Caribbean Journal of Science, Vol. 45, No. 2-3, 151-167, 2009
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Modern Sedimentation in a Mixed Siliciclastic-Carbonate Coral Reel Environment, La Parguera, Puerto Rico

K. RYAN-MISHKIN[1,*], J. P. WALSH[1,2,**], D. R. CORBETT[1,2], M. B. DAIL[3], AND J. A. NITTROUER[4]

[1]*Department of Geological Sciences, East Carolina University, Greenville, NC, 27858*
[2]*Institute for Coastal Science and Policy, East Carolina University, Greenville, NC, 27858*
[3]*ENSR | AECOM, 7041 Old Wake Forest Rd., Suite 103, Raleigh, NC, 27616*
[4]*Department of Geological Sciences, University of Texas, Austin, TX*
**Current affiliation: School of Earth and Environmental Sciences, Queens College, City University of New York, 65-30 Kissena Blvd., Flushing, NY 11367*
***Corresponding Author: Tel: 252.328.5431; e-mail: walshj@ecu.edu*

ABSTRACT.—**Mixed siliciclastic-carbonate systems are globally distributed throughout the tropics, but have received limited research attention on active sedimentation. A detailed examination of sedimentation near La Parguera, Puerto Rico has been conducted to better understand this mixed system on the border of the Caribbean Sea, along the southwest coast of the island. This study includes an assessment of the sediment composition and texture of material accumulating on the La Parguera seabed, as well as an examination of excess ^{210}Pb-activity profiles and accumulation rates. Variations in grain-size distribution and carbonate and loss-on-ignition (LOI) percentages are examined on the shelf. More specifically, an increase in carbonate percentage and a decrease in the LOI fraction in the seaward direction are evident. Excess ^{210}Pb-activity profiles display steady-state and non-steady-state profiles. Steady-state profiles are most common and display a range of thicknesses in surface-mixed layers (3 - >20 cm). Non-steady-state profiles are observed in some nearshore settings, reflecting episodic deposition or human influence. Greatest sediment accumulation rates are generally found close to shore, where maximum rates approach 0.5 cm y^{-1}. Sediment accumulation rates in more seaward reef areas are approximately 0.2 cm y^{-1}. Mass accumulation rates calculated from the composition and accumulation rate data indicate there is a seaward decrease in terrestrial (non-carbonate and LOI-free) sediment flux to the seabed. Fluxes of terrestrial sediment in nearshore areas are typically several times higher (>0.05 vs. 0.01 g cm^{-2} y^{-1}). These trends in composition and mass accumulation reflect sediment supply and dispersal from terrestrial and marine sources along with the reduced wave climate from reef sheltering. A preliminary sediment budget suggests the majority (61%) of terrestrial sediment supplied to the shelf is stored locally. Sediment accumulating on the shelf is principally carbonate (85%) and is assumed to be marine-derived. Terrestrial (12%) and LOI (3%) material represent considerably smaller, but significant constituents of the sediment stored. Collectively, data suggest terrestrial sedimentation is a lesser, but increasing sedimentary component of the La Parguera mixed siliciclastic-carbonate setting.**

KEYWORDS.—**sedimentation, La Parguera, terrestrial, carbonate, sediment, budget**

INTRODUCTION

Where land meets the ocean, sedimentary dynamics are complex because of the diversity of processes at work (e.g., river discharge, waves, tides). This complexity is increased in a mixed siliciclastic-carbonate environment where fluvial sediments are supplied to areas with organisms producing a significant amount of sediments, and the former can potentially impact the latter with changes in environmental conditions. The direct and indirect effects of sedimentation on coral reefs are well-documented (Fabricius 2005); however, the active sedimentation of tropical environments is less documented. Other than the expansive Great Barrier Reef (Belperio 1983; Belperio & Searle 1988; Larcombe & Woolfe 1999; Larcombe et al. 2001; Dunbar & Dickens 2003; Orpin et al. 2004), mixed siliciclastic-carbonate coral reef settings have received relatively limited research attention. Improved comprehension of sediment flux and storage in mixed systems may

provide insights into how human and natural perturbations may affect coral reef ecosystems. In this evaluation of the sedimentation processes on the La Parguera shelf, the major objectives are to: (1) examine the distribution of sedimentary components, (2) determine rates of sediment and mass accumulation on a decadal time scale, and (3) create a preliminary sediment budget for carbonate and terrestrial components.

Regional setting

Geology and climate

The study area is located adjacent to La Parguera, a coastal village in southwestern Puerto Rico. The area lies in the rainshadow of an east-west trending mountain range, Cordillera Central, and as a result, receives relatively little precipitation (average rainfall = 75 cm y^{-1}) (Ewel and Whitmore 1973). With no perennial rivers draining into the study area, terrestrial sediment flux into the marine environment is relatively low. It is likely that the low sediment supply is largely in the form of sheet runoff and ephemeral stream transport induced by strong rainfall events. Because of a mean westward flowing coastal current (Warne et al. 2005), rivers upstream (eastward) of La Parguera may provide an additional sediment source. Several moderately sized rivers drain the southern coast of Puerto Rico, contributing an average of 3.5×10^6 t yr^{-1} (Warne et al. 2005). Río Loco and Río Guayanilla, which discharge approximately 12 and 28 km east of La Parguera, supply an estimated 55,120 t yr^{-1} and 128,790 t yr^{-1} of suspended sediment to the coastal ocean, respectively. Sediment yields of southwestern Puerto Rico range from 1000 to 4300 t km^{-2} y^{-1} (Warne et al. 2005). Hurricanes, which frequently transverse Puerto Rico, may produce significant sediment runoff from intense and voluminous rainfall and impact coastal waters, but sedimentation associated with these events are not specifically addressed here due to the nature of the data collected.

Oceanography

The major currents affecting southwest Puerto Rico are the Caribbean Current, part of the North Atlantic circulation, and the North Equatorial Current, a major controller of the Puerto Rico littoral current system (Warne et al. 2005). Littoral currents generally flow westward, however, due to the irregular coastline, they are often deflected causing an alongshore variation in transport pathways; also, with wind variations the magnitude and the direction of the currents can vary. Sea surface temperatures average 27 °C with a maximum in July and a minimum in January. The La Parguera shoreline experiences a small diurnal tidal range (average = 0.3 m), and southeasterly winds near the coast typically range from 3.1 to 7.7 m s^{-1} (Warne et al. 2005).

Benthic habitats

Using a combination of orthorectified aerial photographs and satellite images, the NOAA Biogeography Team created a benthic habitat map of all of Puerto Rico; reefs from this dataset along with topography and bathymetric data are shown in Figure 1 (Kendall et al. 2001). The La Parguera shelf is suitable for coral reef growth, mangroves, and seagrasses because of its morphology, low rainfall, and low runoff (García-Sais et al. 2005), and as a result the study area has extensive mangroves and reefs (Fig. 2).

The shelf is a carbonate platform that extends 8 to 10 km from the coastline. Shelf depths reach ~25 m, beyond which an abrupt drop is observed at the margin of the submerged shelf reef. The bathymetry is partially a result of the karstic nature of the underlying Cretaceous limestone produced during lowered sea level as well as Pleistocene reef growth that occurred during interglacial high-stands. The modern shelf was submerged and exposed several times during the late Quaternary. Subsequent modification of the bathymetry has resulted from Holocene reef growth and sediment deposition (Morelock et al. 1977). Emergent reefs in addition to submergent reefs are in the form of linear and patch reefs and are home to a diverse population of corals. The dominant scleractinian corals include *Acropora palmata*, *Montastraea annularis*, *Agaricia agaricites*, *Porites astreoides*, and *Colpophyllia natans* (Morelock et al.

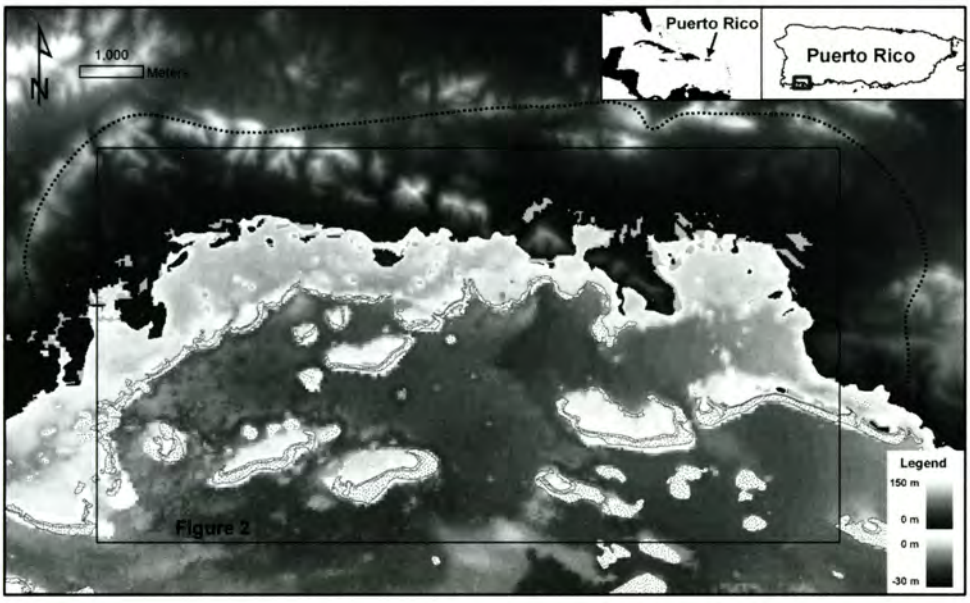

FIG. 1. Topography, bathymetry and reefs in a region encompassing the study area. The inset highlights the region in Puerto Rico. The location of the study area is indicated by the box which also defines the coverage of Figure 2. The dashed line depicts the approximate drainage area boundary; the land area circumscribed by this line is used for generating the local terrestrial sediment production in the sediment budget. Reef structures from the NOAA benthic habitat dataset (Kendall et al., 2001) are denoted by a stippled pattern.

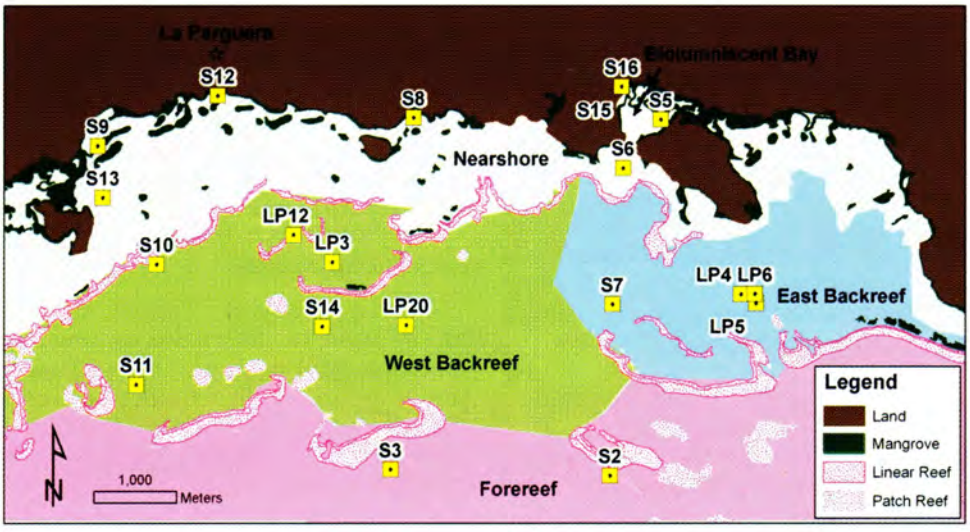

FIG. 2. Core locations and sedimentation regions in this study. Core sites are shown and labeled. Note, these lie within five shaded regions that are anticipated to represent areas experiencing similar sedimentation rates and processes, and thus are used to construct a sediment budget. The five depositional regions are regularly referred to in the text by the following names: Bioluminescent Bay, Nearshore, West Backreef, East Backreef, and Forereef. Mangrove and reef areas are indicated (Kendall et al., 2001).

2001; Garcia-Sais et al. 2005; Warne et al. 2005; Garcia-Sais et al. 1998). A 1979 inventory and evaluation of Puerto Rico coral reefs indicated the La Parguera reefs were healthy and diverse (Goenega & Cintrón 1979). More recent work demonstrates that the state of the reef in Puerto Rico is related to water quality conditions with some indications of recent decline in health (Garcia-Sais et al. 2005; Garcia-Sais et al. 1998). Based on the NOAA benthic habitat map (Fig. 1; Kendall et al. 2001), and for the purposes of discussion and analysis, this research subdivides the study area into 5 sedimentation areas: Nearshore, Bioluminescent Bay, West Backreef, East Backreef, and Forereef (Fig. 2). These names will be referred to throughout the paper.

Methods

Core collection and processing

Site stations across the La Parguera shelf were cored to provide information on spatial and temporal changes in sedimentation. A total of twenty push cores were collected in June 2002 and August 2004 from a diversity of habitats and water depths (Fig. 2). Core lengths were most commonly ~0.5 m, sufficient for characterizing recent sedimentation, but ranged from 0.34 m to 2 m. Sites across the La Parguera shelf were sampled to capture the anticipated spatial variability in sedimentation. In the lab, cores were cut lengthwise for X-radiograph imaging, but core-cutting challenges precluded the collection of high quality X-radiographs. Cores were photographed, described, and sub-sampled at 1- to 2-cm intervals. Before subsequent analysis, samples were homogenized and analyzed for porosity using a freeze-drying method.

Geochemical analysis

Sediments were analyzed for carbonate content following a procedure similar to Gross (1971). Samples were digested in 10% HCl for four hours on a hot plate and allowed to spin for two days on a magnetic stirring plate. The carbonate abundance was determined by filtering dissolved carbonate species and converting the mass lost to percentage carbonate. To ensure complete dissolution of carbonate and to verify our methodology, filters were microscopically analyzed. Carbonate removal was noted in several samples, verifying the completeness of the acid-digestion method. On two samples, composition analyses were performed in triplicate to establish error in the method. A standard deviation of 0.9% was determined for sediments from a low-carbonate site, and a standard deviation of 0.5% was determined for sediments from a high-carbonate site. Following the carbonate procedure, sediments were analyzed for the percentage of loss on ignition (LOI) as a proxy for organic matter content. Samples were placed in a muffle furnace for 4 hours at 500 °C (Krom and Berner 1983). The percentage lost on ignition was calculated from the mass difference. For the evaluation of LOI method error, a standard deviation of 0.2% and 0.3% was determined for a Nearshore and Forereef samples, respectively. The remainder of sedimentary material (100% - carbonate% - LOI%) was used as a proxy for the terrestrial sediment percentage.

Grain-size analysis

The percentages of sand and mud were analyzed on surficial and several downcore samples. Sediments were immersed in a 10% sodium hexametaphosphate solution and spun on a magnetic stirring plate overnight to disaggregate particles. Samples were wet sieved at 4Φ to separate mud from sand. The sand and fine-sediment percentages were determined by mass differences.

Radionuclide analysis

Activity profiles of ^{210}Pb and ^{137}Cs are commonly used to determine sediment accumulation rates in coastal areas. This study primarily used ^{210}Pb activities derived from alpha spectroscopy. ^{137}Cs is often measured in coastal sediments by gamma spectroscopy to verify ^{210}Pb-based accumulations, but activities are below detection limits in our study area and therefore are not reported.

Total ^{210}Pb activities by alpha spectroscopy were determined following the open-digestion technique of Nittrouer et al. (1979).

Samples were spiked with a known activity of ^{209}Po, and were digested in concentrated HNO_3^- and 6N HCl. After centrifugation, ^{210}Po, the granddaughter of ^{210}Pb, and ^{209}Po were plated by electrodeposition onto nickel planchets. Samples were α-counted, and activities were calculated based on the gross counts of ^{209}Po and ^{210}Po. The supported activity was found as the average ^{210}Pb activity at the base of the core. Excess activities were calculated by subtracting the supported activity from the total activity. Accumulation rates reported here were determined using the constant flux:constant supply (CF:CS) model. However, rates derived from the CF:CS model and core-average values of the constant rate of supply (CRS) model were found to be comparable (Ryan 2007).

Sediment accumulation rates (SARs) were derived from a least squares regression of the excess ^{210}Pb activity profile with depth, and the mass accumulation rate (MAR) was then determined by multiplying each SAR by the average dry bulk density (DBD) of the sediments:

$$MAR_{total} = (SAR \times DBD)$$

where the total DBD was calculated using a literature-based bulk density for carbonate (1.48 g cm^{-3}; Harney & Fletcher 2003), a particle density of 2.65 g cm^{-3} to estimate DBD for non-carbonate sediments and their percent abundance. MARs of individual sediment components are a function of the total MAR and the percentage of the component. The mass of the terrestrial and LOI seabed sediment flux was determined using:

$$MAR_{terrestrial} = MAR \bullet Terrestrial\%$$
$$MAR_{LOI} = MAR \bullet LOI\%$$

Results

Carbonate and loss-on-ignition percentages

Average composition values (with standard errors) are reported below for individual cores (where noted) and specific regions (Fig. 2); compositional data for all samples from all cores can be found in Ryan (2007). The largest variation in sediment composition across the La Parguera shelf is in the carbonate content, ranging from 33.7 ± 2.8% (site S15) in Bioluminescent Bay to 96.5 ± 0.2% (site S3) in the Forereef area (Fig. 3A). The average carbonate content across the study area is 84.3 ± 3.7%. Carbonate content is highest in deeper water depths (>18 m) of the Forereef and Backreef areas. Microscopic examination of five surficial samples of carbonate indicates Forereef sediments are composed mostly of unidentifiable material, probably due to reworking caused by waves and currents; however, a few fragments of *Halimeda*,

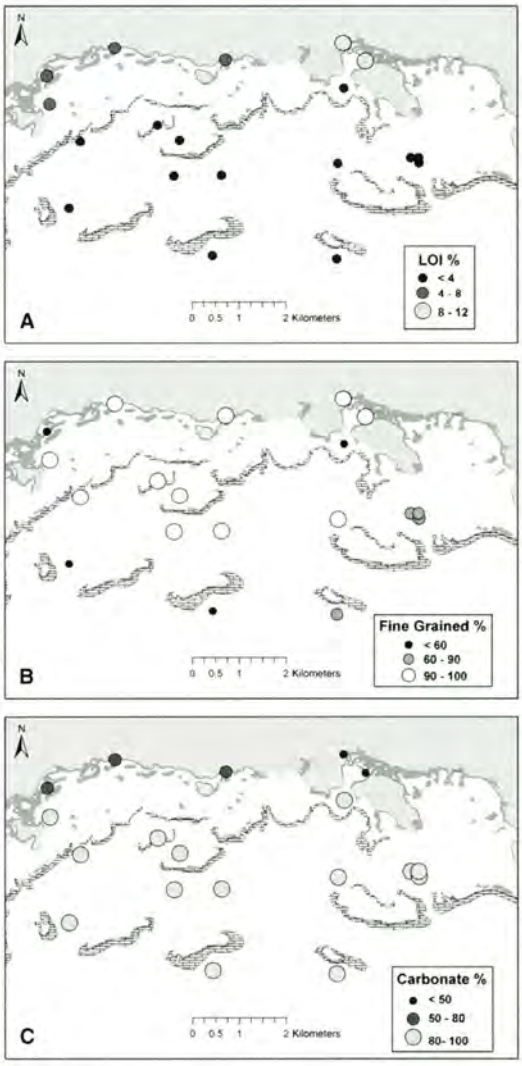

FIG. 3. Maps of sediment composition data on the La Parguera shelf. Carbonate (A), LOI (B), and grain-size (C) percentages are presented. Note, in particular, the cross-shelf variability.

pelecypods, and bryozoans are evident in the coarser material. Carbonate percentages are lowest in the Nearshore zone (Fig. 3A). In Nearshore and Bioluminescent Bay sediments, where maximum water depths reach ~5 m, average carbonate values are 71.1 ± 5.4% and 42.0 ± 0.9%, respectively. Under microscopic observation, Nearshore carbonates are dominantly gastropods and pelecypods, while several porcellaneous foraminifera and some ostracods are noted in Bioluminescent Bay sediments. In water depths from 5 to 20 m, average carbonate content in the West Backreef and East Backreef areas are 91.0 ± 1.8% and 90.6 ± 0.4%, respectively (Fig. 3A). Carbonate sediments from these areas are a diverse suite of biogenically produced material including gastropods, echinoid spines, foraminifera, pelecypods, bryozoans, and coral fragments.

Loss-on-ignition percentages are largest in the Nearshore and Bioluminescent Bay and are lowest in the Backreef and Forereef sites. The range in LOI percentages across the study area is dramatic, from 1.1 ± 0.06% in the West Backreef zone (LP12) to 15.6 ± 0.9% in Bioluminescent Bay (S15), with an average of 3.6 ± 0.17% from all cores (Fig. 3B).

Grain-size data

The percentage of fine-grained sediment in surficial samples range from 49% at a Nearshore site to 99% in a Bioluminescent Bay core (Fig. 3C). Higher percentages of fine-grained sediments generally occur in the Nearshore, Bioluminescent Bay, and East and West Backreef areas, with values in most cases >90% (Fig. 3C). The Forereef area is dominated by sediment of sand or larger in size.

Radiochemical profiles and total sediment accumulation rates

Excess ^{210}Pb profiles are useful for deciphering the nature of sedimentation and specifically measuring the SARs on continental shelves (e.g., Nittrouer et al. 1979; Jaeger et al. 1998; McKee et al. 2004; Walsh & Nittrouer, 2004; Corbett et al. 2006). Each core profile is interpreted by the pattern of activities with depth, and all profiles are categorized as one of two types in this study. Type 1 profiles have a zone of constant activities at the top of the core with an exponential decrease in activity below. This pattern suggests steady-state accumulation below a surface-mixed layer (SML) created by biological and physical processes (Figs. 4 and 5). Note, the SML is defined here as the region/depth of constant or near-constant ^{210}Pb activity at the surface of a core; this is an operational definition that differs slightly from the theoretical surface mixing layer determined by the amalgam of benthic and physical processes (Wheatcroft et al. 2007 and references therein). Type 2 profiles show varying activity versus depth, and are reflective of non-steady-state accumulation (Fig. 6), meaning the nature (e.g., activity or grain size) or rate of sediment supplied to the seabed is variable precluding the use of a simple model for SAR calculation. Although the penetration of excess ^{210}Pb reflects sediments supplied or mixed in the last 100 years (~5 half lives), an accumulation rate is not determined for these cores (e.g., Jaeger et al. 1998; Walsh & Nittrouer 2004).

The Type 1 profile is most commonly observed in this study, occurring in the Nearshore, Bioluminescent Bay, Backreef, and Forereef zones (Figs. 4 and 5). SMLs for these cores show notable variability. Only four cores (S6, S9, S12, S16) exhibit Type 2 profiles, and these are from Nearshore and Bioluminescent Bay areas (Fig 6).

SARs generally vary across the shelf (Table 1; Fig. 2; Ryan et al. 2008). Maximum SARs occur in the Nearshore and Bioluminescent Bay zones (e.g., S5, 0.52 cm y^{-1}). Intermediate rates are observed in the East Backreef (e.g., S7, 0.32 cm y^{-1}), and lowest rates are present in the Forereef (e.g., S3, 0.20 cm y^{-1}).

Total and component mass fluxes

When looking at the total mass accumulation rates a clear cross-shelf relationship is not apparent. However, terrestrial mass accumulation rates (MAR_{terr}) indicate a seaward decreasing trend (Fig. 7B). Terrestrial MARs are considerably smaller (0.01 to 0.08 g cm^{-2} y^{-1}) than total MARs due to the

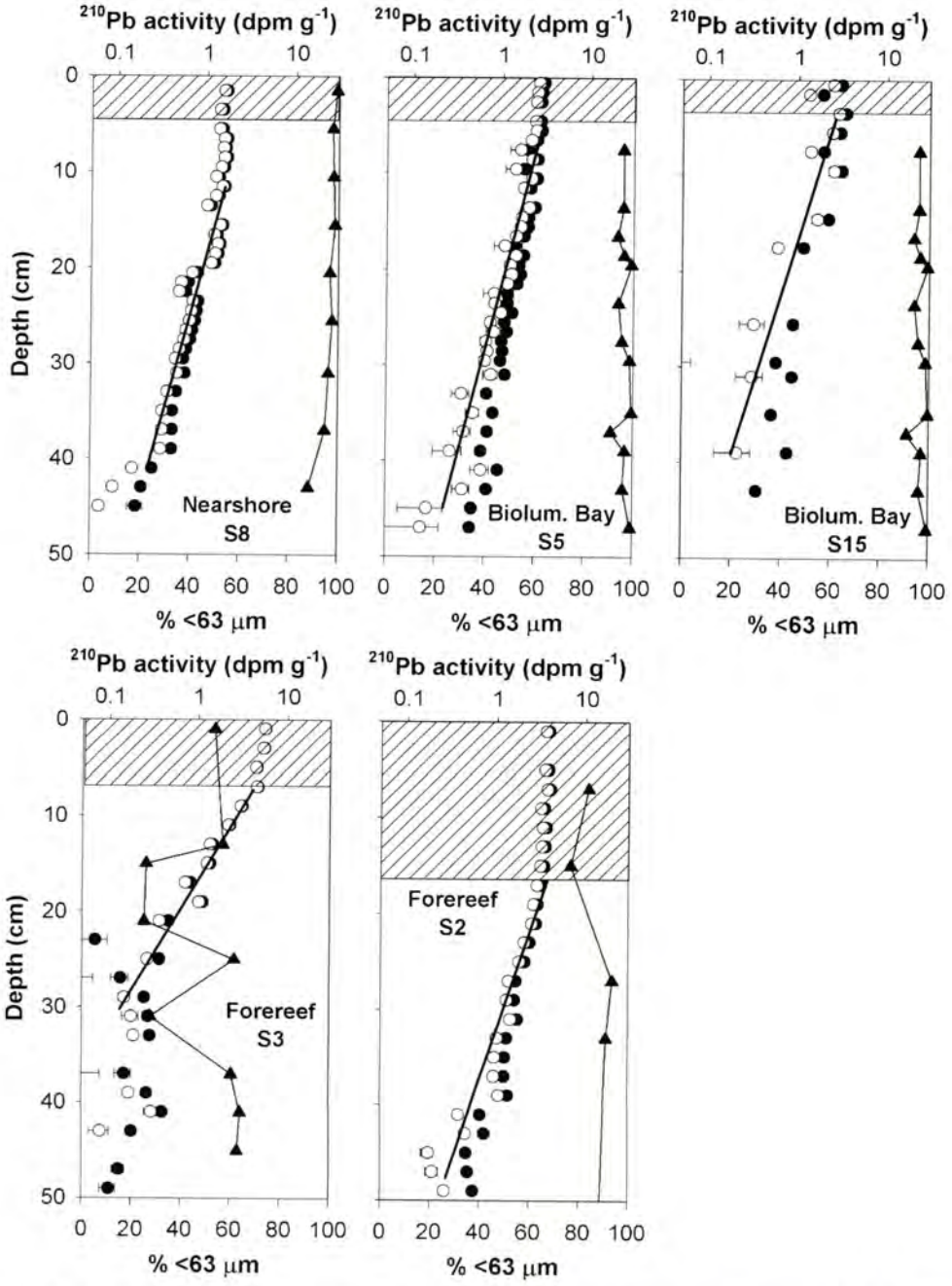

FIG. 4. Down-core profiles of ^{210}Pb activities and fine-grained sediment percentages (triangles) for Type I cores. Solid and open circles represent total and excess ^{210}Pb activities, respectively. The profiles plotted here indicate steady-state accumulation below a surface-mixed layer at several sites in the Nearshore, Biolumniscent Bay and Forereef areas (Fig. 2), and from these data sediment and mass accumulation rates determined (Table 1). Triangles representent percentage of fine-grained sediments in the depth interval.

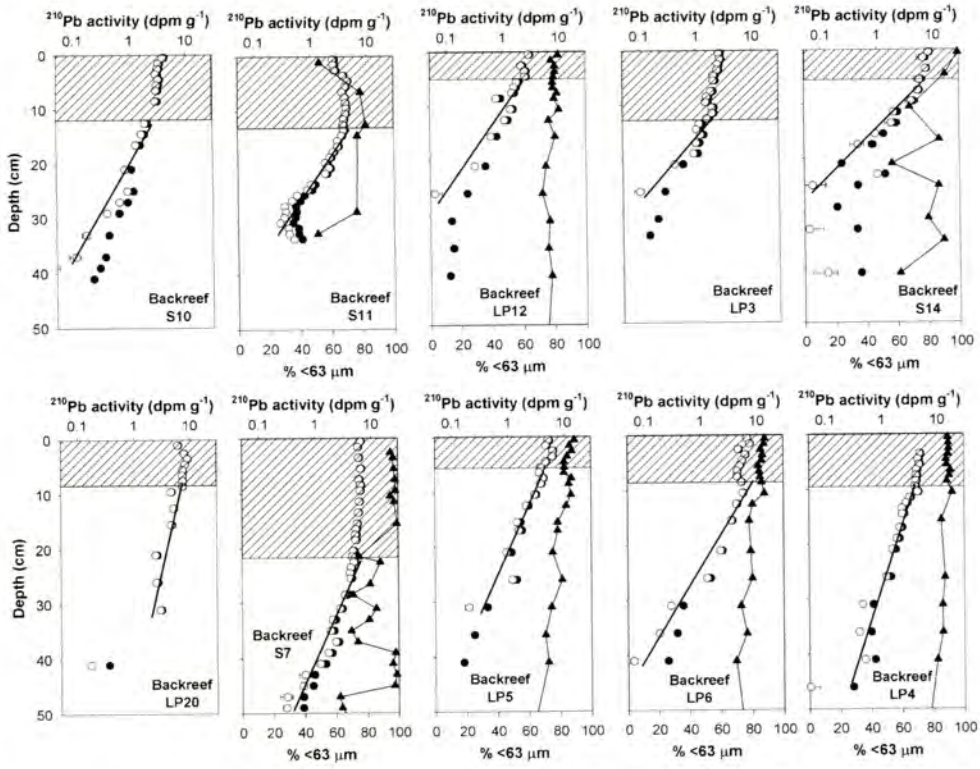

FIG. 5. Down-core profiles of ^{210}Pb activities and fine-grained sediment percentages (triangles) for Type I cores. Solid and open circles represent total and excess ^{210}Pb activities, respectively. The profiles plotted here indicate steady-state accumulation below a surface-mixed layer at several sites in the Backreef (Fig. 2), and from these data sediment and mass accumulation rates determined (Table 1).

abundance of carbonate materials in the system. A reverse trend occurs for carbonate MARs; greatest carbonate percentages are found in more seaward areas (Fig. 7C). However, the relationship is slightly less obvious in carbonate MARs because carbonate sediment is consistently high across the shelf. Carbonate and terrestrial mass accumulation rates provide additional information on the depositional patterns in each zone area. The lowest rate of carbonate mass accumulation is in Bioluminescent Bay (0.02 g cm^{-2} y^{-1}) while the lowest mass accumulation of terrestrial sediment occurs in the Forereef (0.01 g cm^{-2} y^{-1}). The maximum mass accumulation rate of carbonate occurs in the East Backreef (i.e., 0.28 g cm^{-2} y^{-1}) with high rates observed in the Forereef (i.e., 0.25 g cm^{-2} y^{-1}). The most rapid terrestrial mass storage rates occur in the Nearshore (i.e., 0.08 g cm^{-2} y^{-1}) and Bioluminescent Bay (0.08 g cm^{-2} y^{-1}).

DISCUSSION

Sediment accumulation in the La Parguera system

Two types of ^{210}Pb profiles are observed on the La Parguera shelf, steady-state and non-steady-state (Figs. 4-6), and this is important as the profiles reflect different sedimentation processes (e.g., Nittrouer et al. 1979; Jaeger et al. 1998; Sommerfield & Nittrouer 1999). Furthermore, the steady-state profiles in this study display varying rates of sediment accumulation as well as notable differences in the thickness of the SML (Figs. 4 and 5; Table 1). The steady-state nature of many of the profiles provides evidence for a consistent seabed supply and thus a consistent transport mechanism(s) over time. Kuehl et al. (1986, 1996) attributed non-steady-state profiles from the Amazon delta as having resulted from either episodic sedimentation and/or

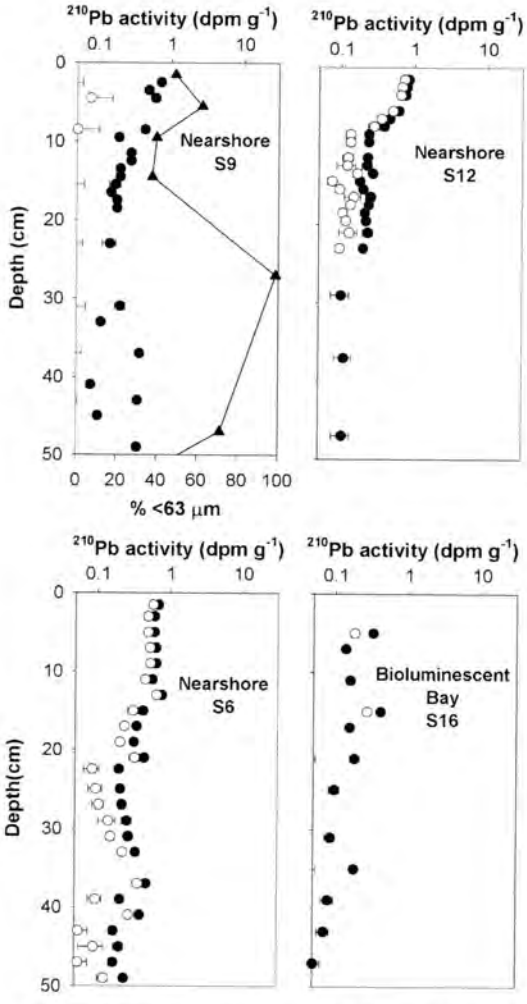

FIG. 6. Down-core profiles of ^{210}Pb activities and fine-grained sediment percentages (triangles) for Type II cores. Solid and open circles represent total and excess ^{210}Pb activities, respectively. These profiles reflect non-steady-state accumulation at several sites in the Nearshore and Biolumniscent Bay (Fig. 2). Sediment and mass accumulation rates are not determined for these sites (Table 1).

variability in radionuclide scavenging or grain size, and many others studies have observed these profiles and attributed them to similar causes (e.g., Dukat & Kuehl 1995; Jaeger et al. 1998; Sommerfield & Nittrouer 1999; Walsh & Nittrouer 2004). Non-steady-state sedimentation is evident at cores collected very close to shore (i.e., S6, S9, S12, S16; Figs. 1 & 6), reflecting the episodic supply or transport and potentially anthropogenic impacts. At one site (S9) where grain-size percentages are known, variability is observed (Fig. 6). From the cores with steady-state profiles, the rates of accumulation reported in Table 1 are determined. The variable rates of sediment accumulation in the study area (Table 1; Fig. 7) are attributed to the coastal setting, and this is discussed further below. The variable SML thickness is likely a function of different benthic habitat communities, where deeper SMLs reflect deeper burrowing or physical mixing (Wheatcroft et al. 2008 and references therein).

Sedimentation rates calculated in La Parguera are similar or slightly higher when compared to published rates in other mixed siliciclastic-carbonate settings. For example in the Florida Keys and Florida Bay, rates are on the order of 0.1 cm y^{-1} (Rude & Aller 1991; Tedesco & Aller 1996). A rate of 0.21 cm y^{-1} (0.40 g cm^{-2} y^{-1}) is reported adjacent to a coral reef in the Herbert River Region of the Great Barrier Reef (Brunskill et al. 2002). On the Ebro River margin, a mixed sedimentary system but a mid-latitude open shelf without hermatypic corals, sedimentation rates (0.26 cm y^{-1}) are similar to values calculated from sites across the La Parguera shelf. Finally, on the opposite end of the spectrum are the rates observed in coastal and shelf areas where major rivers discharge into tropical settings (e.g., mangrove areas, Allison et al. 1995; Walsh & Nittrouer 2004; shelf environments, Dukat & Kuehl 1995; Walsh et al. 2004). Rates can be tens of centimeters to even meters per year; however, sediment accumulation of a few millimeters to centimeters per year is common.

Some carbonate accretion rates have been published based on foraminifera production (Hallock 1981) or whole-reef production of various carbonate producers (i.e., *Halimeda*, molluscs, corals, etc.) (Hubbard et al. 1990; Harney & Fletcher 2003). Without accounting for potential export, which has been shown to be 49-76% (Land 1979; Harney & Fletcher 2003), estimated carbonate accretion rates have ranged from 0.005 cm y^{-1} (foraminifera only; Hallock 1981), to 0.06 cm y^{-1} in the Kailua Bay, to 0.09 cm y^{-1} in St. Croix (Hubbard et al. 1990).

TABLE 1. Compositional data and sediment and mass accumulation rates for the cores in this study. Values represent an average composition or rate for each core and include standard error using the standard deviation calculated from core sample measurements. Data for individual samples can be obtained from Ryan (2007).

Core	%CaCO3	%LOI	%Terrestrial	Total SAR cm y^{-1}	Total MAR g cm^{-2} y^{-1}
S2	95.8 ± 0.2	1.8 ± 0.04	5.9 ± 0.6	0.3 ± 0.1	0.3 ± 0.04
S3	96.5 ± 0.2	1.3 ± 0.3	2.3 ± 0.8	0.2 ± 0.02	0.2 ± 0.4
S5	50.3 ± 0.9	8.6 ± 0.3	41.1 ± 3.7	0.5 ± 0.03	0.2 ± 0.01
S6	95.0 ± 0.4	2.4 ± 0.3	2.7 ± 0.9	n-s-s	n-s-s
S7	89.3 ± 0.4	2.3 ± 0.08	8.4 ± 1.7	0.3 ± 0.02	0.3 ± 0.03
S8	65.7 ± 1.5	5.2 ± 0.4	29.2 ± 7.1	0.5 ± 0.05	0.3 ± 0.03
S9	89.1 ± 1.5	3.3 ± 0.4	7.6 ± 5.2	n-s-s	n-s-s
S10	93.1 ± 0.7	2.4 ± 0.2	4.6 ± 2.1	0.2 ± 0.1	0.2 ± 0.03
S11	93.9 ± 0.4	2.0 ± 0.1	4.2 ± 0.9	0.2 ± 0.1	0.2 ± 0.01
S12	76.4 ± 2.5	1.1 ± 0.3	22.5 ± 11.4	n-s-s	n-s-s
S13	90.6 ± 0.5	3.8 ± 0.2	5.7 ± 1.3	n-s-s	n-s-s
S14	90.7 ± 0.5	2.4 ± 0.2	6.9 ± 1.5	0.1 ± 0.02	0.1 ± 0.01
S15	33.7 ± 2.8	15.6 ± 0.9	50.7± 16.8	0.3 ± 0.04	0.2 ± 0.06
S16	84.1 ± 2.6	4.1 ± 0.5	11.7 ± 10.0	n-s-s	n-s-s
LP3	91.3 ± 1.2	2.7 ± 0.6	6.0 ± 1.9	0.2 ± 0.02	0.2 ± 0.01
LP4	91.2 ± 0.5	2.2 ± 0.1	6.6 ± 2.0	0.4 ± 0.02	0.3 ± 0.02
LP5	90.7 ± 0.4	2.5 ± 0.2	6.8 ± 1.4	0.3 ± 0.02	0.3 ± 0.02
LP6	91.1 ± 0.6	2.0 ± 0.09	6.9 ± 2.6	0.2 ± 0.02	0.2 ± 0.02
LP12	94.6 ± 0.2	1.1 ± 0.06	4.3 ± 0.8	0.3 ± 0.04	0.3 ± 0.04
LP20	82.3 ± 3.0	4.6 ± 1.4	13.1 ± 3.1	0.5 ± 0.07	0.4 ± 0.06

Patterns and controlling factors of sedimentation in the La Parguera system

The eventual fate of sediments in a marine setting is controlled by the processes that govern sedimentary flux, transport and final storage. The processes affecting siliciclastic sediment dynamics are reviewed in Nittrouer et al. (2008), but fundamentally the controls can be distilled down into the magnitude and timing of supply and the spatial and temporal character of the transport conditions and processes (e.g., flocculation) as influenced by the margin morphology. In a mixed system, the carbonate source of sediment is sufficiently large that it also significantly contributes to the sedimentary cycling of the system. Furthermore, the bathymetric structures created by coral reefs can influence the wave climate and thus dramatically impact the transport dynamics and the fate of sediment in a system.

Analysis of cores around La Parguera shows notable changes in composition and mass accumulation rates across the shelf. Terrestrial and LOI-rich sediments compose much of the materials accumulating in the Nearshore and Biolumniscent Bay areas while carbonate percentages exceed 80% at the more seaward sites (Fig. 3). Fine-grained sediments are somewhat variable, but Nearshore, Biolumniscent Bay and Backreef sediments are typically muddy (Fig. 3). Also, terrestrial MARs are highest close to the coast while the opposite is true for carbonate MARs (Fig. 7). This collective group of observations highlights the cross-shelf changes related to supply (terrestrial and marine) and transport. This pattern can be explained as a result of two fundamental controls. As discussed by Belperio (1983) and others, the increase in terrigenous sediments close to shore occurs from the dilution by supply from local rivers, although Woolfe et al. (1998) highlight how transport processes can significantly influence fluvial sediment distribution. Also, it can be argued that the apparent increase in carbonate sediment seaward is explained by an increase in the production of carbonate sediments. The mass flux data presented here strongly attests that both mechanisms are responsible near La Parguera, explaining the inverted patterns of decreased

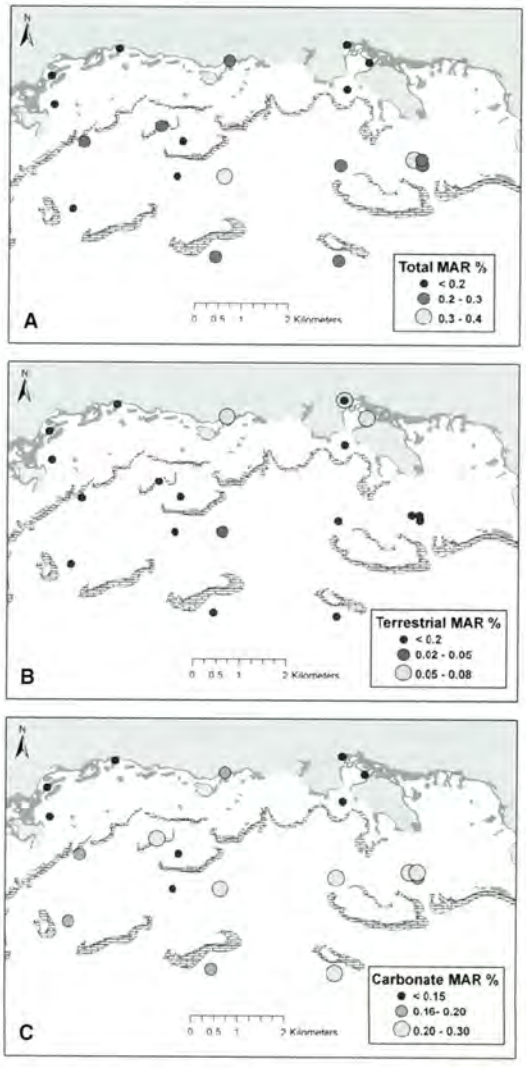

FIG. 7. Maps of mass accumulation rates on the shelf. Total MAR (A), carbonate MAR (B), and terrestrial MAR (C) data are shown. Note the cross-shelf variability.

terrestrial MARs seaward and vice-versa for carbonate MARs.

Similar across-shelf trends in sediment composition and grain-size have been noted in several mixed siliciclastic-carbonate environments (Subba Rao 1958; Maxwell 1968; Belperio 1983; Smith & Schafer 1999; Brunskill et al. 2002; Heap et al. 2002; Orpin et al. 2004). This study builds on previous works by adding radionuclide-derived sedimentation rates and mass accumulation rates, and it is this information coupled with terrestrial (i.e., erosion studies on land; McMahon et al. 1992; Warne et al. 2005) and marine sediment supply literature (i.e., reef sediment production; Hubbard et al. 1990) that clearly indicate both influences are important.

An additional detail to note beyond the described pattern is that LOI values, a proxy for organic carbon, are high in Bioluminescent Bay (Fig. 3). Similarly, in a previous study in La Parguera, Sawyer (1980) reported highest values of organic carbon in Bioluminescent Bay when compared to values collected across the shelf. A possible explanation for this is the nature of the bay, which is described by its name. Dinoflagellate organisms thrive in the shallow, protected bay, creating a bioluminescent character. This high abundance of dinoflagellates indicates there is a considerable marine source of organic matter to the sediments. The LOI levels likely reflect this marine source. However, because mangroves are found at the perimeter of the bay and surface run-off is routed into the system, terrestrial carbon also may be responsible for the high LOI values in Bioluminescent Bay and at other Nearshore sites (Fig. 3).

When sediments are deposited they do not necessarily accumulate, and this is important to consider in coral reef systems (Woolfe and Larcombe 1998). For this reason the waves and currents influencing the seabed may be critical in these coastal systems (Orpin et al. 2004). Shelf environments may experience considerable variability in wave energy, especially in coral reef settings where reef structure largely controls wave propagation and in turn, sediment transport. Previous studies have shown the effect of waves and wave-induced currents on sediment transport within reef environments (Davies 1977; Roberts et al. 1977; Suhayda & Roberts, 1977). Factors such as the geometry of the reef structure, proximity of the reef to the shoreline, linearity of the reef, and physical processes influence sediment transport and deposition (Roberts 1980). The reefs of La Parguera have a lunate or cuspate-like structure, and the seabed is undoubtedly less energetic

in areas landward of the reef structures. A compilation of several studies conducted on the Caribbean islands estimates that wave energy loss from forereef to backreef areas is between 70 - 80% when reefs are discontinuous, and as high as 97% for continuous reefs (Roberts 1980). Roberts (1980) noted that sediments from the reef areas are commonly transported behind coral reefs where they can no longer be moved. Similarly, sediments supplied to the La Parguera coast may not easily be transported seaward. In a wave-energy study conducted on Margarita Reef, located south of the study area, Lugo-Fernández et al. (1994) used a simple wave model to explore wave influences. They illustrate a significant reduction of wave height (25%) and energy (45%) as waves travel from the forereef to the backreef. The semi-continuous network of emergent reef structures that parallel the coastline of La Parguera likely creates relatively low energy conditions in Backreef and Nearshore areas. In an early sedimentation study conducted in La Parguera, Saunders and Schneidermann (1973) noted the backreef and lagoon environments as partially protected due to a blocking of wave energy by the outer reefs. They suggest this condition may cause these environments to act as fine-grained sediment traps (Saunders & Schneidermann 1973). In a similar vane, we hypothesize the Backreef areas of this study serve as good sediment traps and preserve a better temporal record of sedimentation change. Ryan et al. (2008) document a near doubling of terrestrial flux in a core from behind Corral Reef (S7; Fig. 2), and other cores from the Backreef have a comparable record (Ryan 2007). Thus, this work further supports the idea that the Backreef is an important sediment sink and also that terrestrial sediment flux to the area has increased over the last few decades, potentially reflecting human activities on land.

Sediment budgets

Sediment budgets are useful tools to evaluate the sedimentary cycling of a system (e.g., Sommerfield & Nittrouer 1999; Walsh & Nittrouer 2004). This study considers the major sources of "terrestrial" and "marine" sediments and quantifies their storage on the shelf to construct a simple budget. For this budget work the "terrestrial" sediments again are assumed to be the non-carbonate and LOI-free materials while marine-derived sediments are interpreted to be completely composed of carbonate. In reality, a fraction of the LOI material is of marine and terrestrial origin. Terrestrial sediments could be locally generated sediment (eroded lithogenic or organic particles) or fragments from more distal rocks (e.g., volcanic and igneous) from the upland regions of the Cordillera Central. In the local case these sediments may reach the coastal system through transport by sheet runoff or ephemeral stream transport. A potential pathway from more distally generated sediments is alongshore transport from river discharge located upcurrent (towards the east) of the system. Carbonate sediments can be generated from the erosion of an adjacent reef, by in-situ production (i.e., pelecypods, calcareous algae), and/or via alongshore transport.

Using supply rate, dry bulk density and area assumptions, specific sediment sources and sinks are quantified for the study area, and through the balancing of the sedimentary budget, the magnitude of unknown sources or sinks is estimated (Fig. 8). This budget examines a shelf area of 55.3 km^2 of which 3.9 km^2 is classified as reef structure (following Kendall et al. 2001). Non-reef areas are assumed to be covered by (and accumulating) unconsolidated terrestrial and marine sediments.

Terrestrial budget

The supply of terrestrial sediment is estimated using a literature value for the sediment yield and the drainage area as determined with GIS. Warne et al. (2005) provide a range of sediment yields (1000 - 4300 t km^{-2} y^{-1}) for rivers in southern Puerto Rico as the area displays a diverse geomorphology and a large variety of soil types. Because La Parguera is situated in the semi-arid alluvial valley of southwest Puerto Rico with little rainfall, the lowest sediment yield from the work of Warne et al. (2005)

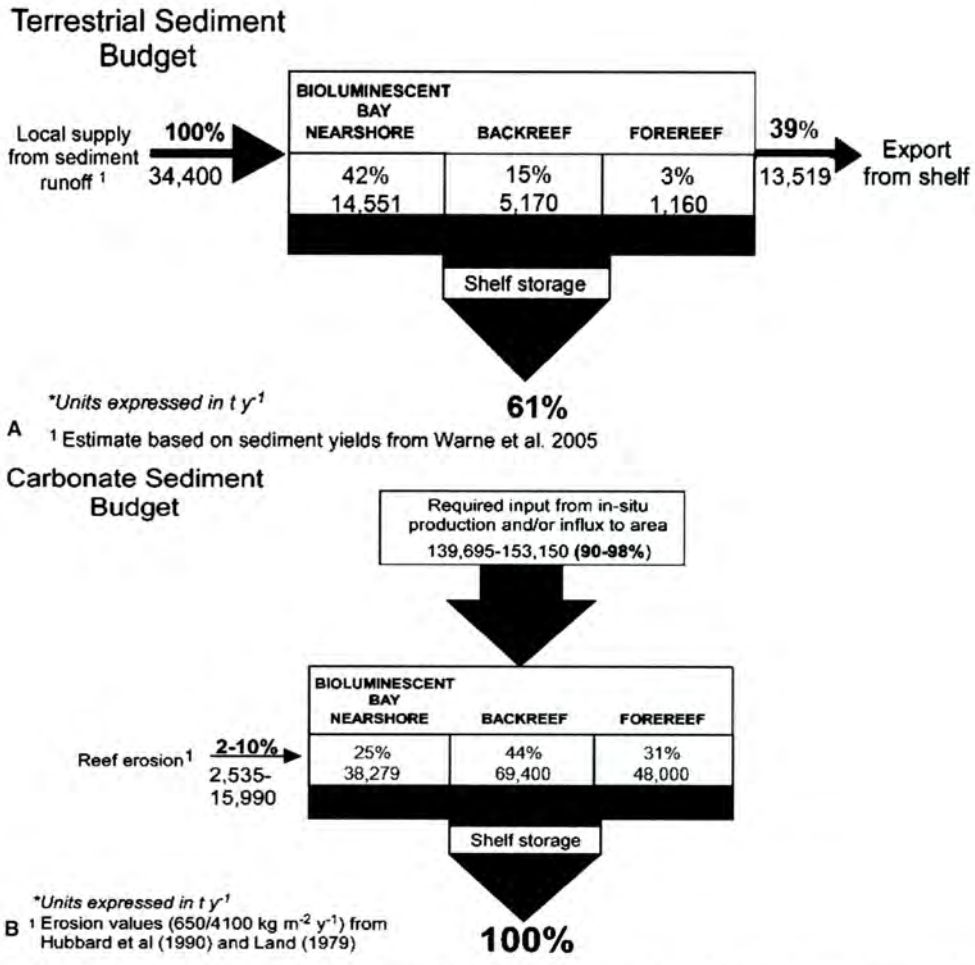

FIG. 8. Terrestrial (A) and carbonate (B) sediment budgets. Note, most if not all (see text) of the terrestrial sediment that is supplied to the shelf from local sources is stored. Also note that reef-erosion plays a minor role in carbonate sediment generation.

was assumed for the La Parguera area (1000 t km^{-2} y^{-1}). When this yield is applied to the watershed surrounding La Parguera (34.4 km^2), a sediment load of 34,400 t is estimated to be introduced to the La Parguera shelf annually (Fig. 8), and this value would include a fraction of organic material (i.e., that lost on ignition). Terrestrial sediment stored is determined using average terrestrial MARs in the various sub-regions (Fig. 7) and is calculated to be 20,881 t y^{-1}. This represents 11.6% of the total sediment storage. The reader is reminded that none of the LOI storage, 4,380 t y^{-1}, is including in this terrestrial budget, but this is well within the error of the budget. These estimates suggest that most of the terrestrial supply remains stored on the shelf (61%).

Note, however, the contribution of sediment from longshore transport is not known and thus not incorporated in this budget, and it is likely that a portion of the storage load is derived from upcurrent sources. The Río Loco and Río Guayanilla, as mentioned, supply a modest amount of sediment (55,120 and 128,790 t y^{-1}, respectively) and are <30 km away from the study area (Warne et al. 2005). Although the low wave and tidal energy on the southern

Puerto Rico coast (including La Parguera) effectively traps much sediment nearshore, an unknown portion is moved alongshore, particularly during floods and storms, as evidenced by *in situ* observations and remotely sensed imagery (Francisco Pagan, unpublished data).

The presented budget suggests some locally generated sediment must escape the system (i.e., supply is greater than storage, Fig. 8). However, it is possible that a yield of 1000 t km^{-2} y^{-1} is an overestimate for the La Parguera drainage basin as La Parguera has a different climate and terrain (i.e., lower slopes) than the Puerto Rico rivers studied by Warne et al. (2005). A watershed associated with the Assif Tala River in Algeria, located in a similarly arid setting (average rainfall = 78 cm y^{-1}) has a sediment yield of 806 t km^{-2} y^{-1} (Demmack 1982). Walnut Gulch, an experimental watershed located in southeast Arizona, which also has similar rainfall to La Parguera, has a sediment yield of 742 t km^{-2} y^{-1} (Renard and Stone 1982). If the sediment yield is an overestimate and, for example, the actual yield is closer to that of Walnut Gulch, the storage would exceed 100% of the supply, suggesting little if any escape as well as some upcurrent supply. The authors hypothesize that this is likely the case.

Carbonate budget

To develop a balanced sediment budget in a mixed system, it is essential to consider the supply and storage of the carbonate materials. In truth, carbonate sediments are the dominant constituent of this system; they compose 86.0% or 155,679t y^{-1} of total sediment stored (Fig. 8B). As for the terrestrial budget, literature insights are needed to estimate carbonate production. Several process-based budgets have determined the rate of carbonate production within coral reef settings (Chave et al. 1972; Stearn & Scoffin 1977; Scoffin et al. 1980; Edinger et al. 2000); however, few have determined physical and biological erosion rates of the reef structure (Hubbard et al. 1990; Land 1979; Harney & Fletcher 2003; Mallela & Perry 2007). Hubbard et al. (1990) determined an average gross carbonate production rate of 1.21 kg m^{-2} y^{-1} in Cane Bay, St. Croix, U.S. Virgin Islands. This gross production value refers to organisms that inhabit the reef and produce calcium carbonate. Principally, this includes corals, coralline-algae and other carbonate producers such as mollusks, foraminifera, echinoderms, serpulids, and bryozoans (Hubbard et al. 1990). Hubbard et al. (1990) estimates carbonate sediment is generated (i.e., eroded) from a reef structure at a rate of 0.65 kg m^{-2} y^{-1}, or 54% of the rate of total gross carbonate production. Applying these rates to the reef area in this study (3.9 km^2), 4,719 t of carbonate are calculated to be produced by the reefs each year, of which 2,535 t would be eroded and converted to sediment. This sediment production accounts for only 2% of the total amount of carbonate stored on the La Parguera shelf based on the average mass accumulation rates; in fact, the amount stored is approximately 60 times greater than that supplied (Fig. 8). Assuming a larger erosion value of 4.1 kg m^{-2} y^{-1}, as determined by Land (1979) in Discovery Bay, Jamaica, a load of 15,990 t of carbonate sediment is generated, accounting for 10.2% of total carbonate sediment accumulating on the seabed (Fig. 8).

The discrepancy between carbonate sediment supply and storage is indeed large but can be explained by several factors: 1) the reef sediment production estimate may be low; 2) the production in non-reef areas is not accounted for and may be large; 3) some carbonate sediments are probably sourced from strata on land; and 4) longshore transport of sediment could be important. Factors 2 and 4 are favored by the authors as the general range in reef production is provided above and little sediment is supplied from land (Fig. 8A). Sediment production from non-reef framework areas is likely to be large as this represents a large area of the system, and *Halimeda*, a form of calcareous algae, is considered a principal sediment producer throughout the Caribbean region (Shinn et al. 1990). In the southwest Florida Keys, Shinn et al. (1990) found the most common surface sediments to be composed of *Halimeda*, coral, ostracods, mollusks, and echinoids, in decreasing order. The average percentage of *Halimeda* in surface sediments was about 48.0%, reaching a high of 91.3% in some areas while

average sediments composed of eroded coral was approximately 16.7% (Shinn et al. 1990). Hudson (1985) determined a carbonate production rate for *Halimeda opuntia* of 1.09 kg m^{-2} y^{-1}. If an even distribution of *Halimeda* were assumed to actively produce carbonate at the rate determined by Hudson (1985), this potentially would account for a maximum of 46% (60,166 t y^{-1}) of total seabed carbonate sediments in the study area (55.3 km^2). The *Halimeda* distribution and density on the La Parguera shelf is not known, but it is common in the area. Additionally, the contribution of other common carbonate producers such as ostracods, echinoids, and other forms of calcareous algae (i.e., *Penicillus*) has not been quantified. Further work is required to better understand the various sources of carbonate sediment on the La Parguera shelf; however, this budget highlights that relatively little carbonate is supplied by reef erosion and suggests in-situ production of carbonate is the dominant source of carbonate in the study area.

Conclusions

This paper provides an investigation into and a first attempt at quantifying modern sedimentation on the shelf adjacent to La Parguera, Puerto Rico. Pronounced cross-shelf changes in sedimentary components and fluxes are presented; in a seaward direction the percentages of carbonate sediments increase while those of LOI and fine-grained sediment decrease. The spatial trends documented in this study are typical of mixed settings; however, this study adds to previous work by providing sediment accumulation rate estimates using a radionuclide technique. ^{210}Pb-derived MARs derived from these data reveal an increase in carbonate MARs and a decrease in terrestrial MARs in a seaward direction. The suite of sedimentation patterns is governed by terrestrial and marine sediment supply and a limited cross-shelf transport due to wave attenuation by reef structures.

A preliminary sediment budget suggests the mixed setting of the La Parguera shelf is a carbonate-dominated system (85%). Most of the terrestrial sediment that is supplied to the area is stored (61%), and it is likely that material is imported into the system. Local carbonate production (e.g., production by calcareous algae) is estimated to represent a large fraction of the budget as sediment supply from reef erosion is relatively low (2-10%) compared to the amount of carbonate sediment stored.

Acknowledgements.—The authors thank NOAA for supporting the Coral Reef Ecosystems Studies (CRES) program; this work was funded under a contract with the University of Puerto Rico, Mayaguez (UPRM) for CRES research in partnership with Amos Winter (UPRM). The research could not have been accomplished without the invaluable support of CRES and other faculty and staff at the UPRM, especially Richard Appeldoorn, Amos Winter, Francisco Pagan, and Michael Nemeth. Additionally, faculty and staff at East Carolina University were helpful in the field preparations, contract administration and lab analyses.

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