SEDIMENTS, FACIES TRACTS, AND VARIATIONS IN SEDIMENTATION RATES OF HOLOCENE PLATFORM CARBONATE SEDIMENTS AND ASSOCIATED DEPOSITS, NORTHERN BELIZE—IMPLICATIONS FOR ‘‘REPRESENTATIVE’’ SEDIMENTATION RATES

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ABSTRACT: **In stratigraphic analysis and simulation, sedimentation rates are typically assumed to be constant for meter-scale sedimentation units of similar lithology. The rates of Holocene, shallow-marine carbonate and associated sediments within an 820 km^2 area of Chetumal Bay in northern Belize were evaluated to test this assumption. Rates were determined from thickness data from 363 locations, durations derived from ^{14}C age dates of mangrove peat on Pleistocene bedrock limestone and of overlying cerithid gravels, and reference to a sea-level curve for this area. The rate of entire Holocene sections (basal transgressive mangrove peat, shelly gravel, and overlying carbonate) varies from 0 to 118 cm/ky and averages 32 ± 26 cm/ky. Rates are the highest at two thick mud-mound depocenters (41 ± 27 cm/ky) and considerably lower elsewhere (16 ± 16 cm/ky). In general, sedimentation rate correlates positively with depth of bedrock below sea level. Basal mangrove peats beneath the mud mounds have the highest rates (214–938 cm/ky), whereas overlying to laterally correlative transgressive shelly gravels have the lowest rates (20–48 cm/ky). Rates of combined transgressive and earliest-highstand carbonates, the latter deposited in a catch-up mode, are 112–166 cm/ky, and rates of overlying youngest highstand carbonates deposited in a keep-up mode are 242–460 cm/ky. Sediment thickness may correlate positively with duration but does not correlate with sedimentation rate. A power-law relationship between sedimentation rate and duration ($R^2 = 0.63$, 30 data points) is related to the completeness of the Holocene record.**

The large vertical and spatial variations in sedimentation rate across this shallow inner shelf during a single phase of sea-level rise are controlled by interactions among bedrock topography, mechanisms of sediment redistribution and accumulation, and rate and magnitude of sea-level rise. The assumption of a constant ‘‘representative’’ sedimentation rate may not be viable in qualitative and quantitative studies of ancient, meter-scale, platform subtidal carbonate units. The thickness of a time-stratigraphic unit is not a faithful proxy for duration of deposition, just the best-available.

INTRODUCTION

Facies type, distribution, and thickness are commonly documented to establish models of peritidal carbonate sedimentation (e.g., Wilson 1975; James 1979; Rankey 2002). The processes controlling type, amount, and pace of sediment accumulation in time and space will, however, be better understood if sedimentation rate (i.e., one-dimensional mass accumulation rate) and its lateral and vertical variations are accurately documented (e.g., Schlager 1981; Enos 1991; Sadler 1994; cf. Wilkinson et al. 1999). The rate is critical to quantitative time-stratigraphic studies (e.g., Yang et al. 1995), estimating stratigraphic completeness (e.g., Sadler 1981), and stratigraphic modeling (e.g., Read et al. 1986; Goldhammer et al. 1990; Bosscher and Schlager 1993), all of which aim at how stratigraphy is built.

Where the sedimentation rate of a facies cannot be determined, a rate considered representative of the facies is commonly used. Many efforts have been made to determine ‘‘representative’’ sedimentation rates of various facies (e.g., Sadler 1981, 1994, 1999; Enos 1991; Bosscher and Schlager 1993; cf. Bruns and Hass 1999). However, processes controlling peritidal carbonate sedimentation cause uneven temporal and spatial volumetric partitioning of sediments, and thus, variable sedimentation rates (e.g., Harris 1994; Yang 2000; Dromart et al. 2002). In addition, the rate is time dependent (Plotnick 1986; Sadler 1999); and different methods of rate calculation may result in different values for similar units (Bruns and Hass 1999; Sadler 1999).

In this study we document and map vertical and lateral variations of sedimentation rate of Holocene carbonate and associated sediments deposited in the shallow Chetumal Bay, northern Belize (Fig. 1). The variations and time dependence of sedimentation rate provide insights into processes controlling sediment production, redistribution, and accumulation, and contrasting styles of deposition during Holocene sea-level rise, and indicate pitfalls of ‘‘representative’’ sedimentation rate. The results may serve as a model for qualitative and quantitative studies of ancient, shallow-subtidal carbonate sedimentation.

STUDY AREA

Chetumal Bay is a wide, shallow bay bordered on the east by Ambergris Caye and on the west by mainland Belize. The study area encompasses 820 km^2 (Fig. 1). Sediment type (described in this paper as unconsolidated sediment lithology and assumed lithified equivalents) and thickness, water depth, and depth to bedrock below mean sea level were compiled from 363 locations (Fig. 1). The data are from Mazzullo et al. (1995), Mazzullo et al. (2003), Teal (1998), Teal et al. (2000), Wilhite (2000), Wilhite and Mazzullo (2000), Dimmick-Wells (2002a, 2002b), and more recent work by the authors. Cores were recovered from 90 of these locations, and surface grab samples taken at the other locations. Two areally extensive, shallow-water mud mounds, the Cangrejo and Bulkhead shoals (Fig. 1), were a focus of study because Holocene sediments are very thick. The Cangrejo Shoals is located at the transition between the inner shelf of Chetumal Bay and the outer shelf east of Ambergris Caye, whereas the Bulkhead Shoals is within the bay. The sedimentology, mineralogy, and diagenesis of these mud mounds, along with radiocarbon ages of buried mangrove peats and cerithid gravels, were described by Pusey (1975), Mazzullo et al. (1995), Mazzullo et al. (2003), Teal (1998), Teal et al. (2000), Wilhite (2000), Wilhite and Mazzullo (2000), and Dimmick-Wells (2002a, 2002b). Water depth in the study area varies from a few centimeters on the crests of shoals to 3.7 m elsewhere, and generally increases southward and northward (Fig. 1). Normal semidiurnal tidal range is < 0.3 m, and persistent winds override negligible tidal effects across the northern Belize shelf.

Unconsolidated Holocene marine carbonate sediments and associated deposits overlie karsted Pleistocene limestone, the surface of which generally slopes S to SW (Fig. 2). Bedrock topography is characterized by narrow, submerged bedrock ridges and intervening dissolution valleys, and a 7.6-m-deep dissolution depression at the southern end of the bay. Both the Cangrejo and Bulkhead mud-mounds have been deposited in depressions on the Pleistocene limestone along the margin of this deep depression (Fig. 2). Holocene surficial carbonate deposits comprise an inner-shelf facies mosaic of shallow-water, soritid- and miliolid-dominated sand shoals in the eastern part of the bay, and pass northward into thin Brachidontes–foraminiferal–molluscan sands and gravels lying on bedrock (Fig. 3A). The lithified equivalents of these deposits would be grainstones. Mostly muddy, shallow-marine carbonate deposits (mudstones and wackestones) are pre-

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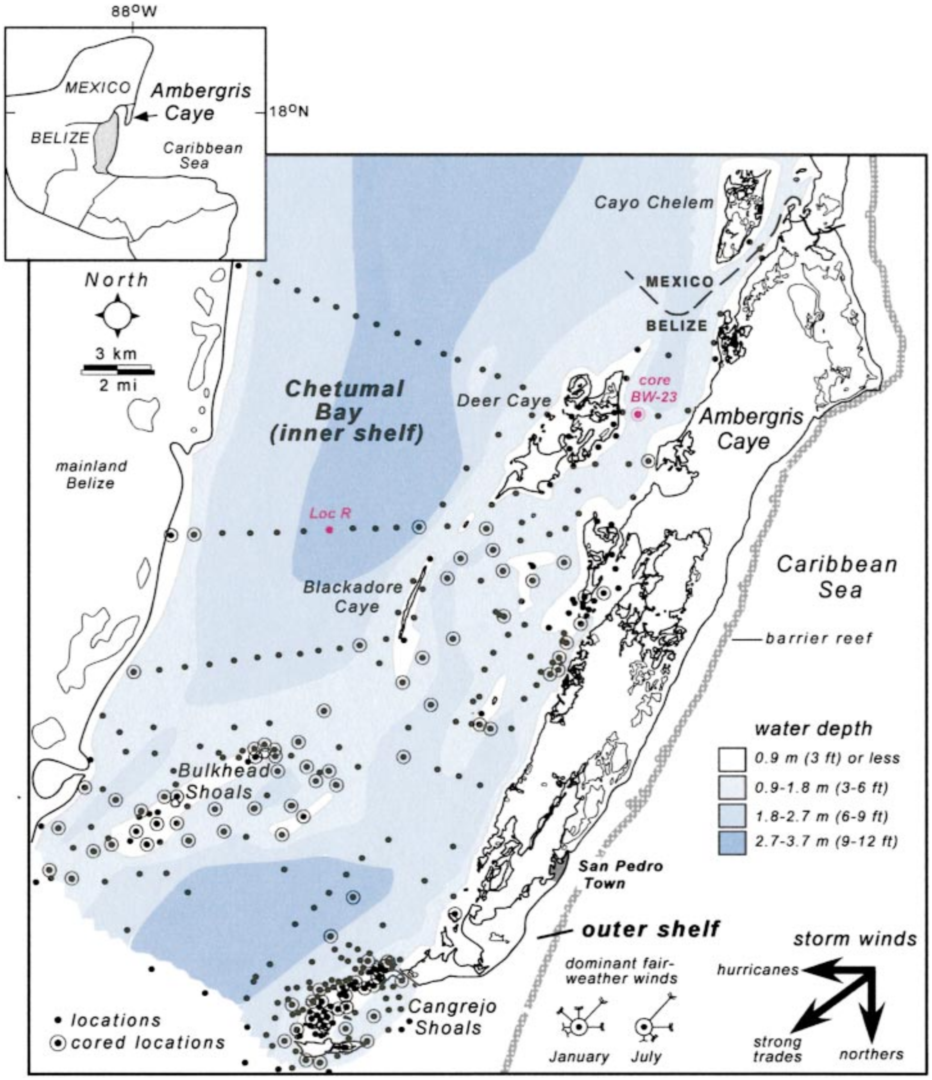

FIG. 1.—Map showing location of the study area, water depth, sampled locations (the words Bulkhead Shoals conceal some data-point and core locations), and wind and storm directions. Location R and Core BW-23 are discussed in the text.

sent elsewhere. Such inner-shelf deposits contrast the coralgal-dominated sands and gravels (grainstones) on the outer shelf.

Winds exert dominant influence on current directions, which result in net S to SW sediment transport and redeposition within Chetumal Bay (Mazzullo et al. 2003). Fair-weather NE trade winds result in predominantly SW-flowing currents. Periodic strong north winds (''northers'') drive S to SW currents and sediment transport out of the bay, and south winds (''Easter winds'') drive NW currents and sediment transport into the bay. Hurricanes, with highly variable wind directions, approach mostly from the east (Stoddart 1963). Holocene sediments thicken to the south as a result of dominant S to SW currents and sediment transport (Fig. 3B). Maximum sediment thickness is 7.6 m and 4.6 m at two main depocenters (the Cangrejo and Bulkhead mud mounds) in the southern part of the bay, respectively. Two subordinate depocenters north of Bulkhead Shoals and east of Blackadore Caye have a maximum sediment thickness of 3.1 m. In contrast, sediments generally are < 0.3 m thick in the northern part of the bay, where water depth varies from 0.9 to 3.7 m (Figs. 1, 3B). Sediments variously thicken into bedrock lows (e.g., at Cangrejo and Bulkhead); thin (< 0.6 m) within the bedrock lows, particularly in the southernmost part of the bay, where bedrock is up to 7.6 m below sea level; or thin on bedrock highs, as in the northeastern part of the bay (Figs. 2, 3B).

SEDIMENTARY ARCHITECTURE IN RELATION TO HOLOCENE SEA-LEVEL RISE

Sea-Level History

Northward marine flooding of Chetumal Bay began approximately 6300 years ago (Pusey 1975; Wilhite 2000; Wilhite and Mazzullo 2000), and sea level rose rapidly until ~ 4500 years BP and decelerated after that (Fig. 4). There are no extensive tidal flats within or bordering the bay, and shoreline position essentially has been stable since ~ 500 years ago. Rising sea level and its effect on water depth and shoreline position, and varying rate of sea-level rise, are the primary controls on the magnitude and change in marine accommodation space in Chetumal Bay in the last ~ 6300 years.

Facies and Depositional Style

The facies types and architecture of the thick mud-mound deposits at the Cangrejo and Bulkhead shoals are similar (Figs. 5, 6) and are illustrative of patterns of sedimentation in the area and the interplay of sea-level rise and temporal variation in accommodation space during Holocene transgression. Locally overlying the Pleistocene bedrock beneath these mud mounds and elsewhere in the study area (Fig. 7) is as much as 0.6 m of organic-rich, stiff and dense, blue-gray clay interpreted as buried grass-

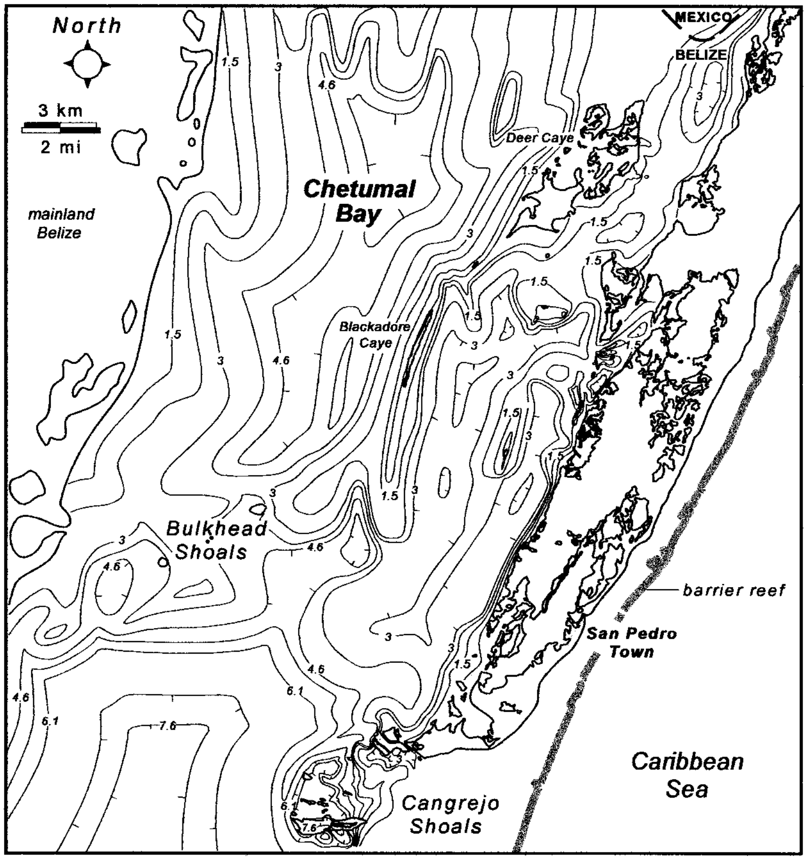

FIG. 2.—Topography of the Pleistocene bedrock limestone in the study area. Contour interval is 0.76 m (2.5 ft), and depths are below mean sea level.

meadow soil (Pusey 1975; Mazzullo et al. 2003). Locally overlying this clay, or Pleistocene limestone where clay is absent, is buried Rhizophora mangle mangrove peat, interpreted as former mangrove cayes. In all peats in the study area, the absence of preserved roots or rooted preexisting sediments, and instead the presence of homogeneous (textureless) layers of peat, indicate that the mangrove peats are depositional (i.e., accumulations of biomass liter) and not of a replacive root origin. Whereas the peat is thin (maximum 0.4 m) and only sporadically present at Cangrejo (Fig. 5), it is thick (up to 2.4 m) and laterally continuous at Bulkhead, where the oldest peat was found. Radiocarbon age of that peat in core BS-30 at ~ 5.2 m below sea level is 6330 ± 70 years BP (Fig. 6). The youngest basal peat, which is 1.7 m below sea level at location D (Fig. 3B), far to the northeast of Bulkhead and Cangrejo shoals, was radiocarbon-dated at 5040 ± 95 years BP (Fig. 7). Hence, the duration of Holocene accumulation decreases from south to north in the study area.

Overlying and, in places, laterally equivalent to the peat is 0.3–0.9 m of coarse-grained, mollusc-dominated, gravelly and locally muddy sand to muddy sandy gravel (packstone to grainstone). These sediments are texturally and biotically similar to the surficial Brachidontes–foraminiferal–mollscan sands and gravels overlying shallow bedrock in the northeastern study area (facies 4, Fig. 3A) and to shelly shoreline sediments along the shallow, back-side coast of Ambergris Caye and other cayes in the bay. The shelly gravels are present in many cores throughout the study area as basal Holocene carbonate sediment overlying bedrock limestone, buried soil, or peat (Figs. 5–7). Sedimentary and biogenic structures are rare, and sediments generally are devoid of *Thalassia* rootlets, rhizomes, and root bioturbation. These characteristics suggest shallow-water environments of shifting sediments on which *Thalassia* could not readily take root, and these sediments were interpreted as pre-mud-mound deposits. Similar shelly gravels underlie mud-mound and intervening ''lake'' deposits in Florida Bay (e.g., Wanless and Tagett 1989; Bosence 1995). Cerithids in the shelly gravel at Cangrejo yielded radiocarbon ages of 4655 ± 160 to 4565 ± 95 years BP (Fig. 5). On the basis of the stratigraphic position, generally onlapping stratal geometry (Figs. 5, 6), and range of radiocarbon ages that track the rapid sea-level rise from ~ 6600 to 4500 years BP (Fig. 4), the peats and shelly gravels are inferred to be deepening-upward transgressive deposits. The cerithids in the shelly gravels and overlying sediments at Cangrejo that were radiocarbon-dated (Fig. 5) are believed to have lived at Cangrejo, rather than having been transported there or representing lags, for the following reasons: (1) there is not a wide range of determined ages from samples taken at similar depths in different cores (e.g., in cores 7, 14, and 16; Fig. 5); (2) determined ages are consistently younger upwards, and the ages of the most recent samples (e.g., at the tops of cores 7, 15, and 22; Fig. 5) are not anomalous; and (3) cerithids are rarely found in outer and inner shelf areas adjoining Cangrejo Shoals, hence, they likely were not derived from those areas.

Overlying carbonate sediments constitute the bulk of the Holocene section and are up to 6.1 m thick. At Bulkhead, however, a considerable part of this section locally is buried mangrove peat, the deposition of which persisted until ~ 2800–2900 years BP (Figs. 5, 6). The carbonate sediments are gravelly to non-gravelly muddy sand and gravelly sandy mud (wackestone to packstone), and at Bulkhead there also are beds of locally slightly gravelly but otherwise pure mud. Bioturbation by vertical *Thalassia* rootlets and horizontal rhizomes defines stacked, mostly erosionally truncated storm-deposited units comprising mound-core deposits (Mazzullo et al. 2003). Erosional boundaries between such units are hiatal surfaces that affect calculation of sedimentation rate (see later sections). Radiocarbon ages of mound-core deposits at Cangrejo range from younger than ~ 4500–4600 years BP (the age of the immediately subjacent transgressive shelly gravels) to less than 100 years BP (Fig. 5). Judging from similar sea-level

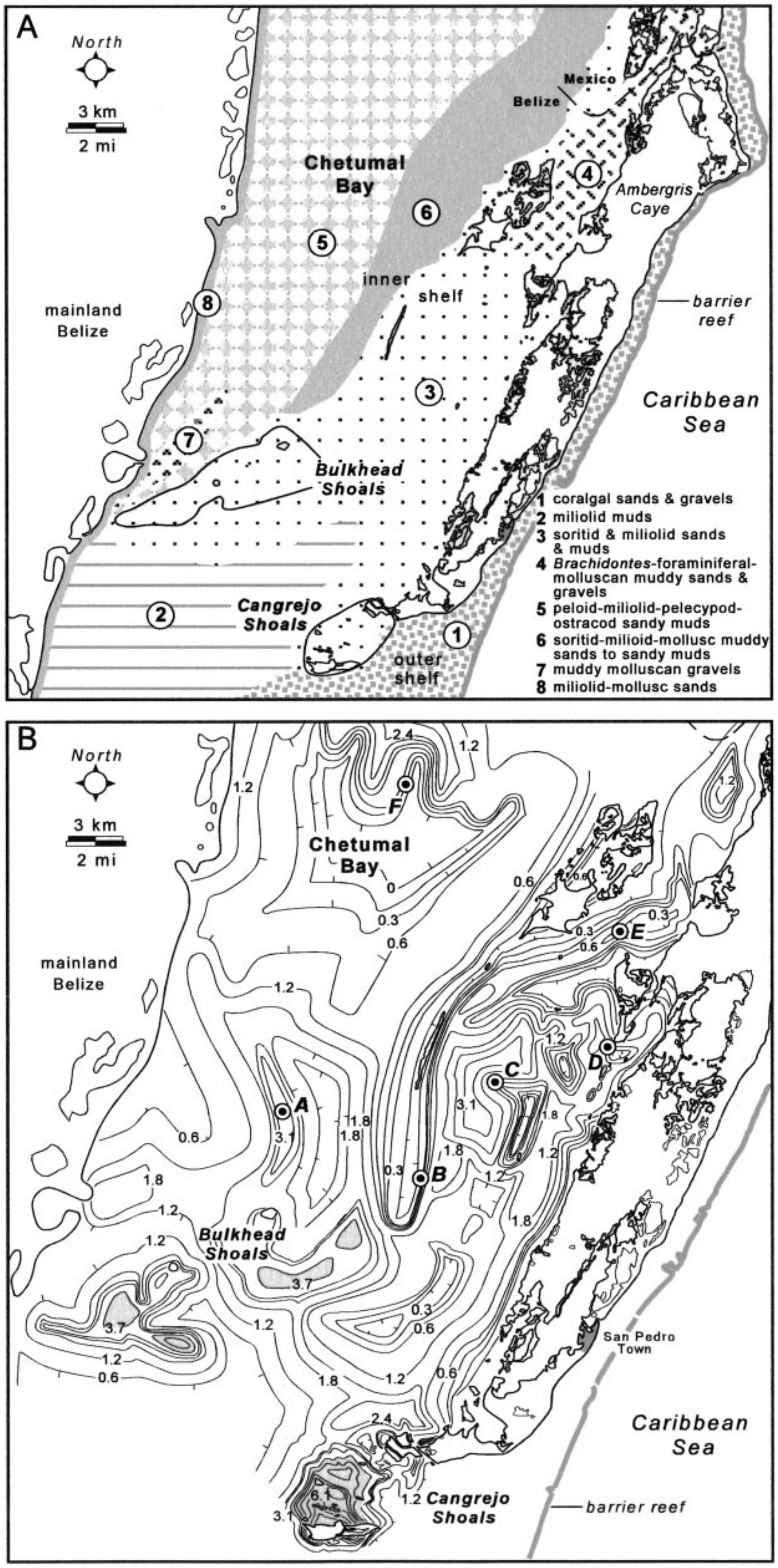

FIG. 3.—**A)** Surficial Holocene facies; lithified equivalents of unconsolidated lithologies included in text. **B)** Thickness of Holocene sediment. Contour interval is 0.6 m (2 ft) where sediment is thicker than 0.6 m, and is 0.15 m (0.5 ft) where sediment is less than that. Depocenters with sediments thicker than 3.1 m (10 ft) are shaded. Letter-designated (A–D) circled black dots are locations of cored sites shown in Figure 7.

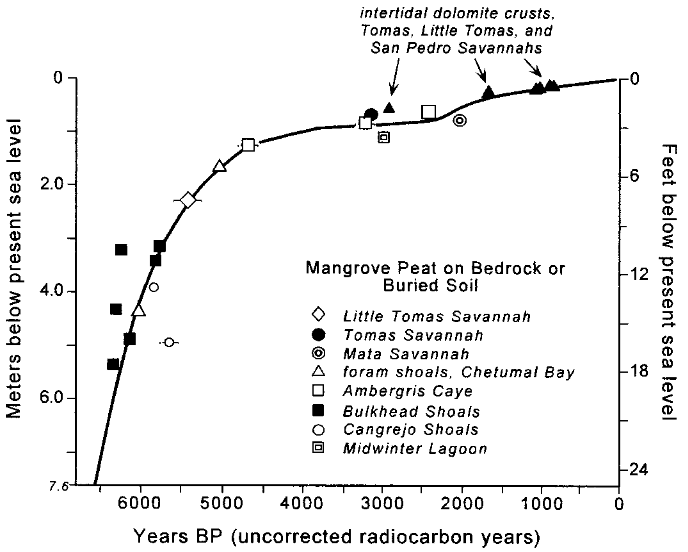

FIG. 4.—Sea-level curve for northern offshore Belize (revised after Teal et al. 2000). Data sources are listed in Mazzullo et al. (1992).

history, stratal architecture, and radiocarbon dates, the age range of mound-core deposits at Bulkhead is considered to be the same as at Cangrejo. Deposition of these sediments coincides with decelerating sea-level rise (Fig. 4); hence, they are inferred to be shallowing-upward deposits.

Coeval deposits away from the mud mounds (Fig. 7) are thin to relatively thick sections of: (1) either muddy foraminiferal sand to sandy mud or muddy foraminiferal sand to sandy mud (wackestone to packstone), both of which grade upward to sand (grainstone) in deeper-water areas between foraminiferal shoals in the eastern part of the bay; (2) dominantly foraminiferal sands (grainstone) beneath shallow-water shoals in the eastern part of the bay and at the two subordinate depocenters north of Cangrejo and Bulkhead (Fig. 3B); and (3) very organic-rich, slightly sandy and gravelly foraminiferal muds (mudstone to wackestone) in the western and northwestern part of the bay (Fig. 7). Although the boundary between deepening-upward and shallowing-upward sections commonly is difficult to locate precisely, it is believed to be within beds immediately overlying the basal transgressive peat and shelly gravels, where they are present. Thin (0.2–0.4 m) intertidal deposits are present on a few low-lying peritidal flats at Cangrejo and Bulkhead (Figs. 5, 6). The sediments include desiccated microbial mats, gravelly sandy mud (wackestone) with layers of modern mangrove peat, and storm-washover skeletal sands and coarse shell gravels (grainstone). Such deposits cap subjacent shallowing-upward subtidal deposits.

Whereas progradational offlapping of storm units is indicated in the lower part of the mound core at both Cangrejo and Bulkhead, overlying units are mostly aggradational and their upper surfaces form current topography (Figs. 5, 6). The vertical stacking of such geometries, together with shallowing-upward sedimentation over time, is consistent with early catch-up sedimentation of the lower part followed by keep-up sedimentation of mainly aggradational upper part. Both depositional phases occurred during slow sea-level rise (Fig. 4). The thicker Holocene section at Cangrejo compared to that at Bulkhead (Figs. 5, 6) reflects greater depth to bedrock, and therefore, greater marine accommodation space.

SEDIMENTATION RATES OF HOLOCENE SEDIMENTS IN CHETUMAL BAY

Methodology

Sedimentation rates were calculated as sediment thickness divided by duration. Mangrove peats overlying Pleistocene limestone were considered as Holocene deposits, but buried soils were not. Thickness of peats and overlying carbonate sediments used in the calculation represents current compaction state. Thus, the rates reported here should be regarded as uncompacted rates comparable to other Quaternary rates (e.g., Enos 1991; Sadler 1994).

Available radiocarbon dates were used to calculate sedimentation rates of parts and entire Holocene sections in ^{14}C-dated cores, specifically in densely cored Cangrejo and Bulkhead mud-mounds. In nearby undated cores where depth to bedrock is similar, ages were assigned to the entire Holocene section on the basis of stratal correlation to dated cores. This approach is considered tenable because marine flooding in a given area was virtually instantaneous as a result of the low-relief bedrock topography (Figs. 5–7). Elsewhere, the approximate age of initial transgressive sedimentation was determined by reference to a sea-level curve for northern Belize (Fig. 4), which was regarded as the duration of the entire Holocene section. This method was tested by comparing the estimated ages with the ^{14}C dates of the same deposits in dated cores. Test results indicate that the error of estimated ages is similar to or smaller than the analytical error of ^{14}C dates. If the error of the determined rates is attributed to the analytical error of ^{14}C dates (maximum $\pm$ 230 years) and age extrapolation, the largest error reaches 111% for the thin, uppermost Holocene deposits with the shortest duration (e.g., core 22 in Fig. 5). The error for the entire Holocene sections in the depocenters is $\sim$ 1.6% assuming a duration of 6,300 $\pm$ 100 years and a thickness of 4 m, and that for the non-depocenters is $\sim$ 1.9% assuming a duration of 5,500 $\pm$ 100 years and a thickness of 0.3 m.

Sedimentation Rates Calculated Using ^{14}C Dates at Cangrejo and Bulkhead Shoals

Sedimentation rate of the entire Holocene section at the Cangrejo and Bulkhead mud-mound depocenters ranges from 20 to 938 cm/ky including peat and carbonate sediments, and from 20 to 460 cm/ky excluding peat (Figs. 8A, B). With the precaution that sedimentation rate is dependent on observational time span (Sadler 1999), the rate nevertheless differs among these deposits. Peats and the uppermost carbonate deposits have the highest rates (119–950 cm/ky and 242–460 cm/ky, respectively), and transgressive shelly gravels have the lowest rate (42–48 cm/ky). The low sedimentation rate of the latter deposits is likely caused mainly by the lag time between initial marine flooding and the onset of carbonate accumulation (e.g., Enos 1991).

Sediment thickness at the Cangrejo and Bulkhead mud mounds shows a variable degree of positive linear correlation ($R^2 = 0.71, 0.33$, respectively) with the duration of deposition (Fig. 8C, D), suggesting that, in deposition-dominated sites, thick sediments represent long durations and sedimentation rate is grossly constant (80 and 50 cm/ky for Cangrejo and Bulkhead, respectively, on the basis of the slope of regression lines). The different degree of correlation between Cangrejo and Bulkhead, however, suggests that stratal thickness may not always be a good proxy of duration of deposition, particularly in ancient rocks, because stratal thickness is not controlled solely by duration (cf. Tipper 1987). Moreover, correlation between thickness and rate is actually too poor to be defined linearly after removal of outliers (Fig. 8E, F). The correlation between thickness and duration, but the lack of correlation between thickness and rate, can only mean that sediment accumulation is significantly non-uniform temporally and spatially (e.g., Figs. 5, 6).

Sedimentation Rates of Entire Holocene Sections

Average sedimentation rate of entire Holocene sections in the study area is 30.9 $\pm$ 25.7 cm/ky (Table 1), ranging from 0 cm/ky in areas of no sediment to a maximum of 110 cm/ky at the Cangrejo Shoals (Figs. 9A, 10). Rate is high (40.8 $\pm$ 36.6 cm/ky) in the Cangrejo and Bulkhead shoals

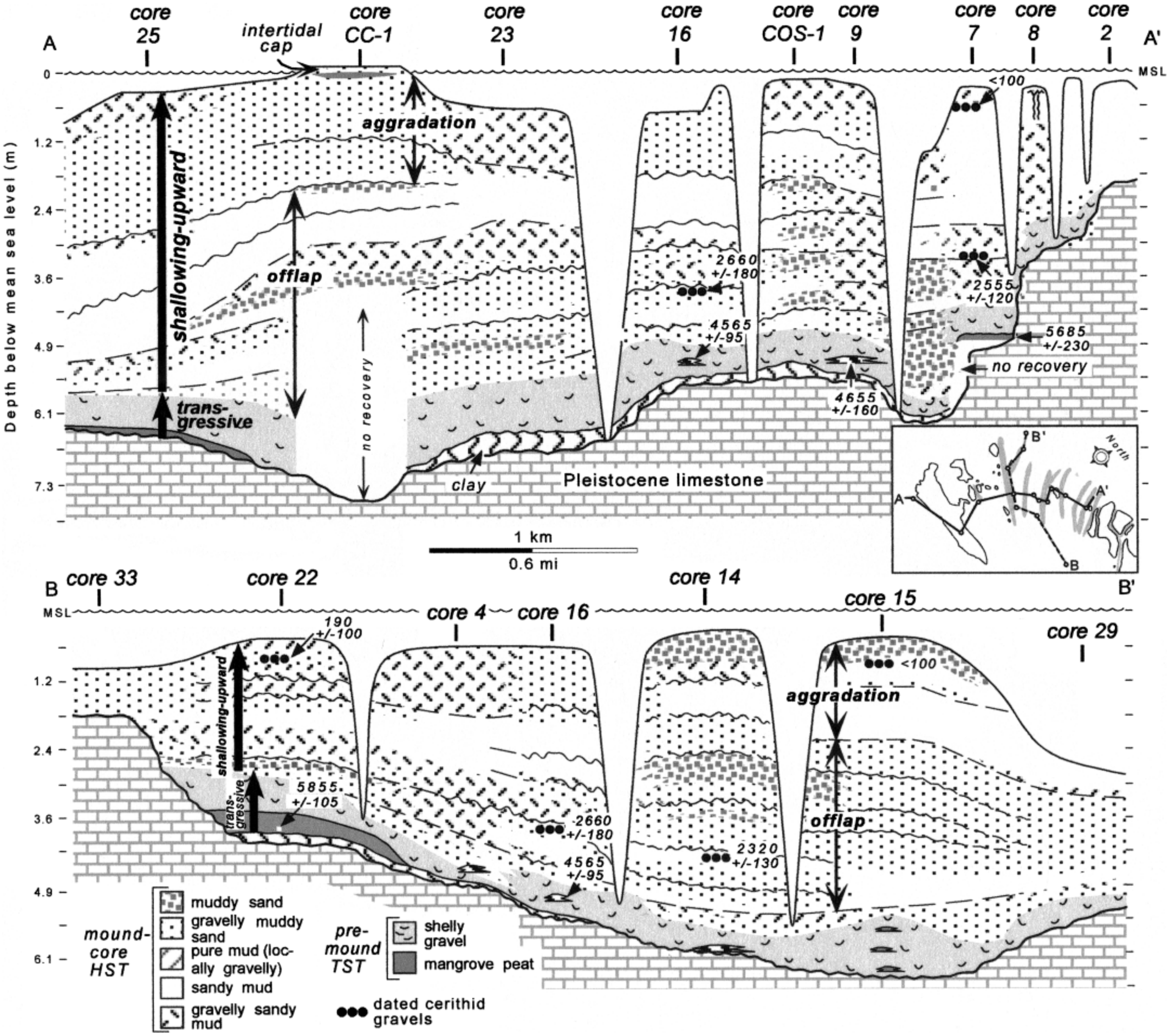

FIG. 5.—Sections across the Cangrejo Shoals mud mound, showing sediment types, radiocarbon ages of mangrove peats and cerithid gravels, depositional style, and stratal geometry of erosional surface-bounded sedimentation units. Numerous NW–SE tidal channels dissecting the shoals are shown on the inset location map.

and low elsewhere (16.4 ± 15.3 cm/ky; Table 1). The rate distribution in the study area is slightly bimodal, with 86% of the rates in the range of 0–60 cm/ky (Fig. 9B). It is polymodal at the Cangrejo Shoals but nearly normal at the Bulkhead (Fig. 9C), suggesting that sediment accumulation in the former area is highly non-uniform compared to that at Bulkhead. Approximately 76% of the rates in the northwestern-central part of the bay, and 63% in the northern and central parts, are in the range of 0–20 cm/ky (Fig. 9D), indicating overall slow accumulation. The mean and distribution of the rates should not be emphasized, because of biased sampling toward sites of thick sediment accumulation, although the range and areal distribution of rates (Fig. 10) reflect highly non-uniform Holocene sediment accumulation. The degree of non-uniformity also varies among geographic subdivisions, as shown on the rate map (Fig. 10) and by the one standard deviations of mean rates (Table 1).

DISCUSSION

Sediment Accumulation during a Single Phase of Sea-Level Rise

Sedimentary history, that is, the changing type and rate of sediment accumulation at a specific site during sea-level rise in the last 6300 years, is graphically displayed as a sediment accumulation curve (Fig. 11). The curve was constructed using the Holocene sea-level curve of northern Belize, present sediment thickness, bedrock depth, and age estimates. Curves at representative sites in depocenters (core 7 at Cangrejo and cores BS-8 and BS-44 at Bulkhead) and non-depocenters (Location R in the western-central part and core BW-23 in the northeastern part) were used to demonstrate variability of Holocene sediment accumulation (Figs. 3, 5, 6, 7). The results provide insight into processes controlling sediment accumulation.

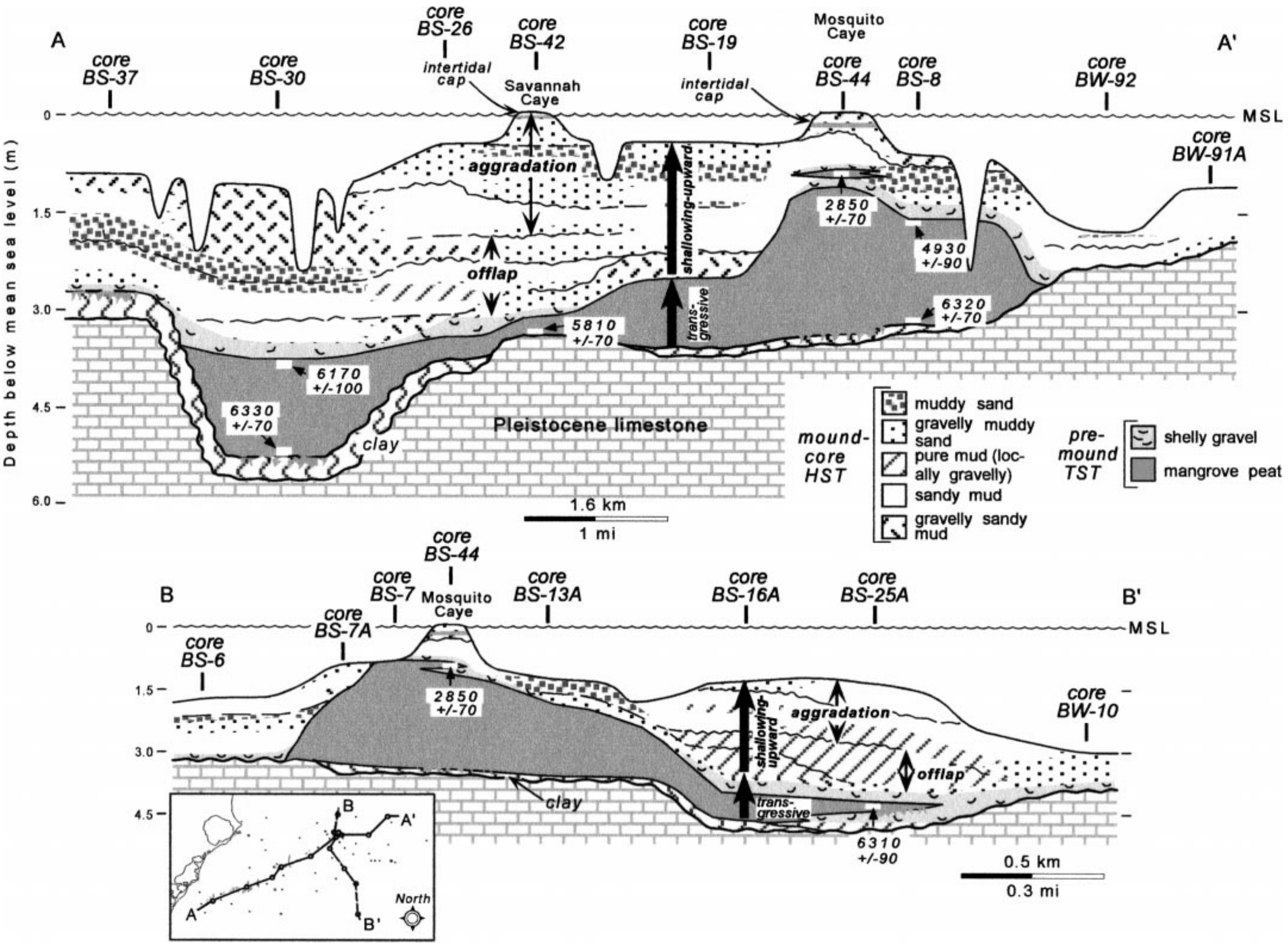

FIG. 6.—Sections across the Bulkhead Shoals mud mound, showing the same features as in Figure 5. Numerous NW–SE tidal channels dissecting the shoals are shown on the inset location map.

Sediment Accumulation at Cangrejo and Bulkhead Shoals Depocenters.—The accumulation curves at these two areas consist of three to four linear segments (cores 7, BS-8, and BS-44 in Fig. 11), the slope of which is sedimentation rate. Each curve generally consists of a steep segment of rapid transgressive peat accumulation, a shallow segment of slow accumulation of transgressive shelly gravel, and a steep segment of rapid shallowing-upward carbonate accumulation. Excluding the peat segment, the overall curve of carbonate accumulation is concave upward, indicating increasing rate of accumulation during decelerating sea-level rise.

The vertical distance between an accumulation curve (i.e., sediment–water interface) and the sea-level curve is water depth (Fig. 11), which increases when sediment accumulation is slower than sea-level rise, and vice versa. In the course of carbonate accumulation at Cangrejo and Bulkhead, water depth first increased during slow accumulation of transgressive shelly gravels, forming a generally thin, deepening-upward section. Core 7 at Cangrejo (Fig. 5) and core BS-44 at Bulkhead (Fig. 6) had experienced deepening for ~ 2000 years since initial accumulation of a thin shelly gravel (Fig. 11). Water depth then decreased as sea-level rise slowed and sediment accumulation increased dramatically, resulting in a thick, shallowing-upward section.

Several differences exist between accumulation curves for the Cangrejo and Bulkhead shoals. First, for example, carbonate accumulation at core 7 in Cangrejo began ~ 800 and 1000 years earlier than at cores BS-8 and BS-44 in Bulkhead, respectively (Fig. 11), because Cangrejo is closer to the outer shelf and has a deeper bedrock surface and, thus, was flooded earlier than Bulkhead (Fig. 2). Second, significant shallowing-upward carbonate accumulation started at ~ 2,500 BP at both the Cangrejo and Bulkhead shoals (Fig. 11), but extremely rapid accumulation at Cangrejo filled accommodation space there because the area has had a larger sediment supply transported from both inner and outer shelves (Teal 1998) and a larger accommodation space. In contrast, at Bulkhead and elsewhere in the bay, sediments have been derived solely from within the inner shelf (Wilhite 2000; Wilhite and Mazzullo 2000; Dimmick-Wells 2002a; Mazzullo et al. 2003). Last, the variability in sediment accumulation within a depocenter can be demonstrated by comparing the accumulation curves of adjacent cores BS-8 and BS-44 at Bulkhead (Figs. 6, 11). Although carbonate accumulation was initiated earlier, and accommodation space was greater at core BS-8 than at core BS-44, net sediment accumulation nonetheless was more rapid at core BS-44, where sediments aggrade to the intertidal zone. In contrast, water depth at core BS-8 has been nearly constant at ~ 60 cm for the last ~ 4500 years (Fig. 11). Sediment bypassing may have been dominant at core BS-8 during sea-level highstand, although it is possible that thick sediments may have accumulated but subsequently been eroded (Fig. 6).

Future sediment accumulation in the shoals areas will be determined mainly by changes in subtidal accommodation space. Assuming that sub-

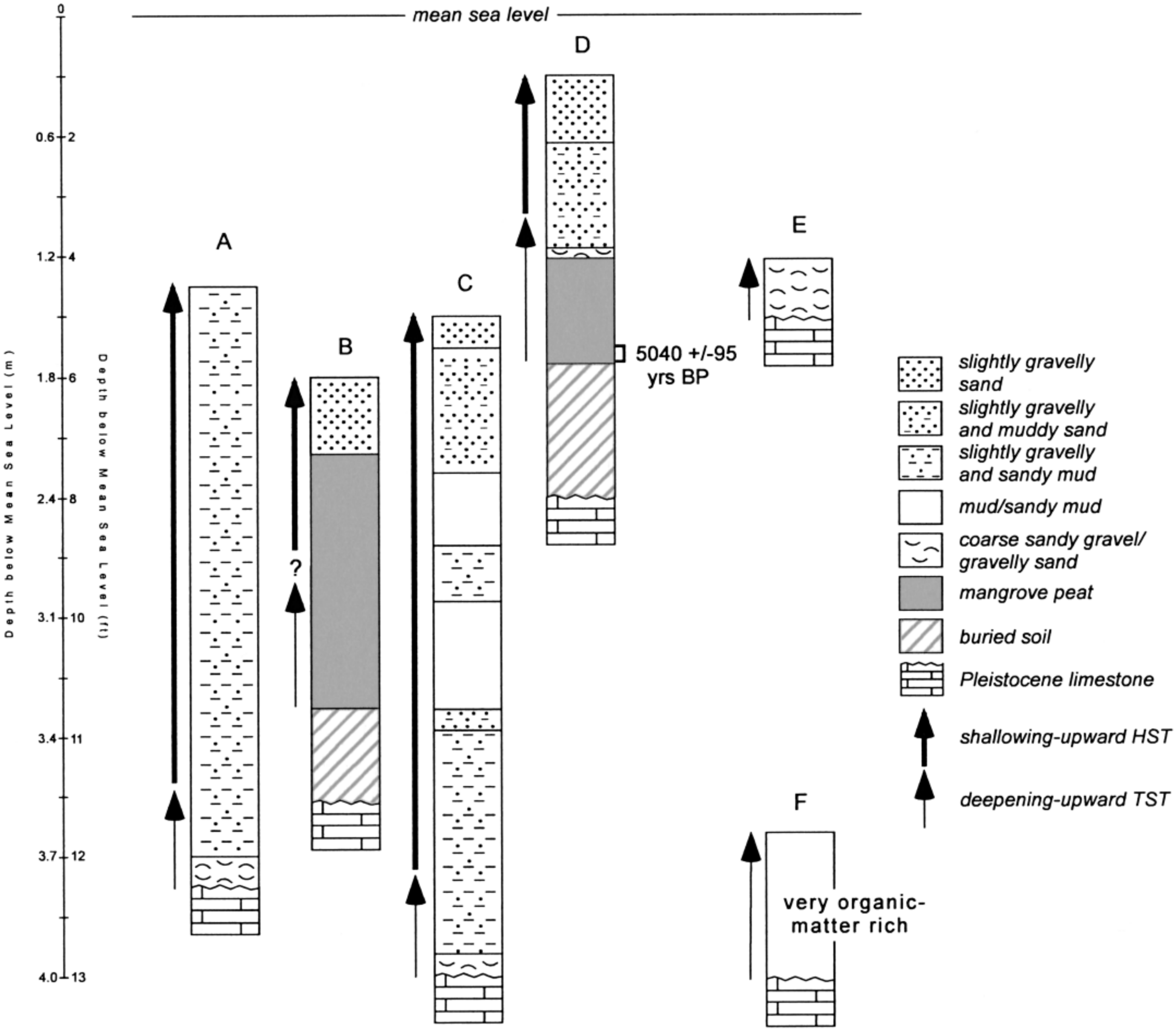

FIG. 7.—Sedimentary architecture in areas away from mud mounds (locations are circled and shown in Fig. 3B). Data are from Wilhite (2000) and Wilhite and Mazzullo (2000).

sidence is outpaced by falling sea level, which is one of several possible future scenarios, subtidal accommodation space will gradually diminish and sediments will aggrade into the intertidal zone (e.g., cores 7 and BS-8 in Fig. 11). Lateral progradation of carbonate sediments into the adjacent subtidal space in the downcurrent direction may continue to expand the mangrove islands at Mosquito Caye, Savannah Caye, and Los Salones (Fig. 6). Subtidal space eventually may be filled sequentially by subtidal, intertidal, and supratidal deposits capped by a subaerial exposure surface. The timing of emergence at a site will be determined by not only accommodation space but also sediment availability, erosion, and transport. Erosion may continue to dominate locally in the upcurrent (NE) part of the Bulkhead Shoals (e.g., at core BS-44; Fig. 6), and northward shoal expansion will not occur until sediment erosion and transport by the southward current weaken.

The final Holocene and post-Holocene succession in depocenters will probably have a variable thickness and a facies stacking pattern that is grossly similar to typical shallowing-upward peritidal cycles (e.g., James 1979). The vertical succession of subtidal sediments is generally composed of a thin, basal upward-deepening transgressive shelly gravel, locally with thin to thick peat, overlain by a thick, upward-shallowing section (Figs. 5, 6). This succession is similar to the subtidal sections of some ancient peritidal carbonate accumulations in Pennsylvanian rocks in the mid-continent, U.S.A. (e.g., Heckel 1984; Yang 1996) and in the Devonian in eastern California (Yang et al. 1995). The results of our study suggest that: (1) peritidal carbonate cycles may contain a basal, thin, upward-deepening section that represents a period of slow sedimentation; and (2) sediment accumulation curve in depocenters is overall concave-upward and comprises several segments with different slopes (Fig. 11). The curve would be convex upward if subtidal carbonate accumulation is strictly upward-shallowing. The single linear sediment accumulation curve used in some models of shallow subtidal carbonate deposition (e.g., Read et al. 1986; Goldhammer et al. 1990) may be an oversimplification of reality (cf. Sadler 1994).

Sediment Accumulation in Non-Depocenters.—Slow sediment accu-

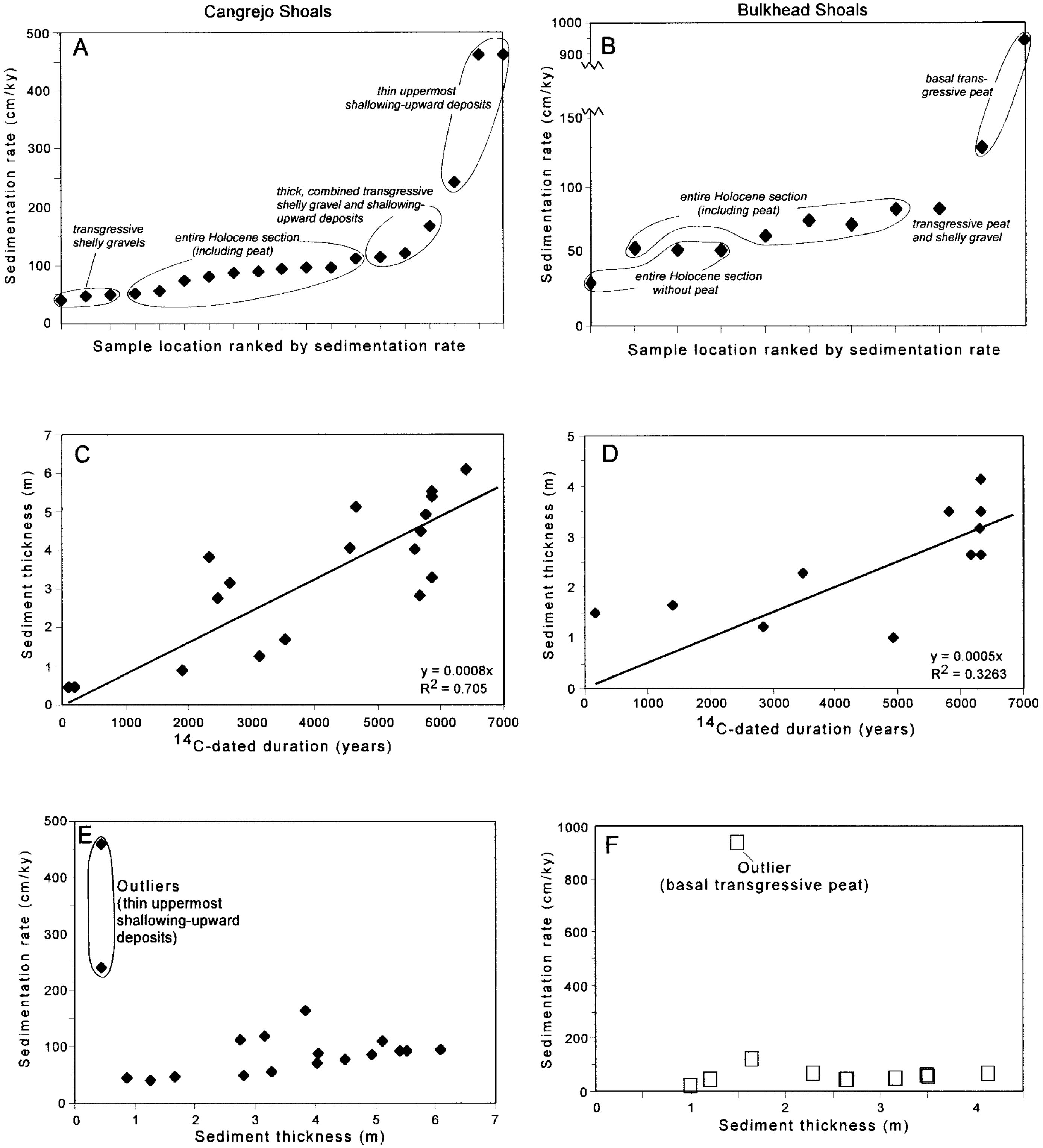

FIG. 8.—**A, B)** Sedimentation rates of ^{14}C-dated, cored sections at the Cangrejo and Bulkhead shoals. **C, D)** Correlation between ^{14}C-dated duration and thickness of cored sections, showing good positive linear correlation at Cangrejo and poor correlation at Bulkhead. **E, F)** Correlation between sediment thickness and sedimentation rate of cored sections at Cangrejo and Bulkhead. Setting the regression line passing through point (0,0) and with removal of outliers, there is no linear correlation and even the second-order polynomial fit is very poor ($R^2 = 0.34$ and 0.005 for Cangrejo and Bulkhead, respectively), suggesting that thick sediments may not have been accumulated rapidly.

TABLE 1.—*Mean sedimentation rates and one standard deviations of Holocene subtidal sediments in depocenters and non-depocenters, Chetumal Bay, northern Belize.*

Geographic Subdivisions of Chetumal Bay		Mean Sedimentation Rate (cm/ky)			Age Model (years)*	No. of Samples
Northwestern-central	Nondepocenters	15.8 ± 11.3	16.4 ± 15.3	30.9 ± 25.7	5810	38
Northeastern and central		16.5 ± 16.5			5040	109 (9 zero rates)
Cangrejo Shoals	Depocenters	42.3 ± 30.8	40.8 ± 26.6		6400	138 (7 zero rates)
Bulkhead Shoals		37.5 ± 15.2			6330	76

* Where available, ^{14}C-dates were used for cores of the entire Holocene sediment sections.

mulation has dominated a large part of Chetumal Bay in the Holocene (Fig. 3B). For example, sediments are 29 cm at core BW-23 in the northern part of the bay and 47 cm at Location R in the western-central part (Figs. 1, 3B). At these sites, the accumulation curves are single shallow lines, and water depth has increased since initial marine flooding because sea-level rise has outpaced sediment accumulation (Fig. 11).

Slow sediment accumulation in north-central Chetumal Bay results mainly from persistent southward sediment transport. Periods of major sediment transport and deposition in the last two decades have occurred during storms (Mazzullo et al. 2003; cf. Tucker 1985; Wanless et al. 1995). This is particularly evident in eastern Chetumal Bay where, despite prevailing NE trade winds, most soritid sand shoals are deposited to the south of cayes, and their N–S orientation is parallel to wind directions during northers (Fig. 1). The NE–SW trends of some of the shoals (e.g., all of Bulkhead) and the presence of small recurved spits with similar trends at the southern ends of some shoals, likely reflect reshaping by exceptionally strong trade winds.

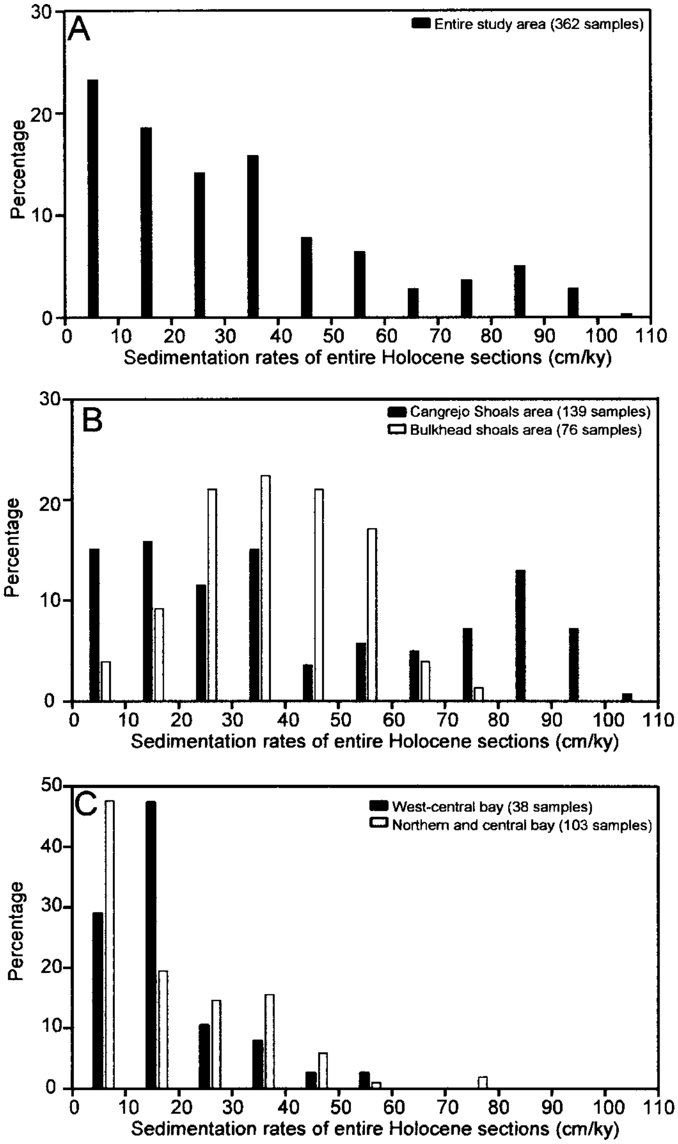

FIG. 9.—Histograms of sedimentation rates of entire Holocene sediment sections in the **A)** entire study area, **B)** shoals areas, and **C)** elsewhere in Chetumal Bay.

High foraminiferal productivity after early rapid sea-level rise has been noted in several places in the world (e.g., Hallock 1981; Hallock et al. 1986). Soritid and miliolid foraminifera are the dominant sediment producers in the bay, and the main nurseries for at least the soritids, are shallow-water grass (*Thalassia*) and algal (*Laurencia* and *Batophora*) beds mainly in the northeastern part of the bay along the back-side coast of Ambergris Caye. Conversely, minimum foraminiferal productivity is noted elsewhere because of the paucity of such shallow-water substrate. Hence, S-to-SW transport of foraminiferal sediments (and mud) from their ''source area'' is consistent with dominant wind directions and thickness variations in the study area (Figs. 1 and 3B, respectively).

In the near future, assuming that falling sea level outpaces subsidence, sediment transport out of northern Chetumal Bay will probably still dominate unless southward currents weaken and/or increased sediment production exceeds southward sediment export. However, it is possible that the thin subtidal sediments in non-depocenters may be capped directly by a subaerial exposure surface (Figs. 3A,B, 11), and the terminal topography of post-Holocene deposits in the bay will not be a level surface but will have a maximum relief of 2–3 m similar to the present topography.

The Holocene sediment accumulation history of both depocenters and non-depocenters in the study area is probably analogous to thickness and facies patterns of subtidal accumulation in inner shelves of ancient carbonate platforms in an icehouse climate, when large-amplitude, high-frequency sea-level fluctuations occurred. The accumulation curves of the depocenters and non-depocenters may serve as end-member references for computer modeling of inner-shelf subtidal carbonate sedimentation.

Bedrock Topographic Control on Sediment Accumulation and Sedimentation Rate

The sedimentation rate of entire Holocene sections correlates positively with bedrock depth in the study area (Fig. 12). Because only four age models were used in calculating sedimentation rates (Table 1), the rate variations reflect mainly sediment thickness variations. Thus, the correlation indicates a direct bedrock topographic control on thickness. The linear correlation in Cangrejo and Bulkhead shoals and the northeastern-central part of the bay ($R^2 = 0.73, 0.68, 0.68$, respectively; Fig. 12A, B, C) suggests that areas of low bedrock surface tend to accumulate thick sediments in the inner shelf, or at least protect initial sediments from erosion (Figs. 2, 3B, 5, 6). In Cangrejo, sediments were focused there by wind-driven currents, southward longshore current on the outer shelf, tidal ebb and flood currents, and storm surges in and out of the bay (Figs. 2, 5; Mazzullo et al. 2003). In Bulkhead, the mangrove islands formed during early transgression in and on the margin of bedrock lows may have trapped

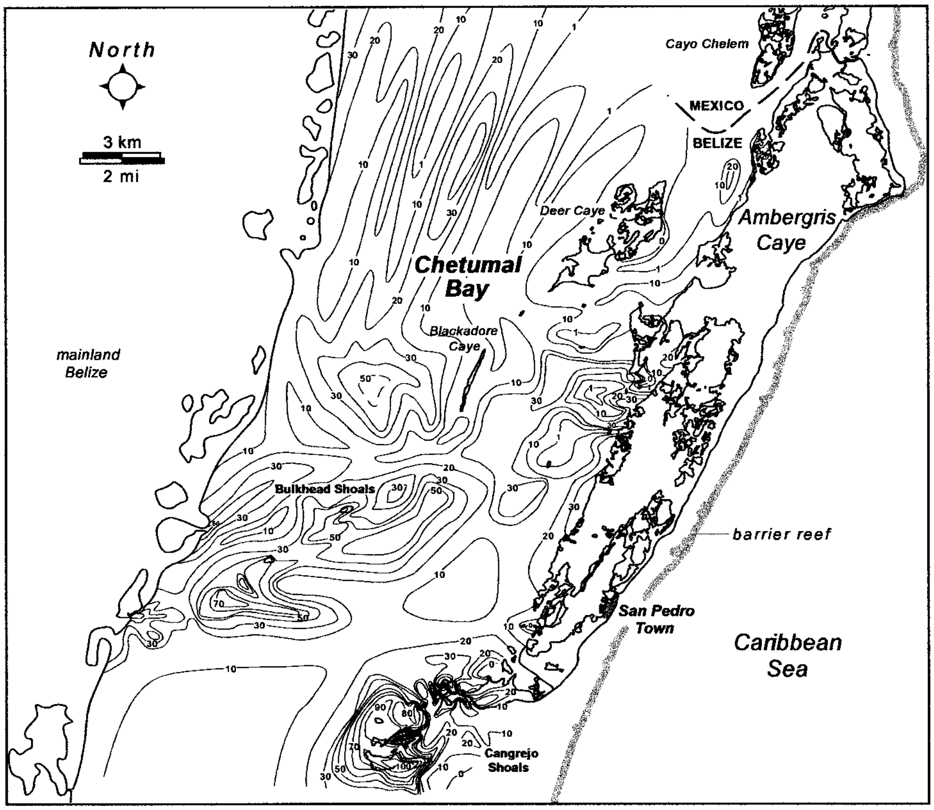

FIG. 10.—Map of sedimentation rate of entire Holocene sediment sections. Contour interval is 10 cm/ky.

sediments transported by southwestward currents (Figs. 2, 6). Once a mud mound with a low but positive relief was established, it became a barrier to current flow, accentuating sediment trapping. However, the poor correlation in the northwestern-central part ($R^2 = 0.39$; Fig. 12D), the outliers in other areas (Fig. 12A, B, C), and only minimal accumulation in the deep depression to the south (Figs. 2, 3B) suggest that bedrock topography is not the dominant control on sediment accumulation at these sites. Instead, sediment availability and/or dispersal by currents may have been the main control.

Sediment accumulation at Cangrejo and Bulkhead shoals has been extremely non-uniform in diverse sub-environments, such as the upcurrent and downcurrent sides and crests of mud mounds, ebb and flood tidal deltas, and tidal channels (Figs. 5, 6; Mazzullo et al. 2003). Fast shoaling of mud mounds around bedrock lows during sea-level highstand has increased sediment thickness and decreased water depth. On the other hand, persistent sediment spreading during southward transport by currents in the northeastern-central and northwestern-central areas of the bay has resulted in thin, but relatively uniform, sediment accumulation. These dynamic and interactive processes have controlled the amount and distribution of sediment accumulation, and ultimately, resulted in vertical and lateral variations of sedimentation rates in the study area.

Time Dependence of Sedimentation Rate

Sedimentation rate decreases with increasing observational time span over which a rate is calculated because of the increasing likelihood of longer erosional and nondepositional hiatuses in the stratigraphic record (Schindel 1980; Sadler 1981, 1999; Plotnick 1986; cf. Schlager et al. 1998; Schlager 1999). This time dependence is demonstrated on the plot of sedimentation rates of the Cangrejo and Bulkhead shoals versus observational time derived from ^{14}C dates (Fig. 13). Power-law relationships appear through linear regression for Cangrejo and Bulkhead shoals separately and for the two shoals as a whole (Fig. 13; Table 2), although the relationships are tentative because only 30 data points from cored and dated sites are available.

Sadler (1999) suggested that the fractal dimension (= 1—power-law slope gradient) of a power-law rate–time relationship is an indicator of the abundance, length, and distribution of hiatuses in a stratigraphic record (see also Plotnick 1986) and can be used to assess the completeness of the record. His numerical experiment suggests that a record with a fractal dimension larger than 0.5 is deposition-dominated, and one with less than 0.5 is erosion and/or nondeposition-dominated. The larger the fractal dimension of a record is, the more complete the record. The fractal dimension of the combined Cangrejo and Bulkhead shoals record is 0.47 (Table 2), suggesting that sedimentation in these areas has been slightly dominated by erosion and nondeposition. Episodic deposition, nondeposition, and erosion caused by storm events and variable direction and strength of tidal and wind-driven currents, which have been operating over an uneven bedrock topography and variable rates of sea-level rise over time, may have formed hierarchical hiatuses in the shoals record.

Furthermore, the Cangrejo record has a greater fractal dimension than the Bulkhead record (0.58 vs. 0.21), suggesting that the former is more complete (Table 2). The Cangrejo mud mounds may have provided a positive feedback on sediment accumulation by trapping bayward and oceanward sediment transport. Sediment dispersal has been restricted by Ambergris Caye to the north and by tidal currents to the east and west, enhancing sediment accumulation in and around Cangrejo in the form of aggradation and southward progradation (Figs. 3B, 5). In contrast, the Bulkhead mud mounds may have had a negative feedback. That is, in the open shallow bay, sediment supply has been limited to the sediments produced in the northern part of the bay, and sediment dispersal by tidal and wind-driven currents has been relatively unrestricted. The thinner and fewer number of sedimentation units at Bulkhead compared to Cangrejo (Figs. 5, 6) supports this contention.

The fractal dimension of Sadler's (1999) power-law relationship for shal-

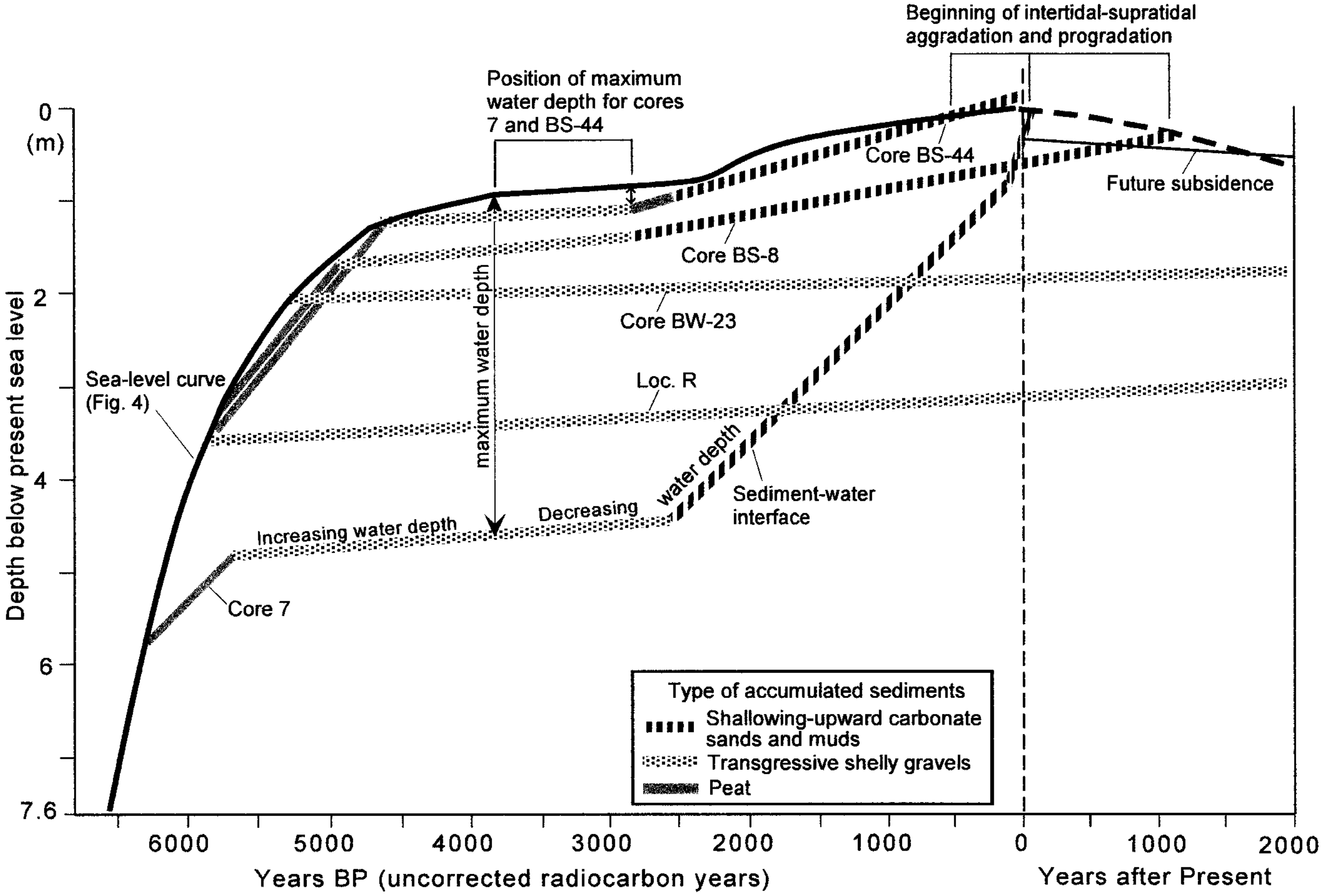

FIG. 11.—Sediment accumulation history at selected sites in Chetumal Bay during Holocene sea-level rise and speculated post-Holocene slow sea-level fall. Core 7 at Cangrejo Shoals and cores BS-8 and BS-44 at Bulkhead Shoals (see Figs. 5 and 6 for locations) are located in depocenters, whereas core BW-23 and location R (see Fig. 1 for location) are in non-depocenters.

low-marine carbonate sediments can be regarded as the global average representative of peritidal carbonate accumulation at the interval of 100–10,000 years (Fig. 13; Sadler 1994). The Cangrejo and Bulkhead records have a fractal dimension similar to the global average but lower sedimentation rates (Fig. 13). This suggests that the distribution of hiatuses in the Belize record and the basic mechanisms of sediment production, redistribution, and accumulation in the study area are similar to the global average, but sediment accumulation is slower. This is expected because the global average was derived from both outer-shelf and inner-shelf sediments, and sediment production and accumulation in the outer shelf generally are greater than those in the more restricted inner shelf (e.g., Enos 1991; Sadler 1994).

It is worthwhile to note that the power-law relationship of globally averaged sedimentation rates masks large variations in sedimentation rate at specific time intervals, as shown in this and other studies (e.g., variations of two to three orders of magnitude in the time span of 1–10 ky; fig. 1 of Enos 1991, and fig. 1 of Sadler 1994). In addition, stratigraphic completeness, as estimated by the fractal dimensions of the Cangrejo and Bulkhead depocenters, overestimates that of non-depocenters. Characterization of 3-D stratigraphic completeness poses a challenge for future research (Harris 1994; Dromart et al. 2002; Burgess and Wright 2003).

The Paradigm of ''Representative'' Sedimentation Rate

Vertical and areal variations in sedimentation rate of Holocene carbonate sediments in Chetumal Bay suggest extreme difficulty, if not impossibility, in finding a representative sedimentation rate for inner-shelf subtidal carbonate facies. Nonetheless, such a rate is critical to quantitative studies of ancient peritidal carbonate sedimentation, thickness–time conversion, and biological evolution (e.g., Dingus and Sadler 1982; Enos 1991; Sadler 1994; Yang and Lehrmann 2003). This constitutes the paradigm of ''representative'' sedimentation rate. The Belize rates are within the range of similar Holocene lithologies (e.g., Enos 1991; Sadler 1994) but have a lesser lower limit, including zero values (Fig. 10), which have rarely been reported in previous studies.

This study sheds light on two aspects that must be considered in selecting a ''representative'' sedimentation rate. First, the selected rate should be derived from analogous strata deposited during a time span of the same order of magnitude as the strata to be studied. For example, if the rate (2.42 m/ky) of the uppermost deposits of a time span of 190 years in core 22 of the Cangrejo Shoals (Fig. 5) were used to convert the thickness (3.29 m)

TABLE 2.—*Power-law relationship between sedimentation rate and length of time derived from cored sections in Cangrejo and Bulkhead shoals, Chetumal Bay, northern Belize.*

	Power-law Relationship	Fractal Dimension	Stratigraphic Completeness
Cangrejo Shoals	$y = 25.737\,x^{-0.4161}$ $R^2 = 0.679$	0.5839	Most complete, deposition dominated
Bulkhead Shoals	$y = 410.43\,x^{-0.79}$ $R^2 = 0.8231$	0.21	Least complete, erosion dominated
Cangrejo and Bulkhead Shoals	$y = 56.494\,x^{-0.5279}$ $R^2 = 0.6834$	0.4721	Moderately complete, slightly erosion dominated

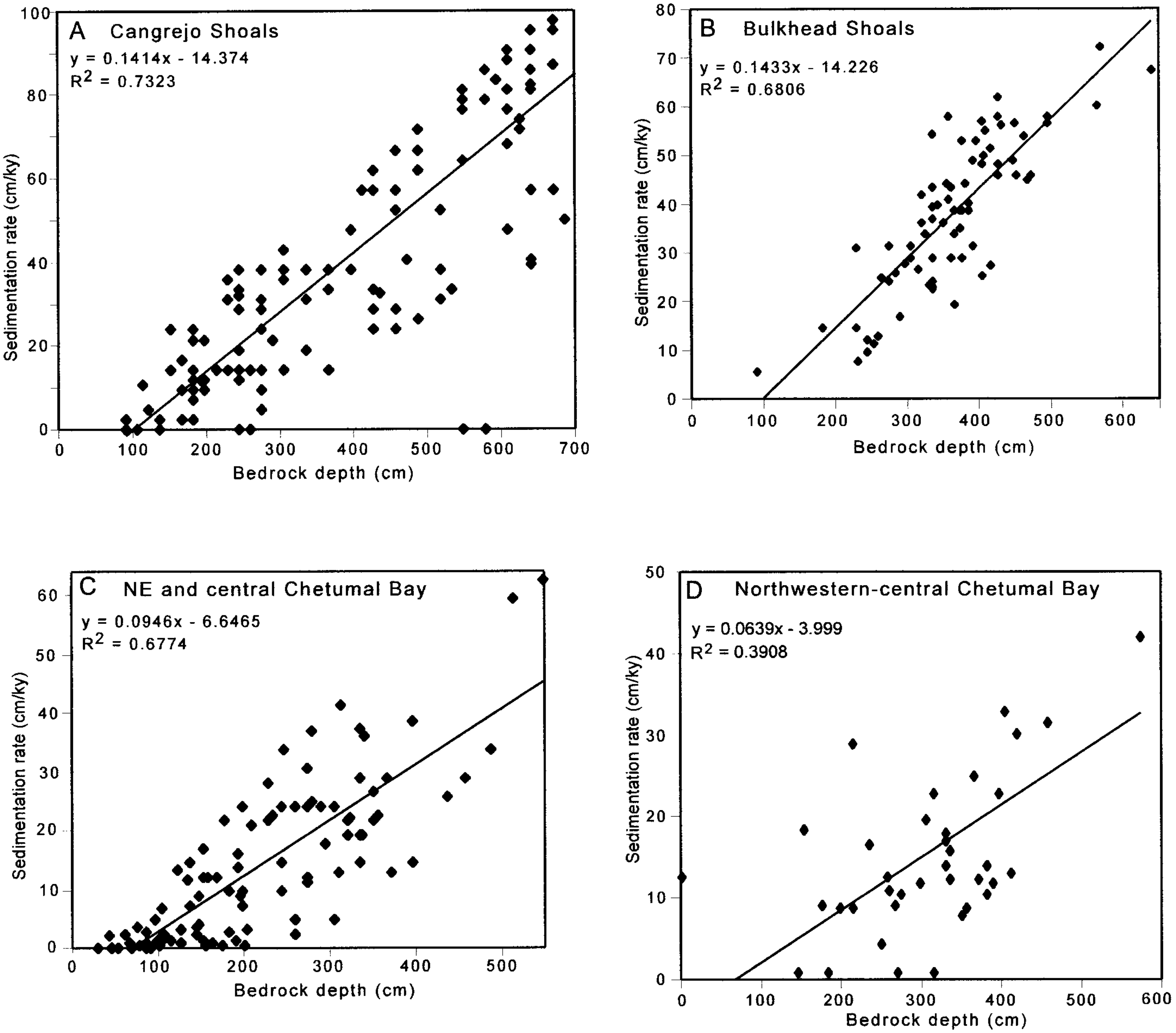

FIG. 12.—Correlation between sedimentation rate and depth to bedrock below mean sea level. Reasonable positive linear correlation exists for all subdivisions of the study area.

of the entire Holocene section into time (~ 1360 years), the duration of the section would be underestimated by ~ 4,500 years (or ~ 77%) in comparison to the actual ^{14}C-dated duration of 5,855 years.

Second, a single sedimentation rate may not be representative of a laterally continuous subtidal section of variable thickness over a large area because, for example, sedimentation rate in the depocenters is generally much greater than that in non-depocenters (Fig. 10). In fact, our results indicate that even a linear trend of sedimentation rate, either in space or in time, will be oversimplified (Figs. 9, 10, 11). Therefore, different sedimentation rates should be assigned to different facies within a section and to sections at different localities, with consideration of lateral and vertical changes of facies type and thickness. If a single rate were applied, then the duration of a section would be grossly overestimated in depocenters and underestimated in non-depocenters. For example, using the mean rate (32 cm/ky) of the study area, the duration of a 4-m-thick section at Cangrejo would be 12,500 years, an overestimation of 6,100 years (or ~ 95%) of the actual duration of 6,400 years (Table 1). The duration of a 30-cm-thick section in the northeastern and central parts of the bay would be 938 years, an underestimation of 4,102 years (or ~ 81%) of the actual duration of 5,040 years (Table 1).

If sediment accumulation were to cease instantly across the study area, the Holocene subtidal section would have a variable thickness (including zero thickness) but approximately the same duration, including time represented by sediments and hiatuses. Accordingly, lateral thickness change may be the best-available indicator of laterally changing sedimentation rate in an area, even though thickness may not be correlative with rate at all (Fig. 8E, F). As a result, the thickness trend of a time-stratigraphic unit may be the best-available proxy for estimating the lateral change in duration of deposition of the unit when the number and duration of stratal hiatus within the unit are unknown (Fig. 8C, D; cf. Tipper 1987).

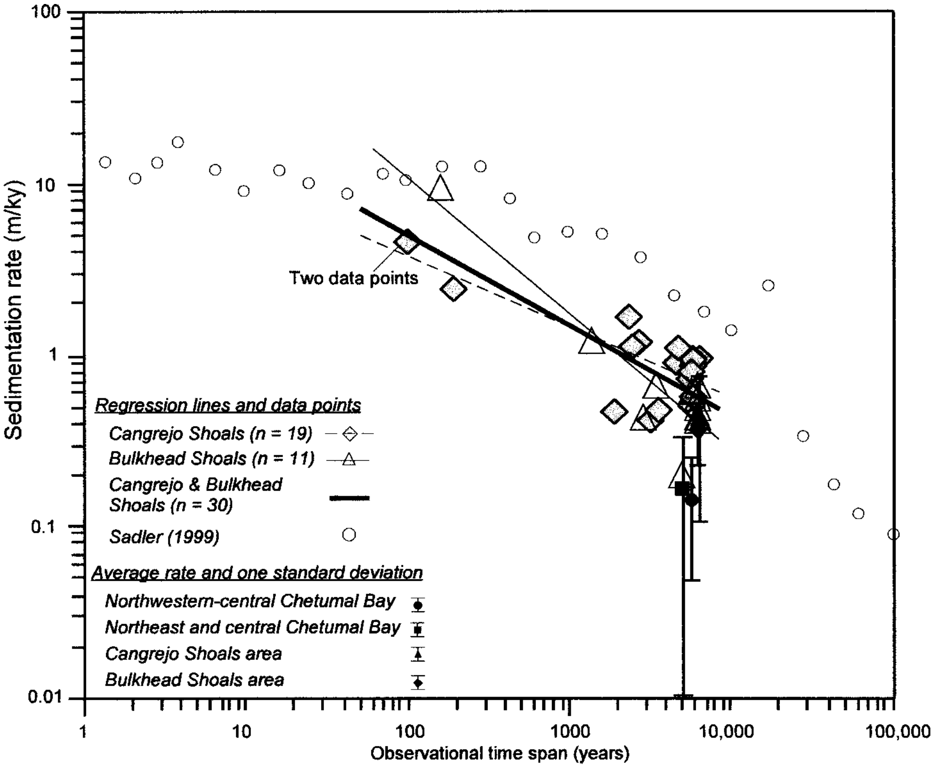

FIG. 13.—Log–log correlation between sedimentation rate and observational time span, using data points of cored sections from Cangrejo and Bulkhead shoals. Power-law relationships may exist for Cangrejo and Bulkhead shoals and their combination (Table 2), and show a trend similar to that of Sadler (1999). Average rates and corresponding one standard deviations of the four subdivisions in the study area are also displayed to show large variations in sedimentation rate (Table 1).

CONCLUSIONS

Sedimentation rates of Holocene, inner-shelf subtidal sediments in northern Belize range from 0 to 110 cm/ky. Mean sedimentation rates are not representative of carbonate sediment accumulation because of spatial and temporal partitioning of sediment thickness. Bedrock topography, sediment availability, direction and strength of storm-related, wind-driven, longshore and tidal currents, and variable rate of Holocene sea-level rise have controlled sediment transport and redistribution, site and amount of sediment accumulation, and thus, variations in sedimentation rate. Such variations provide insights into processes controlling subtidal carbonate sedimentation and facies architecture in the study area during the Holocene, and by extension, in similar settings during the Phanerozoic. A power-law relationship between sedimentation rate and time may exist in the study area. A higher fractal dimension of the relationship indicates a more complete and more deposition-dominated system.

The results of this study suggest that the thickness of a time-stratigraphic unit is not a faithful, but only a best-available, proxy for duration of deposition. In modeling ancient shallow subtidal, inner-shelf carbonate sedimentation, different sedimentation rates should be assigned to different facies within a section, and to sections at different localities, with consideration of lateral and vertical changes of facies type and thickness.

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