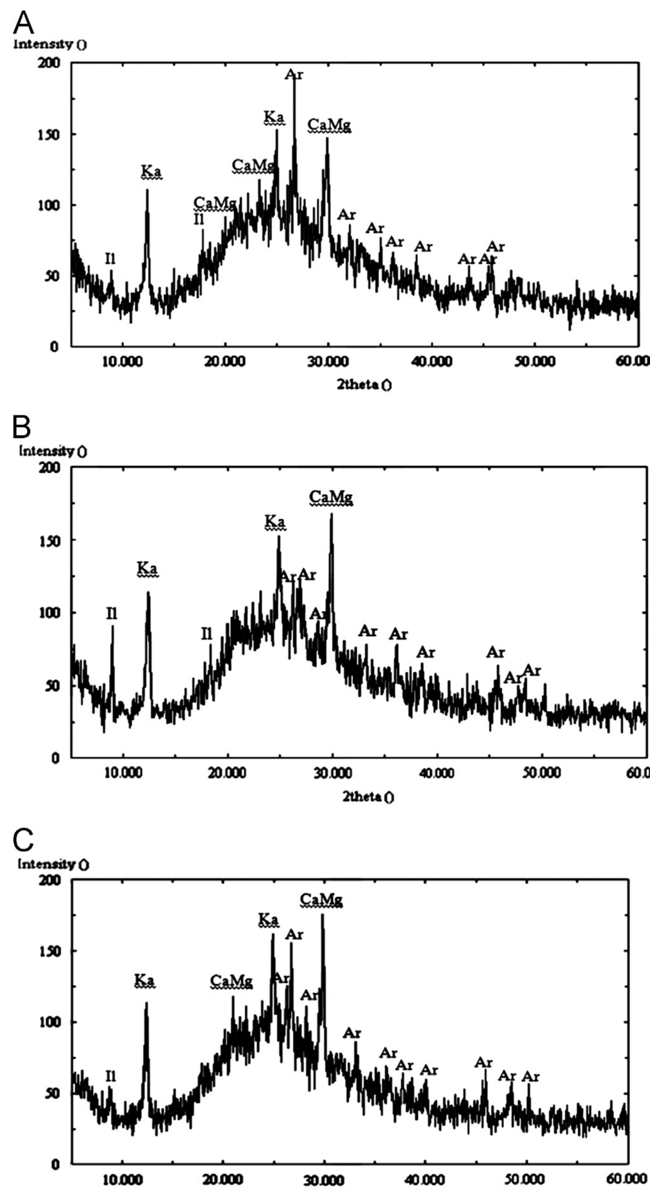

Fig. 2. X-ray difractograms showing the mineralogical composition of the mud size fraction of three samples from the top (A), middle portion (B) and base (C) of Coroa Vermelha reef core.

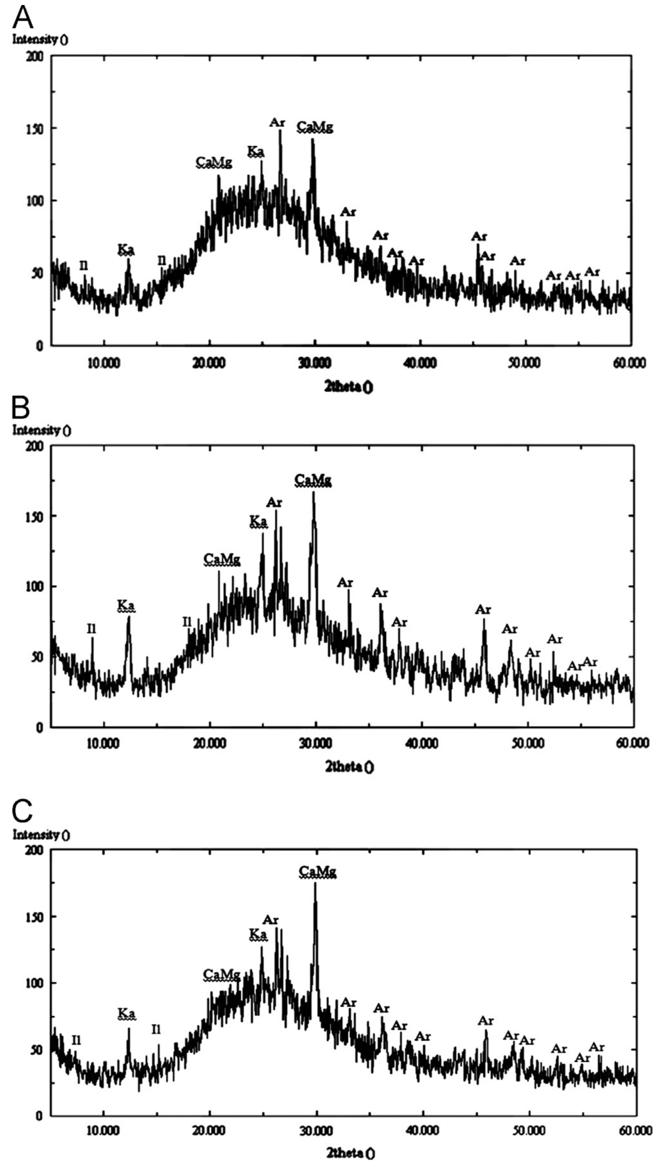

Fig. 3. X-ray difractograms showing the mineralogical composition of the mud size fraction of three samples from the top (A), middle portion (B) and base (C) of Pedra de Leste Reef core.

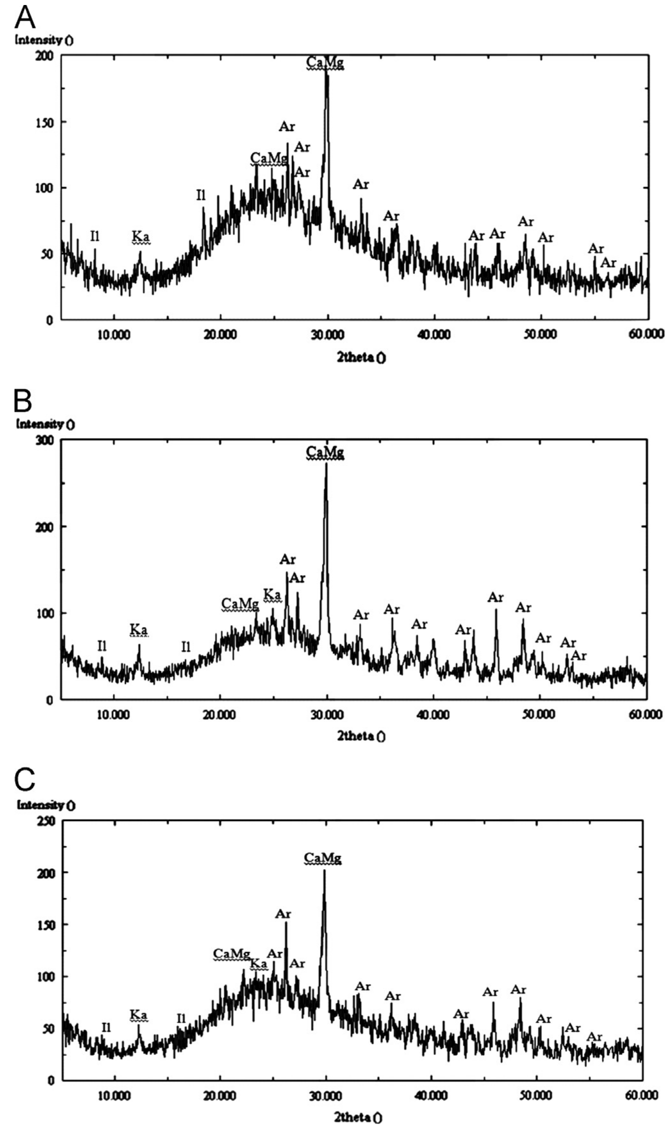

Fig. 4. X-ray difractograms showing the mineralogical composition of the mud size fraction of three samples from the top (A), middle portion (B) and base (C) of Popa Verde reef core.

sizes) and/or the presence of reduced iron sulfides (Love and Murray, 1963; Maiklein, 1967). These conditions are commonly found where there is deposition of fine-grained sediment from continental loads to the marine environment. The average percentage of these fine-grained sediments in each core was high (45–55%), and their mineralogical composition included the clay minerals illite and kaolinite, which both have continental origins. Organic matter is carried in association with clay minerals, and reduced iron can be found filling the micropores of skeletal grains, such as mollusk shells and foraminifer tests (Leão and Machado, 1989).

X-ray diffractograms of three samples from each core indicated larger amounts of illite and kaolinite in the Coroa Vermelha and the Pedra de Leste reefs, which are located closer to the coast, than in the Popa Verde reef, which is located more than 30 km offshore (Figs. 2–4). These results indicate that more continental-derived sediment has been deposited in the reefs closer to the coast. Leão (1982) and Leão and Ginsburg (1997) found similar results in the bottom surface sediment surrounding the Abrolhos reefs. The clay minerals illite and kaolinite were found in the muddy sediment surrounding the coastal reefs, whereas at the offshore reefs, the muddy sediment was predominantly composed of the carbonate minerals aragonite and calcite.

These findings indicate that clay minerals from a continental source are the major cause of the darker color of the muddy sediments surrounding the coastal reefs (Coroa Vermelha and Pedra de Leste), and the higher content of the carbonate minerals accounts for the lighter color of the sediments surrounding the reef that is located farther from the mainland (Popa Verde).

3.1.2. *Texture, composition and source of the constituent particles*

Sediment texture – the core sediment presented sand, silt and clay. The coarser textural sediment class was medium sand (grain size 0.250 mm). Considering the percentage of each size fraction, the sediment from all three cores could be classified as silty sand. Only samples from the Pedra de Leste reef had more than 10% clay (Fig. 5A–C).

In the Coroa Vermelha reef core, sand predominated (>50%) most of the core length, except for its base and top, where silt reached >50%. The clay size fraction contributed with less than 10% in the samples throughout the core (Fig. 5A). The Pedra de Leste reef core

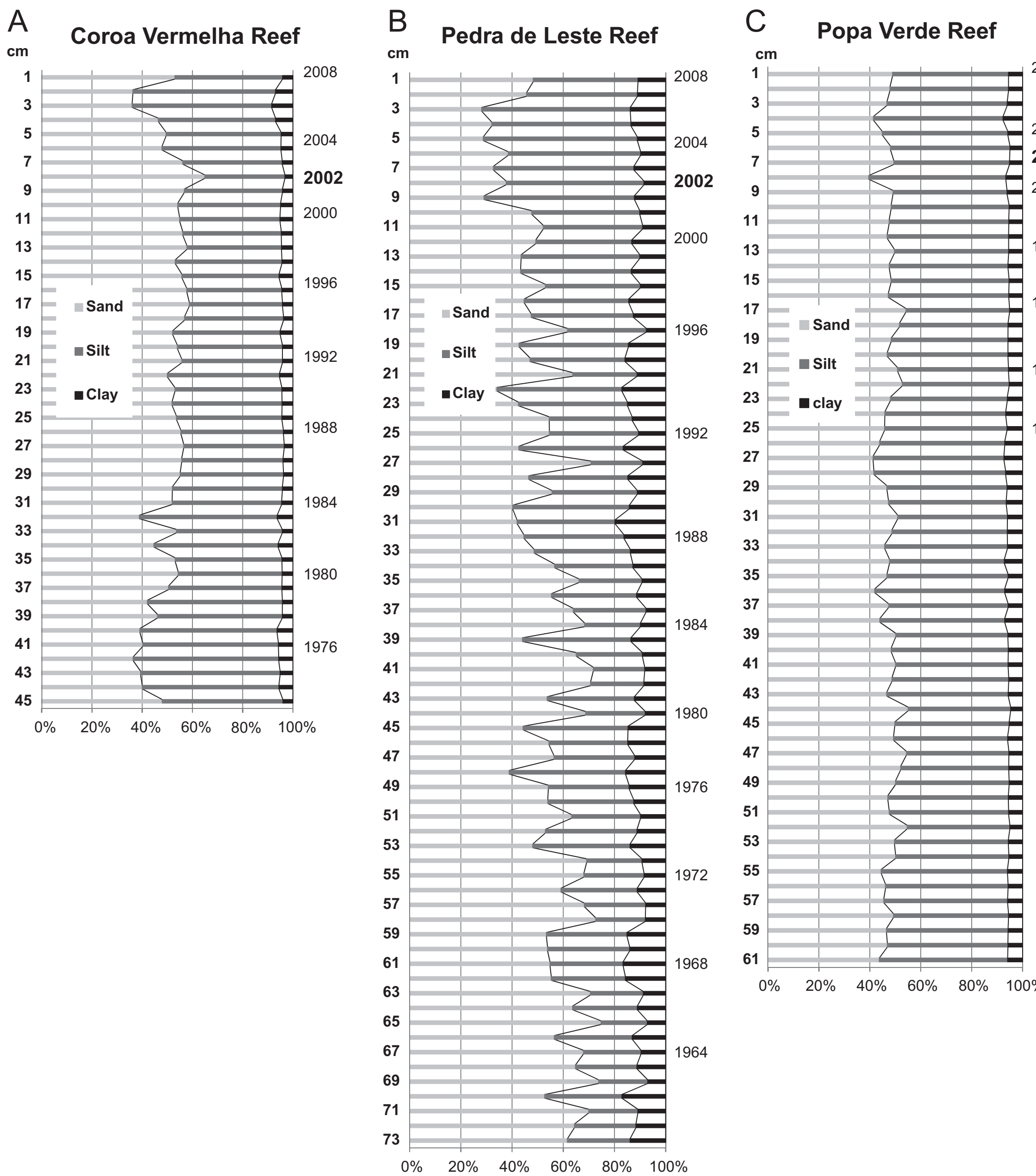

Fig. 5. Textural composition of sediment from the three studied reef cores. In A and B there is a slight increasing of the finer sediment (silt+clay) towards the cores top, approximately around 2002. In C is the core with the most homogenous distribution of the three sediment size fraction (sand, silt, clay) throughout its length.

showed the greatest variation in sediment grain size (Fig. 5B). Sand varied from 30% to 75%, while the percentage of silt varied from 20% to 60% with a slight increase toward the core top, and the clay size fraction was higher than 10% in most of the samples. Conversely, the sediment from the Popa Verde core had the most homogenous distribution of textural classes along the core (Fig. 5C). The percentage of sand and silt sizes varied between 40% and 50%, and the clay size represented less than 10% in all samples.

There was indication of a slight increase in the amount of finer-sized sediment (silt+clay) towards the reefs located closer to the coast. The distribution of these finer sediments, along the core showed a slight increase toward the top of the Coroa Vermelha and Pedra de Leste reefs, which may indicate that there was an increase in the accumulation of terrigenous mud, over recent years, in the vicinity of those nearshore reefs.

Composition and source of the sediment particles – siliciclastic and carbonate grains compose the sediment surrounding the Abrolhos coastal reefs. Siliciclastic grains are rarer than carbonates, with quartz grains most commonly composing the sandy sediment and the clay minerals kaolinite and illite composing the finer sediments. Fluvial suspended loads that are carried out to the marine system are the major source of the siliciclastic sediments, and they originate mainly from the sedimentary rock outcrops bordering the coastal zone (Leão and Ginsburg, 1997, Tintelnot et al., 1994).

Carbonates dominated the sediment from the Pedra de Leste (> 60%) and the Popa Verde (> 70%) reef cores compared to only 40% in the Coroa Vermelha reef core (Fig. 6A). Thus, $CaCO_3$ content increased in the sediment on the reefs concurrent to an increase in the distance from the coast. This same pattern in the distribution of the carbonate content was observed in bottom sediments surrounding the Abrolhos reefs in previous surveys performed in 1977 (Fig. 6C; Leão, 1982) and in 2000 (Fig. 6B; Leão et al., 2006), as well as in a more recent assessment carried out by Segal and Castro (2011). In the latter study, the amount of $CaCO_3$ reached approximately 50% in the reefs located closer to the coast (Pedra de Leste), and the carbonate content at a reef approximately 30 km from the coast was in the order of 65%. Studying the sedimentary evolution of the Abrolhos carbonate shelf, Almeida et al. (2013)

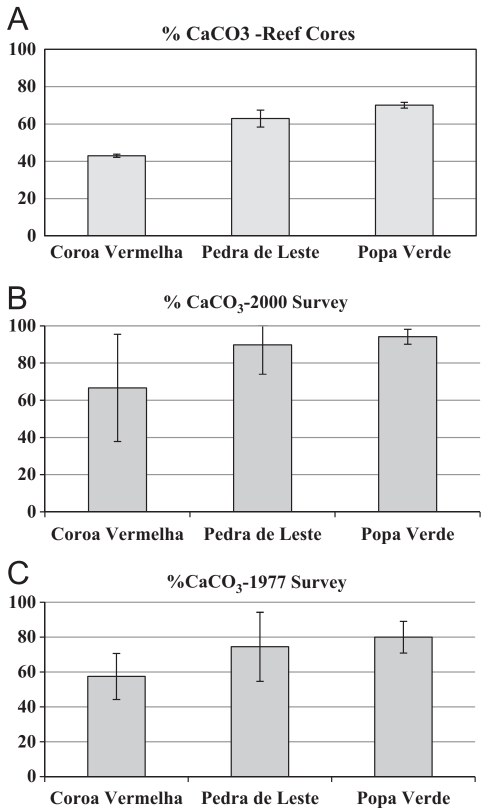

Fig. 6. Average (±SD) percent of $CaCO_3$ content in the sediment from the Coroa Vermelha, Pedra de Leste and Popa Verde reefs. (A) – data from the cores collected in 2008; (B) – data from surficial bottom sediment collected in 2000 (Dutra et al. 2006); and (C) – data from surficial bottom sediment collected in 1977 (Leão 1982).

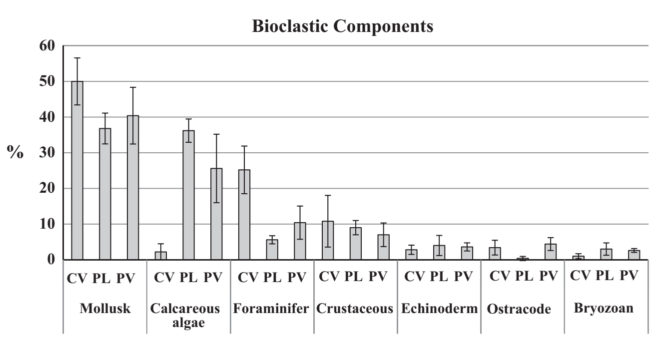

Fig. 7. Average (±SD) percent of major carbonate grains type of the sediment sand size fraction from Coroa Vermelha (CV), Pedra de Leste (PL) and Popa Verde (PV) reefs core.

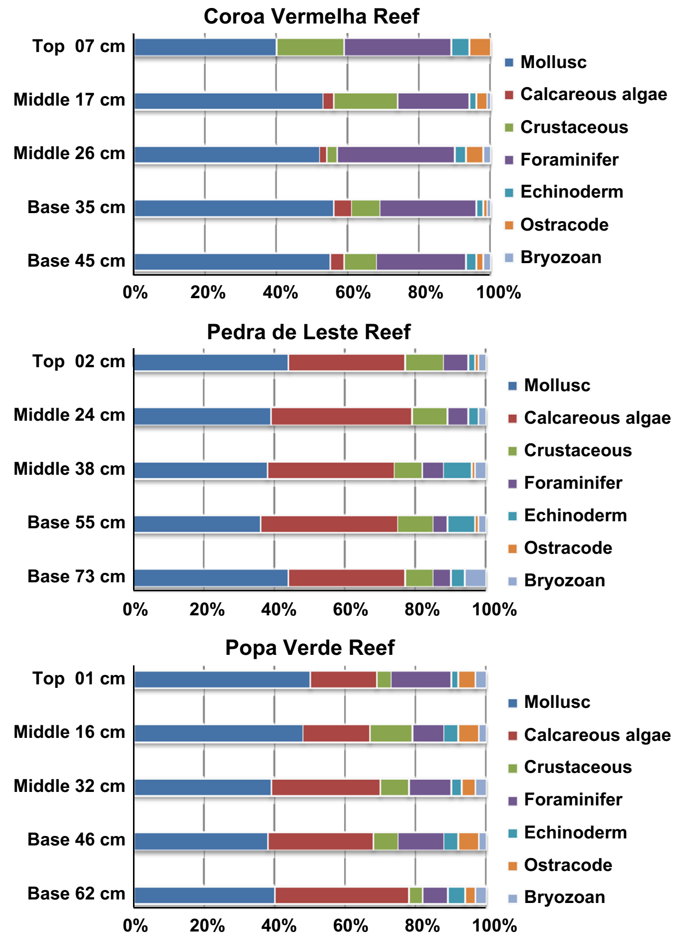

Fig. 8. Major biogenic components of the sand fraction of five samples from the Coroa Vermelha, Pedra de Leste and Popa Verde reefs cores. Samples were selected from the base, middle portion and top of each core. For location of samples see Fig. 5.

found that carbonate sediments surrounding the offshore reefs have predominated for more than 3 kyr.

The carbonate grains that predominated the coarser size fractions are represented by seven major particle types: mollusk shell fragments; debris of calcareous algae, including the encrusting red algae and the calcareous green algae; foraminifer tests; fragments of crustaceous skeletons, echinoderms, ostracod shells, and bryozoans (Fig. 7). Mollusks and calcareous algae fragments were predominant, accounting for more than 50% of the bioclastic content from two cores (Pedra de Leste and Popa Verde). For the Coroa Vermelha reef core, where the fragments of calcareous algae constituted only 2%, foraminifer tests were the predominant bioclastic components. Other components occurred as less than 10% of the total composition. Aside from the aforementioned exception in the Coroa Vermelha reef, there was not a marked difference in the composition of the bioclastic particles among the reefs studied or along the time of sediment deposition. The graphs in Fig. 8 illustrate the biogenic composition of five samples selected along the lengths of the cores, which show that there were no notable changes in the composition of the bioclastic content throughout the depositional layers in the last decades.

3.2. Sedimentation rate and accumulation of fine sediment

Sedimentation rate – the detection depth limit of the excess ^{210}Pb activity along the cores did not vary considerably. The detection limit was 24 cm in the Coroa Vermelha reef core, 27 cm in the Pedra de Leste reef core and 25 cm in the Popa Verde reef core. However, because the corresponding chronology (number of years per cm) of the ^{210}Pb dating varied in each core, the number of years dated was also different in each core (Table 1). The Pedra de Leste core had the highest number of dated years (46 years), while the Popa Verde core had the lowest number of years (25 years). In the Coroa Vermelha core, the depth limit of the ^{210}Pb activity allowed dating 33 years of sediment deposition.

The linear sedimentation rates, i.e., the vertical sediment accretion, in the studied reefs did not present great difference among the cores. The Coroa Vermelha and the Pedra de Leste reef, which are located closer to the coast, had the lowest values (6.94 mm/year and 5.80 mm/year respectively), whereas in the Popa Verde core, which is the reef farther from the continent, the rate was 10.04 mm/year. These differences may be due to different hydrodynamic conditions among the sites. The Coroa Vermelha and Pedra de Leste reefs, which are shallower sites, are prone to

Table 1
Linear sedimentation rates (sediment vertical accretion), core cronology and ^{210}Pb dating of Coroa Vermelha, Pedra de Leste and Popa Verde reefs.

Reefs	Linear sediment accumulation rate (mm/year)	Core chronology (cm/year)	Limit of ^{210}Pb detection (cm)	Number of years dated (years)
Coroa Vermelha	6.94	1.4/01	24	33 (~1975–2008)
Pedra de Leste	5.80	1.7/01	27	45 (~1963–2008)
Popa Verde	10.04	1.0/01	25	25 (~1983–2008)

Table 2
Mean (±SD) of the amount of muddy sediment (silt+clay) accumulated during three periods: (1) the whole period of accumulation of the cores; (2) the time of accumulation between 2002 and 2008; and (3) the time prior 2002. N=number of samples.

Reefs	In the whole period, %	In the period between 2002 and 2008 %	In the period before 2002 %
Coroa Vermelha	49.9 ± 6.9, $N=45$	57.5 ± 7.9 $N=4$	49.2 ± 6.4 $N=41$
Pedra de Leste	46.9 ± 11.7 $N=73$	54.5 ± 0.9 $N=4$	46.5 ± 11.8 $N=69$
Popa Verde	52.5 ± 3.3 $N=61$	51.0 ± 2.7 $N=6$	52.3 ± 3.2 $N=55$

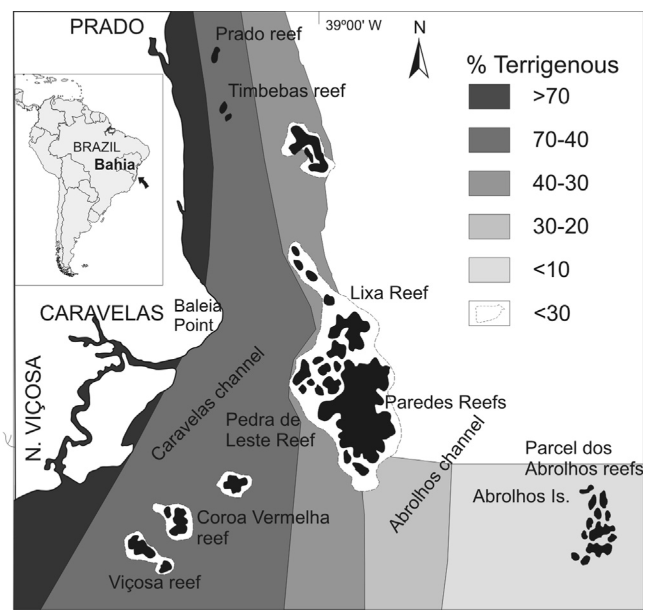

Fig. 9. Map illustrating the percentage of terrigenous sediment in the area of Abrolhos coral reefs. Amount of terrigenous content in the size fraction >0.062 mm was determined by point counting and in the mud fraction was determined by acid dissolution. According to Leão (1982).

higher and more frequent events of turbulence that cause resuspension and the winnowing of fine sediment. At the Popa Verde reef, accumulation of muddy sediment may be enhanced.

Accumulation of fine sediment – the graphs A–C of Fig. 5 illustrate the distribution of the major grain size types (sand, silt, clay) of the sediment from the three cores. They show that in the Coroa Vermelha and Popa Verde cores there was not much variation in the amount of different grain size types along the cores' length, except for the base and top of the Coroa Vermelha core where the muddy sediment (silt+clay) reached >50%. In the Pedra de Leste core there was, also, a slight increase of the muddy sediment towards the core top. These figures suggest that there has been a possible increase, over the last decade, of the deposition of muddy sediment (silt+clay sizes) towards the reefs located nearest to the coast (Coroa Vermelha and Pedra de Leste), though a larger sample would be required to establish such a change definitively.

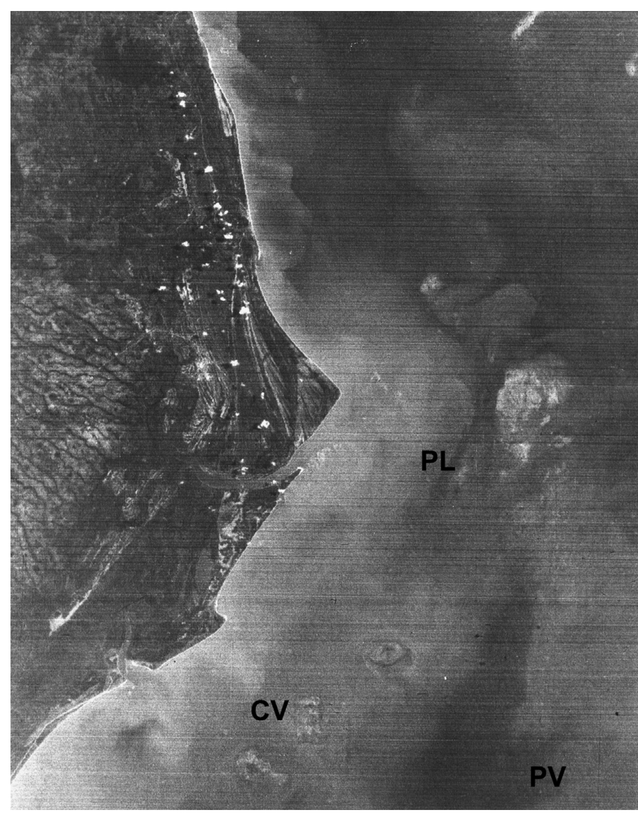

Fig. 10. Landsat image of Abrolhos coastal reefs illustrating the continent-derived sediment plume. PL – Pedra de Leste Reef; CV – Coroa Vermelha Reef; PV – approximate location of Popa Verde Reef.

In order to evaluate the amount of this supposed increase in the accumulation of fine sediment in the coastal waters of Abrolhos, over the past decades, the percentage of the muddy sediment (silt+clay sizes) that was deposited was measured considering the following three periods: (1) the total time of the

Table 3
Average (±SD) of three coral parameters from nearshore and offshore reefs of Abrolhos, measured along six belt (10 m long) transects at each reef site, during a survey performed in 2002 (according to Kikuchi et al. (2010)). N=number of reef sites.

Reef area	Abrolhos					
	Nearshore			Offshore		
Reef names	Lixa N=5	Pedra de Leste N=3	Paredes N=5	Popa Verde N=5	Sta. Barbara Is. N=3	Parcel dos Abrolhos N=6
Living coral cover (%)	6.8 ± 2.2	5.6 ± 0.4	8.5 ± 2.7	11.0 ± 1.8	12.4 ± 4.2	11.4 ± 2.8
Density of coral colonies (#0.60 m^2)	71.0 ± 25.8	11.0 ± 1.4	82.8 ± 14.8	144.2 ± 6.5	125.0 ± 77.5	110.0 ± 29.8
Number of coral species	5.4 ± 0.5	4.5 ± 0.7	5.4 ± 0.9	5.6 ± 0.5	5.5 ± 1.0	6.3 ± 1.6

Table 4
Average (±SD) of three coral parameters from nearshore reefs of two reef areas along the coast of the state of Bahia, measured along six belt (10 m long) transects at each reef site, during a survey performed in 2003 (According to Kikuchi et al. (2010)). N=number of reef sites.

Reef areas	North Coast			Tinharé and Boipeba Islands			
Reef names	Praia do Forte N=2	Itacimirim N=2	Guarajuba N=2	Praia do Quadro N=1	Garapuá N=1	Moreré N=1	Bainema N=1
Living coral cover (%)	2.4 ± 2.6	0.7 ± 0.1	0.8 ± 0.1	2.7 ± 1.3	5.3 ± 2.6	2.8 ± 1.4	2.0 ± 0.7
Density of coral colonies (#0.60 m^2)	1.0 ± 1.4	2.0 ± 0.1	1.0 ± 0.0	25.0 ± 0.0	32.0 ± 0.0	13.0 ± 0.0	13.0 ± 0.0
Number of coral species	0.5 ± 0.7	1.0 ± 0.0	1.0 ± 0.0	4.0 ± 0.0	5.0 ± 0.0	6.0 ± 0.0	4.0 ± 0.0

sediment deposition, i.e., the entire length of the cores; (2) the sediment accumulated during the period between 2002 and 2008, and (3) the sediment accumulated before 2002 (Table 2).

The results showed that near the Popa Verde reef, the amount of mud accumulated during the three evaluated periods varied between 51.0 ± 2.7% and 52.5 ± 3.3%, with a slight decrease after 2002. In contrast, in the vicinity of the Coroa Vermelha and Pedra de Leste reefs, the amount of fine sediment (silt+clay) accumulated after 2002 increased 8%. The sediment of the Popa Verde reef core was predominantly composed of $CaCO_3$ grains (up to 70%) (see Fig. 6A), indicating that the sediment deposited in its surroundings was predominantly produced by the disintegration of carbonate skeletons from the in situ biota. This sediment has accumulated in the bottom of the channels between the coral pinnacles and has not varied during the past decades. Contrarily, in the Coroa Vermelha and Pedra de Leste reefs, the amount of carbonate content deposited over the last decades was lower, varying between 40% and 60% (see Fig. 6A). These numbers suggest that the increased deposition of muddy sediments in the vicinity of the nearshore reefs of Abrolhos, approximately after 2002 (see Fig. 5 A, B), is mostly due to the deposition of terrigenous mud of continental origin, indicated by the larger amount of the clay minerals illite and kaolinite in their composition (see Figs. 2–4).

The pattern of distribution of the reef sediments in Abrolhos, from a transition of terrigenous-dominant in the nearshore zone to carbonate-dominant towards the offshore reefs, was described by Leão (1982) and Leão and Ginsburg (1997) in the early 1980s, as it is illustrated in the map of Fig. 9. This is a common feature along the coast of the state of Bahia, a similar trend was also described in the zone of the nearshore reefs of the north coast of the state (Nolasco and Leão, 1986; Kikuchi and Leão 1998; Kikuchi, 2000). The hydrologic processes acting in the coastal zone of Abrolhos originate longshore currents that promote sediment transport parallel to the coast (Bittencourt et al., 2000). The sediment deposits mainly in the channel that separates the nearshore reefs from the shoreline, forming a plume of sediment that is illustrated in the satellite image of Fig. 10.

Increasing rates of muddy terrigenous sediment deposition could be highly deleterious to the vital condition of coral reefs (Bak, 1974; Loya, 1976; Dodge and Vaisnys, 1977; Cortés and Risk, 1985; Rogers, 1990; Brown et al., 2002). Dutra et al. (2006) comparing the biotic parameters of the Abrolhos reefs with recent sedimentation rates found that sediment accumulation rates were negatively related to the vitality of the reefs. Average sedimentation rates higher than 10 mg cm^{-2} day^{-1} with high percentage of terrigenous mud were negatively related to the coral health indicators (living coral cover, coral species diversity, size of coral colonies and density of coral recruits). This condition of sediment stress for the coral community of the nearshore reefs of Abrolhos was also found during a survey performed in 2002, by comparing the coral health parameters of three nearshore and three offshore reefs (Table 3). The values of the reefs vitality indices (living coral cover, density of coral colonies and coral species diversity) were much lower in the nearshore reefs (Lixa, Pedra de Leste – studied in the present assessment, and Paredes) compared with the offshore reefs (Popa Verde, studied in the present assessment, Santa Barbara Islands and Parcel dos Abrolhos) (Kikuchi et al., 2010). Similarly, low numbers for the coral health indices in nearshore reefs were found in two other areas, the north coast of the state of Bahia and the region of the Tinharé and Boipeba islands (Table 4) (Kikuchi et al., 2010), where deposition of terrigenous mud also occurs (Nolasco and Leão, 1986, Leão et al., 2006).

4. Conclusion

Our results show that the composition and the distribution of the sediment from the studied reef cores are broadly similar to the previously described sedimentation pattern for the Abrolhos reefs, which consisted of terrigenous mud in the nearshore reefs to carbonate-dominated sediment towards the offshore reefs. The presence of terrestrial clay minerals indicates a continental source for the muddy sediment surrounding the reefs located nearest the coast, and the carbonate content, mainly composed of reef derived constituents, shows an increase around the reefs concurrent to an increase of the distance from the coast. These sedimentation features did not show notable changes throughout the last decades.

On the other hand, measurements of the amount of sediment accumulated in the last decades provide evidence of an increase in the deposition of terrigenous mud on the vicinity of the inshore reefs. This increase is an indication that anthropogenic interference on the coastal zone, such as dredging, deforestation and coastal development, may become a significant impact on the reefs in a short time period, despite the fact that the local coral fauna have been surviving in turbid waters for a long time. This situation is more critical facing the fact that there will be a need of the reef fauna and flora to adjust to the superimposed effects of climate changes. To minimize this situation, there is an urgent need for the development of new management strategies to protect the already disturbed Abrolhos coastal reefs.

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References

Almeida, C.M., Barbosa, C.F., Cordeiro, R.C., Seoane, J.C.S., Fermino, G.M., Silva, P.D., Turcq, B.J., 2013. Paleoecology of a 3-kyr biosedimentary record of a coral reef supporting continental shelf. Continental Shelf Research.

Anthony, K.R.N., 2000. Enhanced particle-feeding capacity of corals on turbid reefs (Great Barrier Reef), Australia. Coral Reefs 19, 59–67.

Anthony, K.R.N., Fabricius, K.E., 2000. Shifting roles of heterotrophy and autotrophy in coral energetics under varying turbidity. Journal of Experimental Marine Biology and Ecology 232, 85–106.

Anthony, K.R.N., Larcombe, P., 2000. Coral reefs in turbid waters: sediment–induced stresses in corals and likely mechanisms of adaptation. In: Proceedings of the 9th International Coral Reef Sympsium, vol. 1, pp. 239–244.

Arruda, W.Z., Campos, E.J.D., Soutelino, R.G., Silveira, I.C.A., 2013. Events of equatorward translation of the Vitoria Eddy. Continental Shelf Research 70, 61–73.

Babcock, R., Smith, L., 2000. Effects of sedimentation on coral settlement and survivorship. In: Proceedings of the 9th International Coral Reef Symposium, vol. 1, pp. 245–248.

Bak, R.P.M., 1974. Available light and other factors influencing growth of stony corals through the year in Curaçao. In: Proceedings of the 2nd International Coral Reef Symposium, vol. 2, pp. 229–234.

Bittencourt, A.C.S.P., Dominguez, J.M.L., Martin, L., Silva, I.R., 2000. Patterns of sediment dispersion coastwise the State of Bahia, Brazil. Anais da Academia Brasileira de Ciências 72, 271–287.

Brown, B.E., Clarke, K.R., Warwick, R.M., 2002. Serial patterns of biodiversity change in corals across shallow reef flats in Ko Phuket, Thailand, due to the effects of local (sedimentation) and regional (climatic) pertubations. Marine Biology 141, 21–29.

Brown, B.E., Howard, L.S., 1985. Assessing the effects of "stress" on reef corals. Advances in Marine Biology 22, 1–63.

Cortés, J., Risk, M.J., 1985. A reef under siltation stress: Cauhita, Costa Rica. Bulletin of Marine Science 36, 339–356.

Dodge, R.E., Aller, R.C., Thompson, J., 1974. Coral growth related to ressuspension of bottom sediments. Nature 247, 574–676.

Dodge, R.E., Vaisny, J.R., 1977. Coral populations and growth patterns: response to sedimentation and turbidity associated with dredging. Journal of Marine Research 35, 715–730.

Dutra, L.X.C., Kikuchi, R.K.P., Leão, Z.M.A.N., 2006. Effects of sediment accumulation on reef corals from Abrolhos, Bahia, Brazil. Journal of Coastal Research (Royal Palm Beach) 39, 639–644.

Edinger, E.N., Jompa, J., Limmon, G.V., Widjatmoko, W., Risk, M., 1998. Reef degradation and coral biodiversity in Indonesia: effects of land-based pollution, destructive fishing practices and changes over time. Marine Pollution Bulletin 36, 617–630.

EMBRAPA, 1997. Manual de métodos de análise do solo, 2nd Ed. Empresa Brasileira de Pesquisa Agropecuária, Ministério da Agricultura, Rio de Janeiro, Brasil. (24p.).

Goddard, E.N., Trask P.D., Ford, R.K., Rove, O.N., Singewald, J.T., Overbeck, R.M., 1963. Rock-Color Chart. Printed in the Netherlands by Huyskes-Enschede. Reprinted by Henry, R. Aldrich Publication Fund.

Hodgson, G., 1993. Sediment damage to reef corals, Colloquium on Global Aspects of Coral Reefs: Health, Hazard and History, Rosenstiel School of Marine and Atmospheric Science. University of Miami, pp. 298–303.

Hughes, T.P., Tanner, J.E., 2000. Recruitment failure, life histories, and long-term decline of Caribbean corals. Ecology 81, 2250–2263.

Kikuchi, R.K.P., 2000. Evolução dos recifes e das comunidades de corais hermatípicos da plataforma continental norte da Bahia durante o Holoceno (Tese de Doutorado). Universidade Federal da Bahia. (147 pp.).

Kikuchi, R.K.P., Leão, Z.M.A.N, Oliveira, M.D.M., 2010. Spatial patterns of AGRRA vitality indexes in Southwestern Atlantic Reefs. International Journal of Tropical Biology 58, 1–31.

Kikuchi, R.K.P., Leão, Z.M.A.N., 1998. The effects of Holocene sea level fluctuation on reef development and coral community structure, Northern Bahia, Brazil. Anais da Academia Brasileira de Ciências 70, 159–171.

Larcombe, P.W., Costen, A., Woolfe, K.J., 2001. The hydro-dynamic and sedimentary setting of nearshore coral reefs, Central Great Barrier shelf, Australia: Paluma Shoals, a case study. Sedimentology, 48; , pp. 811–835.

Leão, Z.M.A.N., 1982. Morphology, Geology and Developmental History of the Southernmost Coral Reefs of Western Atlantic, Abrolhos Bank, Brazil (Ph.D. dissertation). Rosentiel School of Marine and Atmospheric Science, University of Miami, Florida, USA. (218 pp).

Leão, Z.M.A.N., 1996. The coral reefs of Bahia: morphology, distribution and the major environment impacts. Anais da Academia Brasileira de Ciências 68, 439–452.

Leão, Z.M.A.N., Dutra, L.X.C., Spano, S., 2006. The characteristics of bottom sediments. In: Dutra, G.F., Allen, G.R., Werner, T., Mckenna, S. (Eds.), The Rapid Marine Biodiversity Assessment of the Abrolhos Bank, Bahia, Brazil. RAP Bulletin of Biological Assessment, Washington, pp. 75–80.

Leão, Z.M.A.N., Ginsburg, R.N., 1997. Living reefs surrounded by siliciclastic sediments: the Abrolhos coastal reefs, Bahia, Brazil. In: Proceedings of the 8th International Coral Reef Sym, pp. 1767–1772.

Leão, Z.M.A.N., Kikuchi, R.K.P., 2001. The Abrolhos reefs of Brazil. In: Seeliger, U., Kjerfve, B. (Eds.), Coastal Marine Ecosystems of Latin America. Springer-Verlag, Berlim, pp. 83–96.

Leão, Z.M.A.N., Machado, A.J., 1989. Variação de cor dos grãos carbonáticos de sedimentos marinhos atuais. Revista Brasileira de Geociencias 19, 87–91.

Leão, Z.M.A.N., Oliveira, D.M., Kikuchi, R.K.P., 2008. Os recifes de coral da APA Ponta da Baleia, Bahia. vol. 8. OLAM-Ciência e Tecnologia, Rio Claro, São Paulo, Brasil, pp. 287–315.

Lessa, G.C., Teixeira, C.E., Castro, C.B., 2005. Variabilidade da turbidez e taxas de sedimentação na zona costeira de Caravelas (Ba): existem evidências e impacto das atividades de dragagem do canal do Tomba nos recifes de coral? Associação Brasileira de Estudos do Quaternário (ABEQUA), Vila Velha, Espírito Santo. CD-Rom.

Love, L.G., Murray, J.W., 1963. Biogenic pyrite in recent sediments of Christchurch Harbour, England. Journal of American Science 261, 433–448.

Loya, Y., 1976. Effects of water turbidity and sedimentation on the community structure of Puerto Rican corals. Bulletin of Marine Science 26, 450–466.

Maiklein, W.R., 1967. Black and brown speckled foraminiferal sand from the southern part of the Great Barrier Reef. Journal of Sedimentary Petrology 37, 1023–1030.

Miller, C., Kosmynin, V., 2008. The effects of hurricane-deposited mud on coral communities in Florida. In: Proceedings of the 11th International Coral Reef Symposium, vol. 2, pp. 776–780.

Nolasco, M.C., Leão, Z.M.A.N., 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, 4. Balkema Publishers, Rotterdam, pp. 159–190.

Ogston, A.S., Storlazzi, C.d., Field, M.E., Presto, M.K., 2004. Currents and suspended sediment transport on a shallow reef flat: south-central Molokai, Hawaii. Coral Reefs 23, 559–569.

Otero, E., Carbery, K.K., 2005. Chlorophyll a and turbidity patterns over coral reefs systems of La Parguera Natural Reserve, Puerto Rico. Revista de Biologia Tropical 53, 1–6.

Perry, C.T., Smithers, S.G., Johnson, K.G., 2009. Long-term coral community records from Lugger Shoal on the terrigenous inner-shelf of the central Great Barrier Reef, Australia. Coral Reefs 28, 941–948.

Potts, D.C., Jacobs, J.R., 2000. Evolution of reef-building scleractinian corals in turbid environments: a paleo-ecological hypothesis. In: Proceedings of the 9th International Coral Reef Symposium, vol. 1, pp. 249–254.

Rogers, C.S., 1990. Responses of coral reefs and reef organisms to sedimentation. Marine Ecology 62, 185–202.

Segal, B., Castro, C.B., 2011. Coral community structure and sedimentation at different distances from the coast of the Abrolhos Bank, Brazil. Brazilian Journal of Oceanography 59, 119–129.

Soutelino, R.G., Gangopadhyay, A., Silveira, I.C.A., 2013. The holes of vertical shear and topography on the eddy formation near the site of origin of the Brazil Current. Continental Shelf Research.

Teixeira, C.E.P., Lessa, G.C., Cirano, M., Lentini, C.A.D., 2013. The inner shelf circulation on the Abrolhos Bank, 18°S, Brazil. Continental Shelf Research 70, 13–26.

Tintelnot, M., Brichta, A., Morais, J.O., Iron, G., 1994. Clay mineralogy of river sediments on the Brazilian coast. Anais XXXIX Congresso Brasileiro de Geologia 1, 317–319.

Woolfe, K.J., Larcombe, P., 1999. Terrigenous sedimentation and coral reef growth: a conceptual framework. Marine Geology 155, 331–345.