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Sedimentary architecture and genesis of Holocene shallow-water mud-mounds, northern Belize

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ABSTRACT

Cangrejo and Bulkhead Shoals are areally extensive, Holocene biodetrital mud-mounds in northern Belize. They encompass areas of 20 km^2 and 35 km^2 in distal and proximal positions, respectively, on a wide and shallow-water, microtidal carbonate shelf where storms are the major process affecting sediment dynamics. Sediments at each mound are primarily biodetrital and comprise part of a eustatically forced, dominantly subtidal cycle with a recognizable deepening-upward transgressive systems tract, condensed section and shallowing-upward highstand systems tract. Antecedent topographic relief on Pleistocene limestone bedrock also provided marine accommodation space for deposition of sediments that are a maximum of 7·6 m thick at Cangrejo and 4·5 m thick at Bulkhead. Despite differences in energy levels and location, facies and internal sedimentological architectures of the mud-mounds are similar. On top of Pleistocene limestone or buried soil developed on it are mangrove peat and overlying to laterally correlative shelly gravels. Deposition of these basal transgressive, premound facies tracked the rapid rate of sea-level rise from about 6400–6500 years BP to 4500 years BP, and the thin basal sedimentation unit of the overlying mound-core appears to be a condensed section. Following this, the thick and complex facies mosaic comprising mound-cores represents highstand systems tract sediments deposited in the last ≈ 4500 years during slow and decelerating sea-level rise. Within these sections, there is an early phase of progradationally offlapping catch-up deposition and a later (and current) phase of aggradational keep-up deposition. The mound-cores comprise stacked storm-deposited autogenic sedimentation units, the upper bounding surfaces of which are mostly eroded former sediment–water interfaces below which depositional textures have largely been overprinted by biogenic processes associated with *Thalassia*-colonized surfaces. Vertical stacking of these units imparts a quasi-cyclic architecture to the section that superficially mimics metre-scale parasequences in ancient rocks. The locations of the mud-mounds and the tidal channels transecting them have apparently been stable over the last 50 years. Characteristics that might distinguish these mud-mounds and those mudbanks deposited in more restricted settings such as Florida Bay are their broad areal extent, high proportion of sand-size sediment fractions and relatively abundant biotic particles derived from adjoining open shelf areas.

Keywords Belize, cyclicity, Holocene, mudbanks, mud-mounds, parasequences, storm deposits.

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INTRODUCTION

Carbonate mud-mounds (*sensu* James & Bourque, 1992; Bosence & Bridges, 1995) present in shallow platform and deep-water settings in the late Precambrian and Phanerozoic are of diverse origin (papers in Monty, 1995). In contrast, Cenozoic mud-mounds (or mudbanks) are represented mainly by biodetrital accumulations, shallow-water occurrences of which are relatively rare in Holocene deposits (Longman, 1981; Pratt, 1995). Because of their rarity, mudbanks in south Florida, and particularly those in Florida Bay, have become archetypical analogues of some ancient micritic rocks (e.g. Feldman & Maples, 1989; Tedesco & Wanless, 1995). Although studies in Florida have provided valuable insight into the genesis and recognition of such deposits (e.g. Ginsburg & Lowenstam, 1958; Wanless, 1976; Enos, 1977, 1989; Enos & Perkins, 1979; Quinn & Merriam, 1988; Wanless & Tagett, 1989; Tedesco & Wanless, 1991, 1995; Bosence, 1989a,b,c, 1995; Taberner & Bosence, 1995; Wanless *et al.*, 1995), they are not necessarily analogous to some ancient mud-dominated accumulations in shallow-water environments that are less restricted than Florida Bay (Wilson & Jordan, 1983).

Two thick and areally extensive Holocene mud-mounds – the Cangrejo Shoals and Bulkhead Shoals – are present in distal and proximal areas, respectively, on the northern Belize shelf (Fig. 1). In contrast to the semi-restricted environment in which the Florida Bay mudbanks are deposited, the northern Belize study area is a relatively wide and strongly wind-affected, shallow-water shelf. The Belize mud-mounds not only provide an opportunity to examine additional occurrences of such deposits, but also to do so in a setting that is significantly different from Florida Bay. This paper describes the facies, sedimentary architecture and genesis of the Cangrejo and Bulkhead Shoals mud-mounds in a sequence-stratigraphic perspective, and relates their sedimentological characteristics and development to Holocene

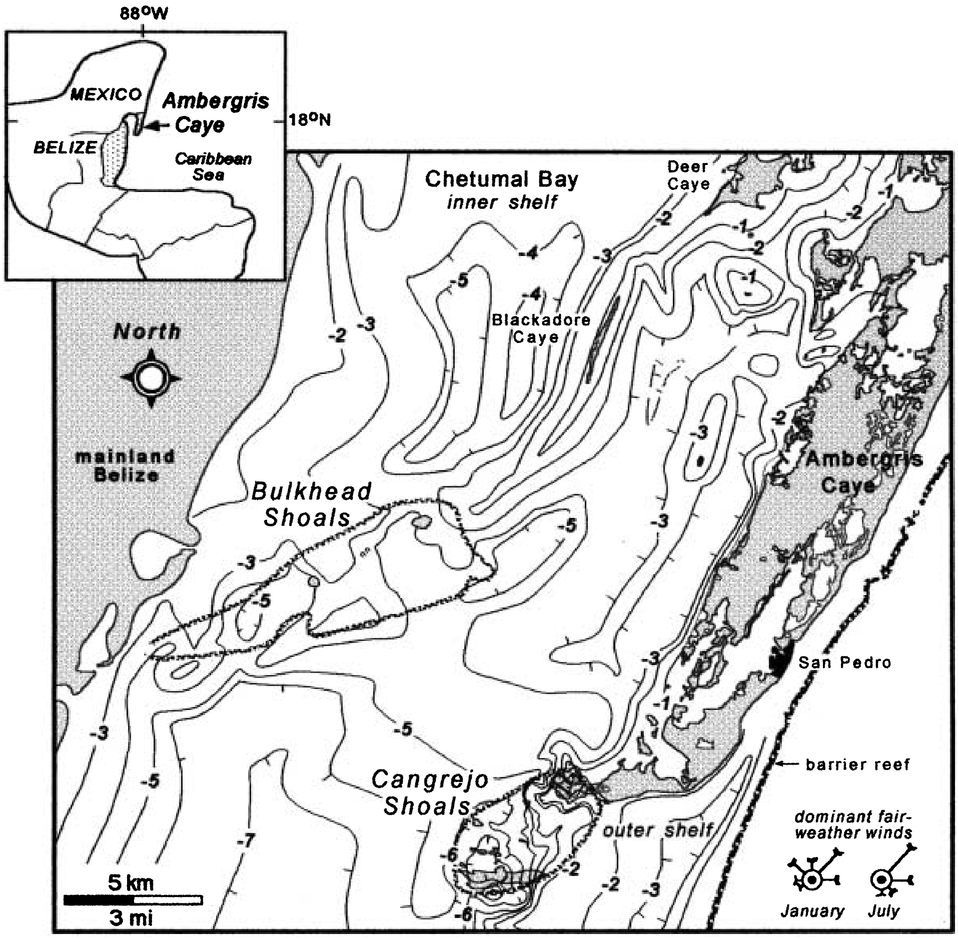


Fig. 1. Location of Cangrejo and Bulkhead Shoals in northern Belize, and depth to top of Pleistocene bedrock limestone below mean sea level (contour interval is 1 m).

sea-level history, bedrock topography, sediment source and depositional processes. It then compares them with the Florida Bay occurrences to evaluate similarities and differences in mud-mound facies and sedimentary architecture, developed in disparate environmental settings, that might be used in interpretive studies of analogous ancient deposits.

METHODS

Aerial photographs and satellite images were used to locate sampling sites. Water depth, sediment thickness and depth to bedrock were measured at all localities, and surficial sedimentary and biogenic structures and annotation of live and dead organisms were recorded during snorkelling and wading traverses. Thirty-five soft-sediment cores were recovered at Cangrejo and 30 at Bulkhead. Coring was done with a 5 cm diameter piston core with longitudinally cut plastic sleeves inserted into the barrel, supplemented by collection of surface samples. Sediments were described and divided into lithological units on the basis of sediment type, colour, types and amount of particles present, and presence or absence of sedimentary and biogenic structures. In the laboratory, samples of each unit were wet-sieved to identify texture using terms for both sediments and rocks (Fig. 2A); in this paper, only terms for sediments are cited. Sediment mineralogy was determined by X-ray diffraction (XRD) with a Phillips 3100XRG unit using CuKα radiation with internal quartz standards. Mole% $MgCO_3$ in calcites was calculated by peak shift referring to data in Mackenzie *et al.* (1983), and the relative percentage of carbonate minerals present was determined by comparison with prepared standards. Carbon-14 ages of samples of buried peats and shells were determined by Geochron Laboratories, Cambridge, MA, USA, and reported ages are uncalibrated and uncorrected for reservoir effect.

SETTING OF STUDY AREA

The study area lies to the S and W of Ambergris Caye on the northern Belize shelf (Fig. 1), where fairweather, semi-diurnal tidal range is $< 0{\cdot}3$ m. The shelf is 25 km wide and comprises a narrow outer shelf seaward of Ambergris Caye and a wide inner shelf, within Chetumal Bay, leeward of the caye. The Cangrejo Shoals are located at the southern tip of Ambergris Caye, in a physically unrestricted transition zone between the outer and inner shelves. The Bulkhead Shoals are within the central to western part of Chetumal Bay, about 10 km inshore of Ambergris Caye but on a wide inner-shelf platform where tidal flux and intensity are about half that at Cangrejo. Persistent winds over-ride tidal effects in the study area and are the dominant influence on current directions, sediment transport and deposition (Wilhite & Mazzullo, 2000). Fairweather NE trade winds, for example, result in W- to SW-flowing currents across the shelf and S longshore drift along the windward (E) coast of Ambergris Caye. Strong N winds ('northers') and S winds ('easter winds') periodically drive S–SE flow out of, and NW flow into, Chetumal Bay respectively. Hurricanes, with highly variable wind directions, approach mostly from the E (Stoddart, 1963). The net result of such a wind-dominated system is that the wide-fetch inner shelf, including the area around Bulkhead Shoals, is much less restricted, in this case by the presence of Ambergris Caye, than for example semi-enclosed Florida Bay.

Unconsolidated Holocene marine carbonate sediments and associated deposits overlie karsted Pleistocene limestones, the surface of which generally slopes towards the S–SW (Fig. 1). Ambergris Caye is a NE-trending ridge of bedrock limestone that crops out from near the Mexican border to the latitude of San Pedro Town. Narrow, submerged bedrock ridges and intervening dissolution valleys with NE trends are also present in Chetumal Bay, and they pass into a 6 m to 7 m deep dissolution depression on the S. Both Cangrejo and Bulkhead mud-mounds are deposited along the margin of this depression (Fig. 1).

PREVIOUS STUDIES

Regional aspects of the sedimentology, mineralogy and invertebrate biota in northern Belize were described initially by Ebanks (1975) and Pusey (1975) and, more recently, by Mazzullo & Bischoff (1992), Reid *et al.* (1992), Reid & Macintyre (1998), Teal (1998), Wilhite (2000), Wilhite & Mazzullo (2000) and Dimmick-Wells (2002a). The general setting and inferred origin of the Cangrejo Shoals were only briefly discussed by Vermeer (1959), Ebanks (1975) and Pusey (1975), with the last two authors examining only the top few metres of sediments here. A more detailed sedimentological and diagenetic study of Cangrejo was done by Teal (1998). Gross aspects of the sedimentology of the

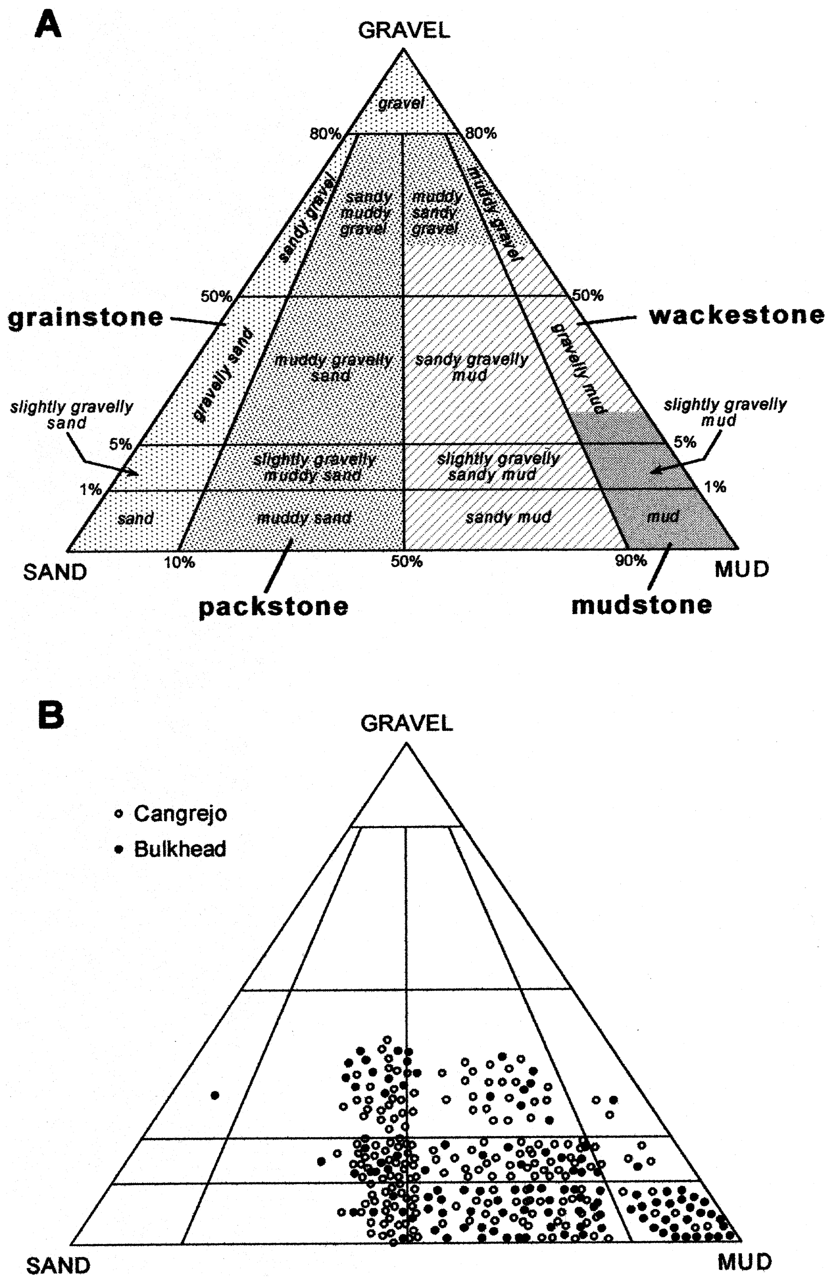


Fig. 2. (A) Terminology for textures of unconsolidated carbonate sediments and, according to Dunham (1962), their lithified equivalents. (B) Textures of surface and buried sediments at Cangrejo and Bulkhead. Vertical axis between 1% and 5% expanded for easy viewing.

Bulkhead Shoals were discussed by Pusey (1975), Wilhite (2000), Wilhite & Mazzullo (2000) and Dimmick-Wells (2002b).

GEOMETRY AND SURFACE FEATURES OF THE MUD-MOUNDS

The Cangrejo Shoals is a broad, oblate-shaped feature encompassing ≈ 20 km^2 of contiguous shallow-water flats transected by a number of tidal channels (Fig. 3). Length is 6 km from the S tip of Ambergris Caye to Cayo Cangrejo, and maximum width is ≈ 3·5 km. Water depths are 0·7 m or less on the flats and increase away from them (Fig. 3A). Holocene sediment thickness varies from 1 to 2 m on the NE end of the shoals to a maximum of 7·6 m beneath and around Cayo Cangrejo, and sediments are only 1–2 m thick in surrounding areas (Fig. 3B). Sediments were deposited on the sloping margins of and within a prominent depression in the bedrock limestone, the maximum depth of which is 7·6 m below mean sea level (Fig. 4A). The Bulkhead Shoals comprise a more linear feature that parallels Cangrejo (Fig. 1). It is larger

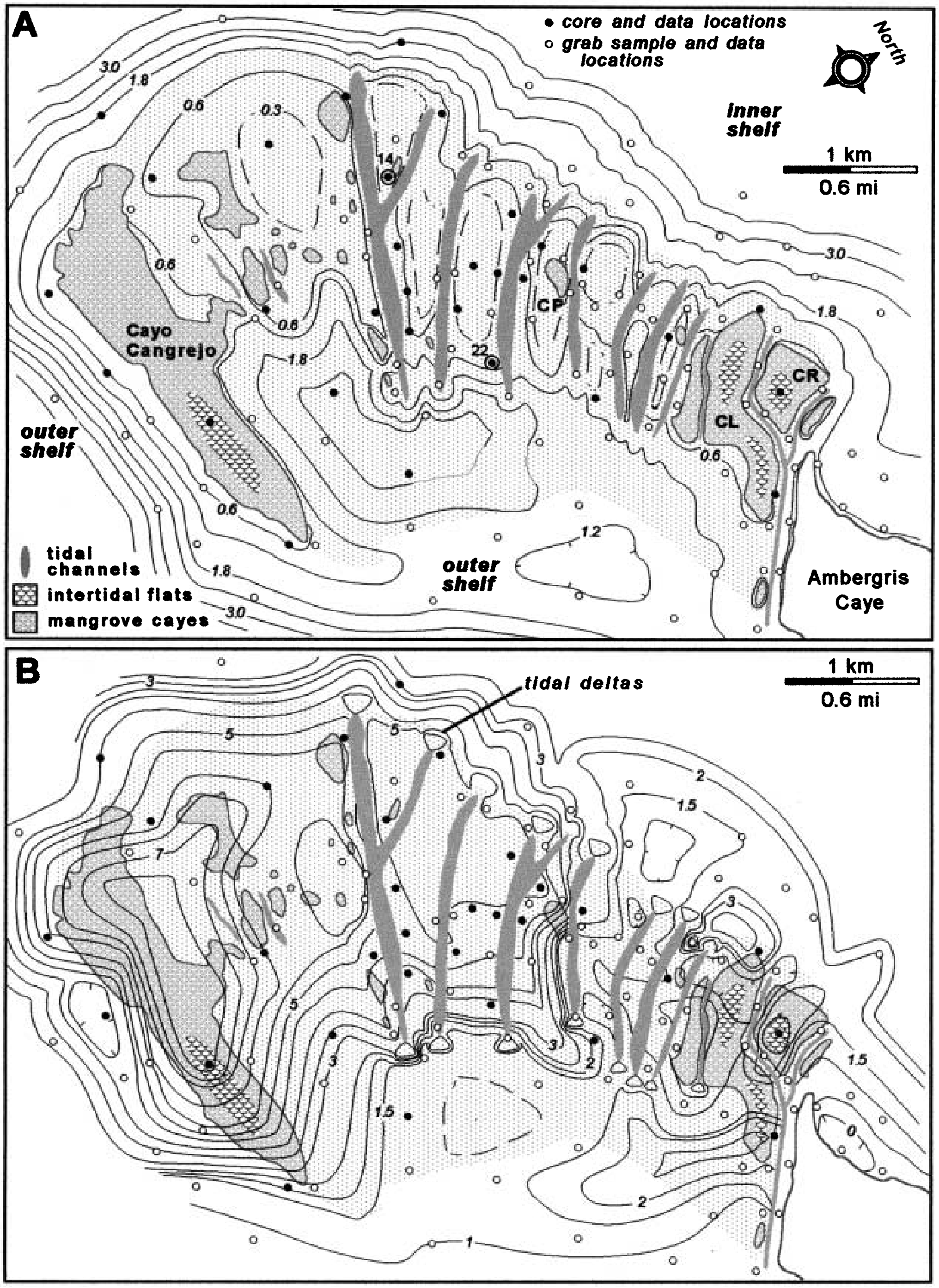


Fig. 3. Cangrejo mud-mound; these maps and Fig. 4A are rotated 90° clockwise from Fig. 1. (A) Locations of cores, surface sediment samples and additional data points, and water depth; contour interval is 0·6 m except for dashed 0·3-m contour on the shoals. Depths of channels cannot be shown at this scale. CR, Cayo Rombo; CL, Cayo Luisito; CP, Cayo Pescador. (B) Sediment thickness, including local peat and clay; contour interval is 0·5 m. The fine stippled pattern in (A) and (B) indicates the areal extent of the mud-mound.

than Cangrejo, encompassing ≈ 35 km^2 of shallow-water (< 0·5 m) flats that are also transected by tidal channels (Fig. 5). Length is ≈ 13 km, and maximum width is 6 km. The Cangrejo and Bulkhead accumulations are referred to as mud-mounds rather than mudbanks because of their convex depositional geometries and relief above the surrounding sea floor (see later; Figs 9 and 10), and following many workers (e.g. Bosence, 1995; Bosence & Bridges, 1995; Monty, 1995;

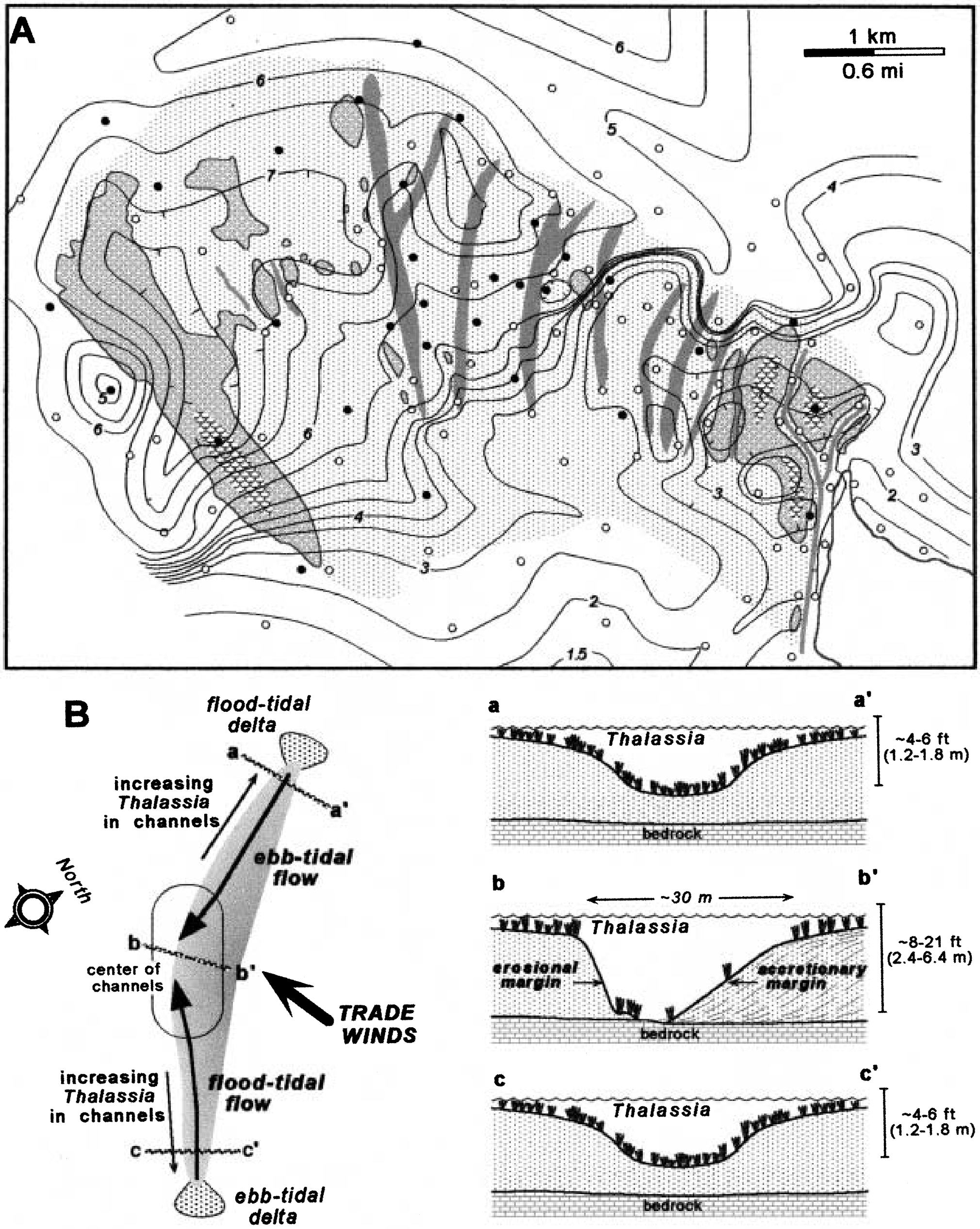


Fig. 4. (A) Depth to bedrock limestone below mean sea level at Cangrejo; contour interval is 0·5 m. The fine stippled pattern indicates the extent of the mud-mound. (B) Left – generalized plan view of channels showing tidal deltas, *Thalassia* cover and deflection of tidal flow to SW by trade winds. Right – cross-sectional channel morphology.

Pratt, 1995), the occurrence of mud-mounds is not restricted solely to deeper water deposits.

The Bulkhead Shoals mud-mound actually consists of two parallel shoals, the longest and most continuous of which averages ≈ 2 km wide and extends from Mosquito Caye SW to beyond Savannah Caye and almost to the mainland (Fig. 5A). It is separated from the shorter and narrower (average 1 km) shoal, which extends from Slackchwe Lighthouse SW towards Bulkhead Lighthouse, by an area where water is as much as 2 m deep. Otherwise, water depths generally increase in all directions away from the mud-mound. Deposition is on a topographically irregular, NE-trending ridge on the Pleistocene limestone, the top of which varies from 3 to 5 m below mean sea level and increases in depth into a 7+ m deep depression towards the S (Fig. 5B). Sections of clay and peat (also present at Cangrejo) directly overlie the limestone and

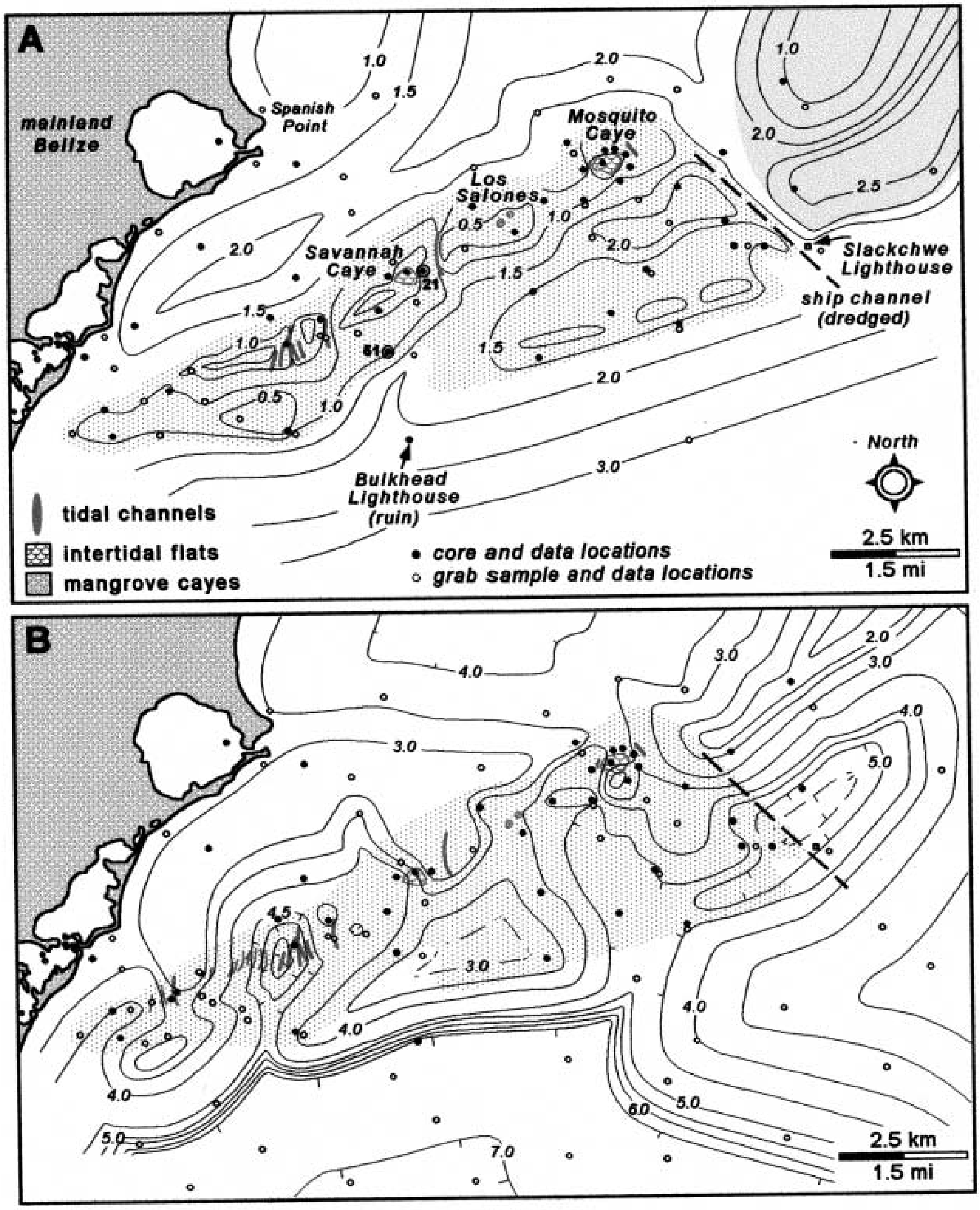
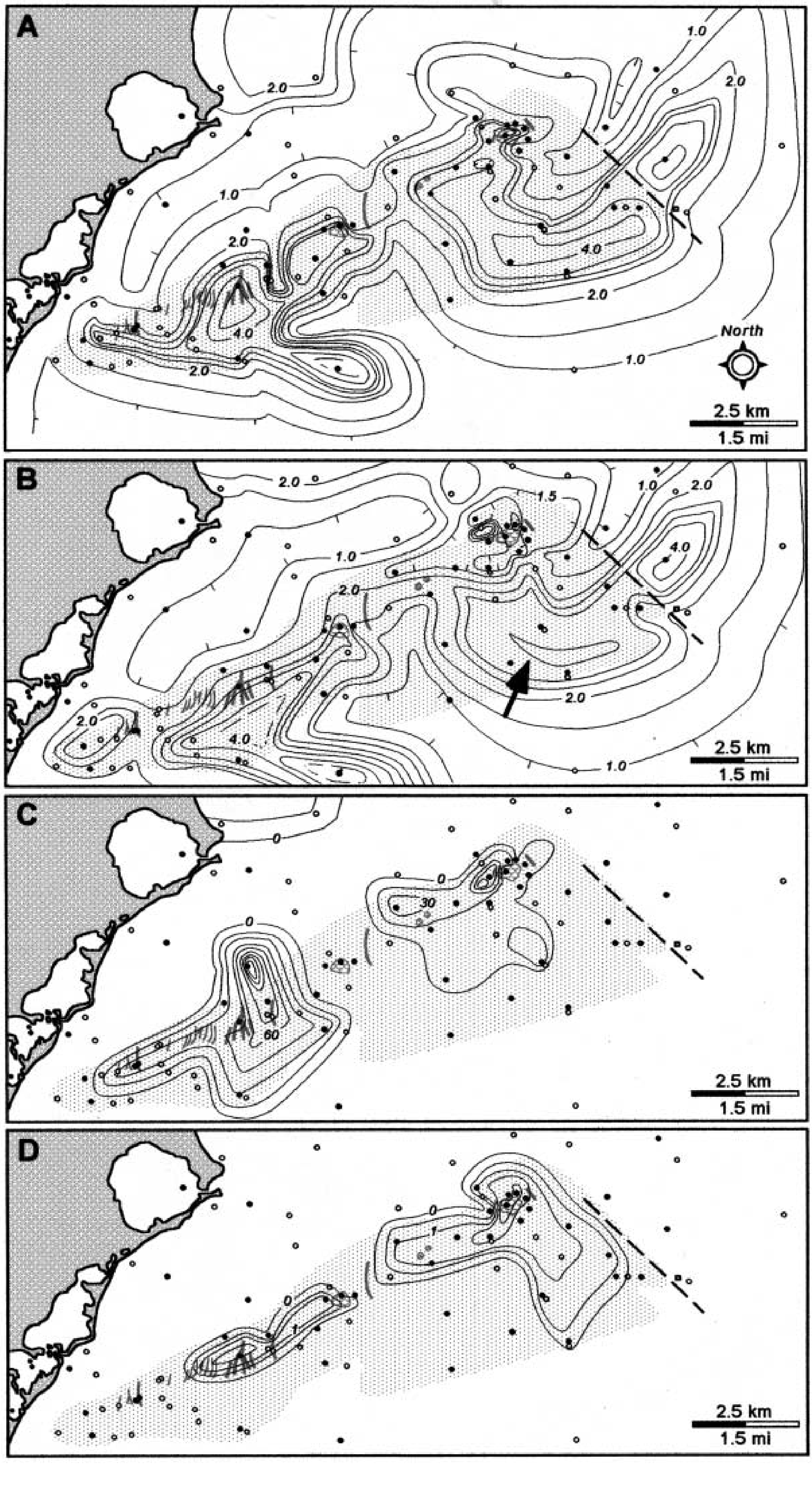


Fig. 5. Bulkhead mud-mound. (A) Locations of cores and data points, and water depth (contour interval is 0·5 m). Depths of channels, and the intertidal flats on Mosquito and Savannah Cayes, cannot be shown at this scale. Shaded area to the NE of Bulkhead Shoals is floored by SW-prograding soritid sand shoals. (B) Depth to top of Pleistocene bedrock limestone below mean seal level; contour interval is 0·5 m. The fine stippled pattern in (A) and (B) indicates the areal extent of the mud-mound.

underlie Holocene carbonate sediments at Bulkhead. The combined thickness of these deposits varies from ≈1 m on bedrock highs to 4·5 m overlying bedrock lows (Fig. 6A). Thickness of just the carbonate sediments likewise varies from 0·5 m in isolated areas to a maximum of ≈4 m over bedrock lows (Fig. 6B). Thickness distributions of the underlying clay and peat are shown in Fig. 6C and D respectively.

Thalassia is sparse to absent on the shallow flats at the Cangrejo Shoals, and becomes denser locally along and within tidal channels. The amount of grass increases towards both the windward (SE) and leeward (NW) sides of the mud-mound, and generally is quite dense off the shoals. In contrast, there is much less *Thalassia* at Bulkhead, even in channels. Surficial marine sediments within *Thalassia*-free areas in very


A
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2.0
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60
2.5 km
1.5 mi
D
0
1
0
1
2.5 km
1.5 mi

Fig. 6. Bulkhead Shoals. (A) Combined thickness of carbonate sediments and underlying buried clay and peat; contour interval is 0·5 m. (B) Thickness of carbonate sediments only; contour interval is 0·5 m. Arrow points to local deflection of main sediment thickness trend to the NW. (C) Thickness and distribution of buried clay; contour interval is 15 cm. (D) Thickness and distribution of buried peat; contour interval is 0·5 m. In all illustrations, the fine stippled pattern indicates the areal extent of the mud-mound.

sheltered parts of both mud-mounds are locally stained dark grey, which may indicate significant amounts of H_2S degassing to the surface. Scalloped erosional embayments are rare at Cangrejo and are observed only locally at Bulkhead, where they are present mostly along the N and NW sides of Mosquito and Savannah Cayes (the locations of which are shown in Fig. 5A). Blowouts, which are slightly depressed circular to ovate surficial features devoid of *Thalassia* (e.g. Enos & Perkins, 1979; Wanless & Tagett, 1989), are locally present on both mud-mounds, and callianassid shrimp mounds are present in a few places only at Cangrejo. Surficial sediments in relatively *Thalassia*-free areas on the flats and along channel margins are sticky and somewhat cohesive, presumably because of the presence of organic matter and/or microbial-scum mats. Near-surface sediments on both shoals are water saturated and non-cohesive, and sediment cohesiveness increases with depth as a result of compaction (Teal, 1998; Wilhite, 2000; Dimmick-Wells, 2002a). We have found that sediments are typically quite compacted by $\approx 3{\cdot}5$ m below the surface.

The shallowest water areas at Cangrejo are colonized by dense thickets of red mangrove (*Rhizophora mangle*) beneath which there is no exposed land ('mangrove cayes' of Vermeer, 1959). Enough carbonate sediment has accumulated locally within some mangrove thickets, however, to have created low-lying land with interior intertidal flats. Such cayes, referred to as 'mangrove-rimmed islands', are present on parts of Cayo Rombo, Cayo Luisito and the eastern half of Cayo Cangrejo (Figs 3 and 4A). These islands do not have peripheral beaches but, instead, they are bordered by dense tangles of *Rhizophora* that pass inwards to less vegetated intertidal flats with black (*Avicennia nitida*) and red mangroves. In contrast, there are only four cayes on Bulkhead (Fig. 5A). Mosquito and Savannah Cayes are also mangrove-rimmed islands with interior carbonate intertidal flats, and Savannah Caye has a narrow sandy beach on its NW side. Los Salones are two small mangrove cayes. Except for the mangrove-rimmed islands, the broad expanses of shallow subaqueous flats at Cangrejo and Bulkhead are not exposed periodically even during lowest low tide.

Tidal channels

The individual flats comprising the Cangrejo Shoals are separated by tidal channels, most of which are curvilinear and convex towards the SW, and nearly all of which bifurcate in a NW direction (Fig. 4A). Maximum channel width is 35–50 m, and channels are deepest (6–7 m) in the S part of the mud-mound and shallower (maximum depth 1·8 m) in the N; channel width generally decreases to the N. The depth of individual channels decreases longitudinally towards both their windward and leeward termini, which are barred by ebb- and slightly larger flood-tidal deltas, both of which are densely colonized by *Thalassia* (Figs 3B and 4B). The deepest areas of the channels are cut down to bedrock or nearly so, and sediments are typically absent to $< 0{\cdot}5$ m thick. Channel-floor sediments are mostly slightly sandy, gravelly mud that are locally mantled by sparse to dense *Thalassia*. Levees are not present along channel margins as they are, for example, in some Florida Bay mudbanks (Enos & Perkins, 1979). Whereas cross-sectional channel geometries are nearly symmetrical near tidal deltas, channel margins in the geographical centres of channels slope steeply into adjoining thalwegs on their SW sides (Fig. 4B), which locally contain metre-size blocks of cohesive mud. Sediments along the SW sides of channels are also fairly cohesive. In contrast, the opposite sides of channels are more gradual, and sediments are quite fluid and non-cohesive. Measured average fairweather tidal-flow velocity along the SW sides of deep channels is $0{\cdot}25$ m s^{-1} and $< 0{\cdot}1$ m s^{-1} in shallow channels and on the top of the shoals.

Channel trends and morphology suggest the combined influence of tides and NE trade winds on their development. Steep slopes on the SW sides of channels indicate scour of adjoining shoal margins (i.e. cutbanks) resulting from deflection of ebb- and flood-tidal currents in that direction by trade winds (Fig. 4B). Opposite sides of channels are probably accretionary, although this contention cannot be proved because core recovery is not possible in these fluid muds. Sediments here were probably transported from adjoining upwind shoals and/or via cross-channel flow from cutbanks. The dense thickets of *Thalassia* on the tidal deltas stabilize channel termini and, with decreased current effectiveness, the grass traps sediment and maintains shallow-water conditions and symmetrical cross-sectional profiles. Focusing of tidal current energy along the SW sides of channels, coupled with only episodic erosion in stabilized tidal delta areas, is thought to maintain longitudinal convexity of the channels.

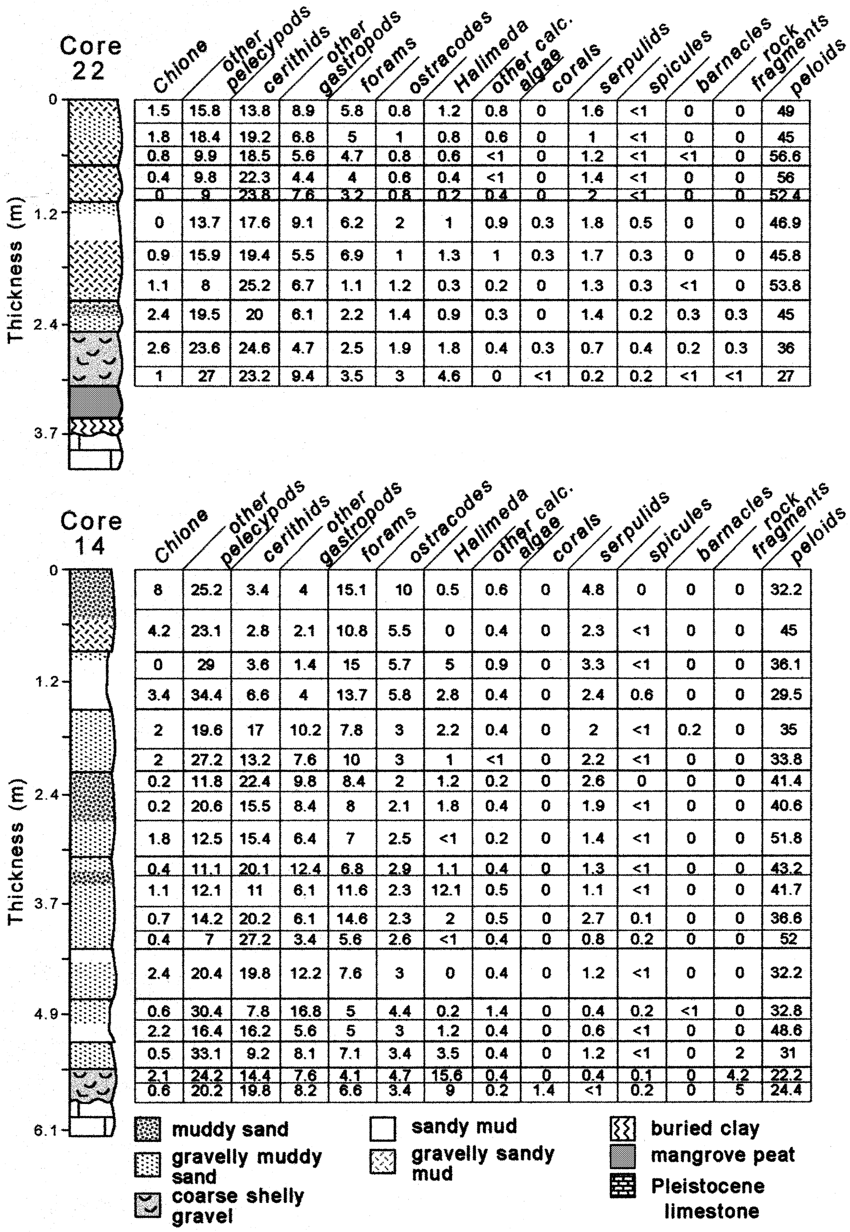
Tidal channels at Bulkhead are closely spaced and are present only on the western shoal, where they increase in number towards the SW (Fig. 5A). The channels are shorter than those at Cangrejo, and mostly trend a few degrees W of N and are only slightly curved. In general, channels N of Savannah Caye are fairly narrow (4–12 m wide) and shallow (< 1·5 m deep), whereas those to the S are wider (maximum 30–40 m) and as deep as 2·4 m. None of the channels cuts down to bedrock, and the relatively thick sediments within them are lithologically similar to those on adjoining flats. Cross-sectional channel geometries are nearly symmetrical, and there also are no marginal levees. Many of the channels have shallow but not well-formed tidal deltas at their mouths, the largest of which appear to be ebb-tidal deltas, and some channels bifurcate on their S sides. Channel bifurcation at both Bulkhead and Cangrejo probably occurs when tidal deltas grow large enough to force channel shifting. Tidal deltas in both areas could not be cored because of extreme sediment fluidity, but surface grab samples indicate that the sediments are mud and slightly sandy to slightly gravelly mud. Channel characteristics suggest that winds and tides exert less influence on shaping their morphology than at Cangrejo. Measured fairweather tidal-flow velocities in the Bulkhead channels are only about half as much as those at Cangrejo. Prominent N–S channel trends are probably maintained by northers and periodic strong tides. Why none of the channels cuts down to bedrock is unclear, but it is possibly related to less water volume and velocity draining through them during tidal cycles than at Cangrejo, where higher tidal-flow velocities are apparently more effective in flushing channels of sediment and maintaining their depths. According to Pusey (1975), occasional ebb flow of saline bottom currents may also contribute to sediment transport within the channels at Bulkhead.

CARBONATE SEDIMENTS AND MINERALOGY

Surficial and buried carbonate sediments at Cangrejo and Bulkhead include mud, slightly sandy and/or gravelly mud and, locally, gravelly, muddy sand (Fig. 2A). Sediments at Bulkhead are mud dominated and muddier than those at Cangrejo, but mud also dominates at Cangrejo because, in addition to muddy lithologies, the sands are very muddy (Fig. 2B). Buried sediments in both areas are medium to dark grey and emit a strong odour of H_2S when cored. Except for minor amounts of detrital quartz and fragments of Pleistocene limestone, all sediments are of skeletal origin. Peloids, most of which appear to be micritized skeletal fragments, and some faecal pellets are common in finer size fractions. Sediments in both areas contain abundant authigenic dolomite and some pyrite (Mazzullo *et al.*, 1995, 2002; Teal, 1998; Teal *et al.*, 2000; Wilhite, 2000; Wilhite & Mazzullo, 2000; Dimmick-Wells, 2002a,b). Surficial and buried sediments also contain minor amounts (1–5%) of low-Mg calcite (LMC) derived from skeletal grains (mainly ostracods) and fragments of reworked Pleistocene limestone. Notwithstanding dolomite and LMC, bulk-average amounts of particulate high-Mg calcite (HMC) and aragonite at Cangrejo are 65% and 35% respectively (Mazzullo *et al.*, 1995, 2002; Teal, 1998; Teal *et al.*, 2000). In contrast, particulate HMC and aragonite comprise 90% and 10%, respectively, of sediments at Bulkhead (Mazzullo & Bischoff, 1992; Wilhite, 2000; Dimmick-Wells, 2002a,b; Mazzullo *et al.*, 2002).

Biota and source of sediments

Skeletal particle types in coarser-than-mud size sediment fractions at Cangrejo are tabulated in Fig. 7. Fragments of coral, *Halimeda*, branching red algae (*Neogoniolithon strictum* and *Amphiroa* sp.) and *Homotrema rubrum* are present in only seaward (outer shelf)-side sediments, and there are slightly greater percentages of miliolid and soritid foraminifera, gastropods and ostracods in a few zones within leeward (inner shelf)-side sediments. Otherwise, there is little difference in the relative abundance of major particle types relative to windward or leeward locations. The shallow-burrowing pelecypod *Chione* and grazing gastropods, such as cerithids, batillarids and *Marginella*, were occasionally found alive here. *Chione* is found living among the roots of *Thalassia* below the sediment–water interface.



Core 22

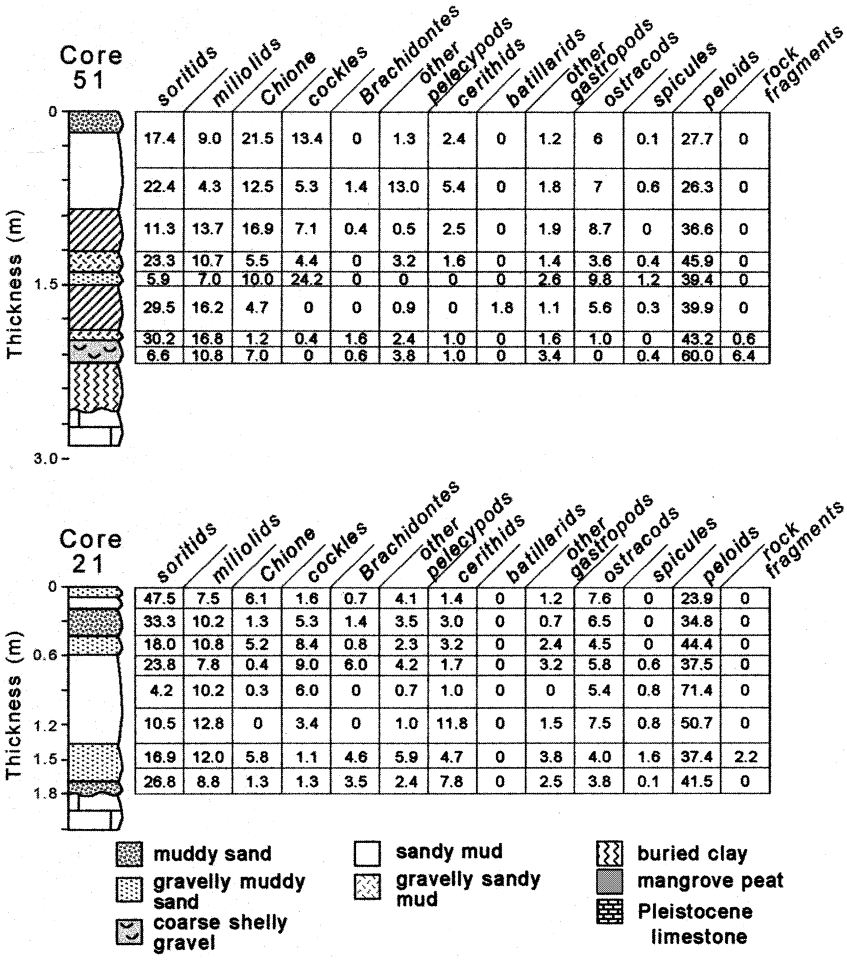
Chione	other pelecypods	cerithids	other gastropods	forams	ostracodes	Halimeda	other calc. algae	corals	serpulids	spicules	barnacles	rock fragments	peloids
1.5	15.8	13.8	8.9	5.8	0.8	1.2	0.8	0	1.6	<1	0	0	49
1.8	18.4	19.2	6.8	5	1	0.8	0.6	0	1	<1	0	0	45
0.8	9.9	18.5	5.6	4.7	0.8	0.6	<1	0	1.2	<1	<1	0	56.6
0.4	9.8	22.3	4.4	4	0.6	0.4	<1	0	1.4	<1	0	0	56
0	9	23.8	7.6	3.2	0.8	0.2	0.4	0	2	<1	0	0	52.4
0	13.7	17.6	9.1	6.2	2	1	0.9	0.3	1.8	0.5	0	0	46.9
0.9	15.9	19.4	5.5	6.9	1	1.3	1	0.3	1.7	0.3	0	0	45.8
1.1	8	25.2	6.7	1.1	1.2	0.3	0.2	0	1.3	0.3	<1	0	53.8
2.4	19.5	20	6.1	2.2	1.4	0.9	0.3	0	1.4	0.2	0.3	0.3	45
2.6	23.6	24.6	4.7	2.5	1.9	1.8	0.4	0.3	0.7	0.4	0.2	0.3	36
1	27	23.2	9.4	3.5	3	4.6	0	<1	0.2	0.2	<1	<1	27

Core 14

Chione	other pelecypods	cerithids	other gastropods	forams	ostracodes	Halimeda	other calc. algae	corals	serpulids	spicules	barnacles	rock fragments	peloids
8	25.2	3.4	4	15.1	10	0.5	0.6	0	4.8	0	0	0	32.2
4.2	23.1	2.8	2.1	10.8	5.5	0	0.4	0	2.3	<1	0	0	45
0	29	3.6	1.4	15	5.7	5	0.9	0	3.3	<1	0	0	36.1
3.4	34.4	6.6	4	13.7	5.8	2.8	0.4	0	2.4	0.6	0	0	29.5
2	19.6	17	10.2	7.8	3	2.2	0.4	0	2	<1	0.2	0	35
2	27.2	13.2	7.6	10	3	1	<1	0	2.2	<1	0	0	33.8
0.2	11.8	22.4	9.8	8.4	2	1.2	0.2	0	2.6	0	0	0	41.4
0.2	20.6	15.5	8.4	8	2.1	1.8	0.4	0	1.9	<1	0	0	40.6
1.8	12.5	15.4	6.4	7	2.5	<1	0.2	0	1.4	<1	0	0	51.8
0.4	11.1	20.1	12.4	6.8	2.9	1.1	0.4	0	1.3	<1	0	0	43.2
1.1	12.1	11	6.1	11.6	2.3	12.1	0.5	0	1.1	<1	0	0	41.7
0.7	14.2	20.2	6.1	14.6	2.3	2	0.5	0	2.7	0.1	0	0	36.6
0.4	7	27.2	3.4	5.6	2.6	<1	0.4	0	0.8	0.2	0	0	52
2.4	20.4	19.8	12.2	7.6	3	0	0.4	0	1.2	<1	0	0	32.2
0.6	30.4	7.8	16.8	5	4.4	0.2	1.4	0	0.4	0.2	<1	0	32.8
2.2	16.4	16.2	5.6	5	3	1.2	0.4	0	0.6	<1	0	0	48.6
0.5	33.1	9.2	8.1	7.1	3.4	3.5	0.4	0	1.2	<1	0	2	31
2.1	24.2	14.4	7.6	4.1	4.7	15.6	0.4	0	0.4	0.1	0	4.2	22.2
0.6	20.2	19.8	8.2	6.6	3.4	9	0.2	1.4	<1	0.2	0	5	24.4

Fig. 7. Representative cores showing relative percentage abundances of particle types in gravel to fine sand-size fractions of sediments from seaward (core 22) and landward (core 14) parts of the Cangrejo mud-mound. See Fig. 3A for circled locations of these cores. Tops of the cores are at the sediment–water interface. 'Forams' refers to both miliolids and soritids; 'other gastropods' refers to particles for which generic classification is not possible; 'other pelecypods' includes those discussed in the text; 'spicules' are mainly from sponges; 'rock fragments' are derived from the Pleistocene bedrock limestone.

These organisms and other pelecypods (e.g. tellins and *Anomalocardia*) and gastropods (e.g. *Bulla* and *Fasciolaria*), however, are the dominant biota of the inner shelf (Wilhite, 2000). Hence, aside from these living organisms, the bulk of at least the smaller molluscan particles in the Cangrejo sediments were derived as particles from the inner shelf, with only a minor contribution from *in situ* living sources (Teal, 1998). The red algae *Melobesia* and ?*Fosliella*, which encrust *Thalassia* blades, and sparse calcareous green algae were also occasionally found living on the flats along some tidal channels on the seaward side of the mud-mound, albeit in exceedingly small numbers. These organisms, as well as coral fragments, branching red algae, the foraminifer *Homotrema rubrum* and gastropods such as *Neritina* and *Oliva*, particles of all of which are found in the Cangrejo sediments, are diagnostic outer shelf biota. Hence, the bulk of these taxa were derived as particles from the outer shelf, similarly with only a minor contribution from *in situ* living sources (Teal, 1998). Other biota occasionally found alive here include spirorbid and serpulid worms, the non-calcifying alga *Laurencia*, black sponges, ostracods, the gastropod *Fasciolaria tulipa* and barnacles encrusting mangrove roots. These organisms and others found in the



Core 51

soritids	miliolids	Chione	cockles	Brachidontes	other pelecypods	cerithids	batillarids	other gastropods	ostracods	spicules	peloids	rock fragments
17.4	9.0	21.5	13.4	0	1.3	2.4	0	1.2	6	0.1	27.7	0
22.4	4.3	12.5	5.3	1.4	13.0	5.4	0	1.8	7	0.6	26.3	0
11.3	13.7	16.9	7.1	0.4	0.5	2.5	0	1.9	8.7	0	36.6	0
23.3	10.7	5.5	4.4	0	3.2	1.6	0	1.4	3.6	0.4	45.9	0
5.9	7.0	10.0	24.2	0	0	0	0	2.6	9.8	1.2	39.4	0
29.5	16.2	4.7	0	0	0.9	0	1.8	1.1	5.6	0.3	39.9	0
30.2	16.8	1.2	0.4	1.6	2.4	1.0	0	1.6	1.0	0	43.2	0.6
6.6	10.8	7.0	0	0.6	3.8	1.0	0	3.4	0	0.4	60.0	6.4

Core 21

soritids	miliolids	Chione	cockles	Brachidontes	other pelecypods	cerithids	batillarids	other gastropods	ostracods	spicules	peloids	rock fragments
47.5	7.5	6.1	1.6	0.7	4.1	1.4	0	1.2	7.6	0	23.9	0
33.3	10.2	1.3	5.3	1.4	3.5	3.0	0	0.7	6.5	0	34.8	0
18.0	10.8	5.2	8.4	0.8	2.3	3.2	0	2.4	4.5	0	44.4	0
23.8	7.8	0.4	9.0	6.0	4.2	1.7	0	3.2	5.8	0.6	37.5	0
4.2	10.2	0.3	6.0	0	0.7	1.0	0	0	5.4	0.8	71.4	0
10.5	12.8	0	3.4	0	1.0	11.8	0	1.5	7.5	0.8	50.7	0
16.9	12.0	5.8	1.1	4.6	5.9	4.7	0	3.8	4.0	1.6	37.4	2.2
26.8	8.8	1.3	1.3	3.5	2.4	7.8	0	2.5	3.8	0.1	41.5	0

Fig. 8. Representative cores showing relative percentage abundances of particle types in gravel to fine sand-size fractions of sediments from seaward (core 51) and landward (core 21) parts of the Bulkhead mud-mound. See Fig. 5A for circled locations of these cores. Tops of the cores are at the sediment–water interface. Designation of specific particles as in Fig. 7.

sediments (e.g. scaphopods, *Caecum*, crabs and miliolid and soritid foraminifera) live on both inner and outer shelves. Hence, their presence is not diagnostic of sediment derivation from a particular region on the northern shelf. Sediment sources at Cangrejo appear to be more-or-less equally divided between those derived from the outer and inner shelves (Teal, 1998).

Skeletal particle types comprising the fine sand to fine gravel size sediment fractions at Bulkhead are dominated by soritid and miliolid foraminifera (Fig. 8). There also are a few living biota here, mainly some gastropods (cerithids, batillarids, *Marginella* and *Melongena*), pelecypods (*Chione cancellata*, *Anomalocardia auberiana* and some tellins), *Batophora*, worms, spirorbids and serpulids, and miliolid and soritid foraminifera encrusting *Thalassia* blades and *Laurencia*. Similar biota are found alive and in the sediments elsewhere on the inner shelf. Typical outer shelf biota are not present at Bulkhead as either particles or taxa found alive (Dimmick-Wells, 2002a). Hence, the bulk of the sediments here are also of transported origin and were derived solely from the inner shelf. There is no significant difference in the relative abundance of biotic particle types vs. location (Fig. 8). The dominance of transported sediments at Cangrejo and Bulkhead indicates that they are mainly of physically deposited, biodetrital origin.

INFERRED SEDIMENTARY FACIES

Pre- and Early(?) Holocene

The Pleistocene limestones exposed in northern offshore Belize are between 128 280 ± 1330 and 135 000 ± 900 years old (Gischler *et al.*, 2000; Weed & Mazzullo, 2002 respectively). Buried clays locally overlie the limestone at Cangrejo and Bulkhead, and are thicker and more widespread in the latter area (Figs 6C, 9 and 10). The clay is organic-rich, stiff and dense, with relatively little water content, and typically breaks along conchoidal surfaces. Colour is dark bluish-grey with some yellow-brown mottles. Corroded, pebble-size fragments of Pleistocene limestone, silt-size grains of detrital quartz and brownish, incipient ferroan glaebules are present in most samples. XRD analyses indicate that the clay is mostly amorphous material with minor quartz and authigenic pyrite. The clay is interpreted as a buried grass-meadow soil and is similar mineralogically to soils on San Salvador Island, Bahamas. Similar buried soils are locally present elsewhere in Belize (Ebanks, 1975; High, 1975; Wilhite & Mazzullo, 2000), and Pusey (1975) previously noted the soil at Bulkhead.

Unconsolidated Holocene sediments

Pre-mound deposits

Rhizophora mangrove peat and/or shelly gravel overlie Pleistocene limestone or buried soil at a number of localities at both mounds (Figs 9 and 10). Whereas thin (maximum 0·4 m) layers of peat were found in only three cores (7, 22 and 25) at Cangrejo, thick (up to 2·4 m) and laterally

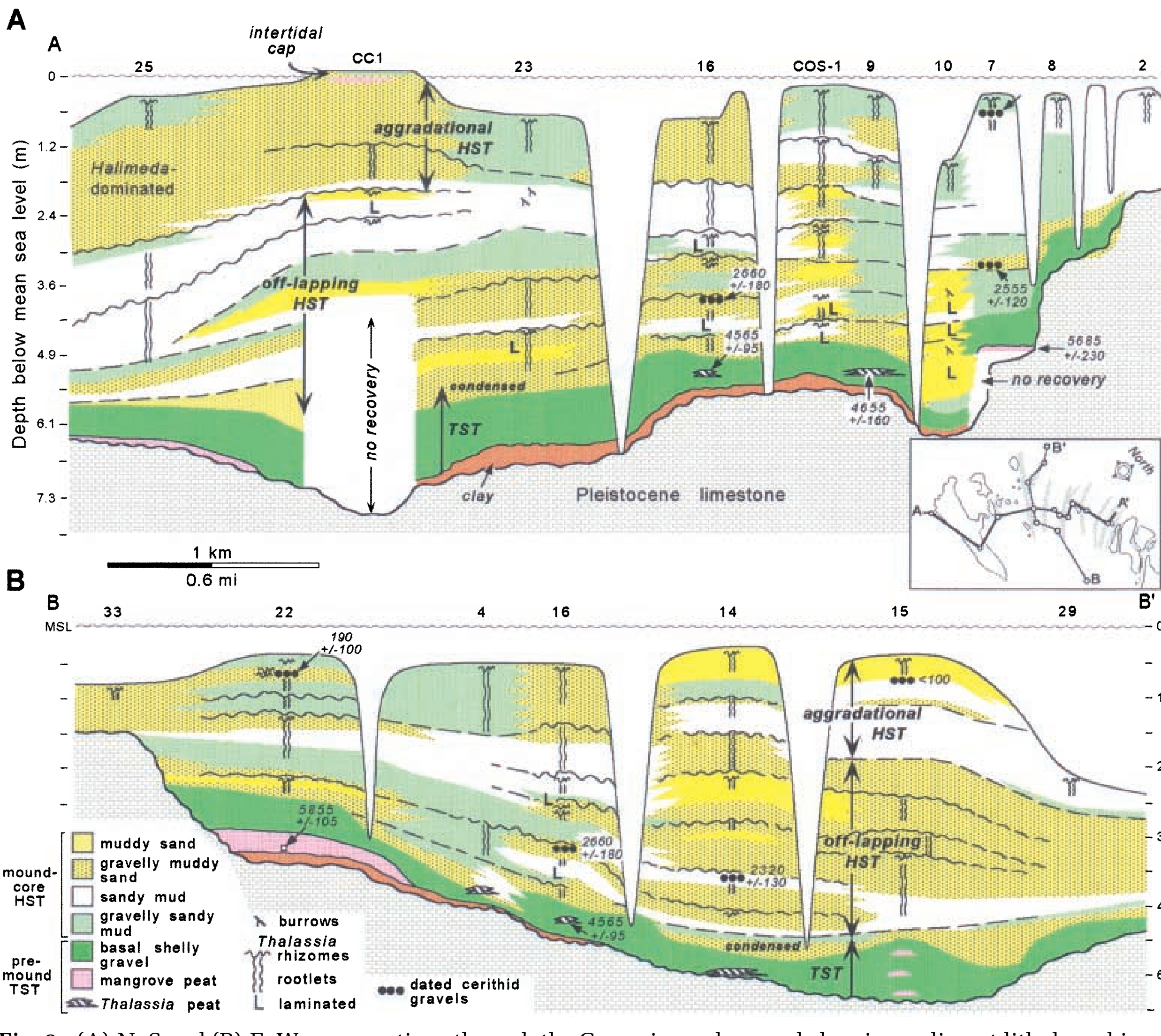


Fig. 9. (A) N–S and (B) E–W cross-sections through the Cangrejo mud-mound showing sediment lithology, biogenic and sedimentary structures, dated peats and cerithid-bearing horizons, and inferred sedimentation units and systems tracts. Muds include both sandy mud and gravelly sandy mud. Basal coarse shelly gravels are mollusc dominated. Contacts between sedimentation units with *Thalassia* that are erosional are represented by wavy lines, and contacts between units with and without *Thalassia* that are either erosional or conformable are represented by dashed lines. Note aggradational and prograding offlapping geometries of HST sedimentation units, and downlapping of lower HST units onto inferred condensed section.

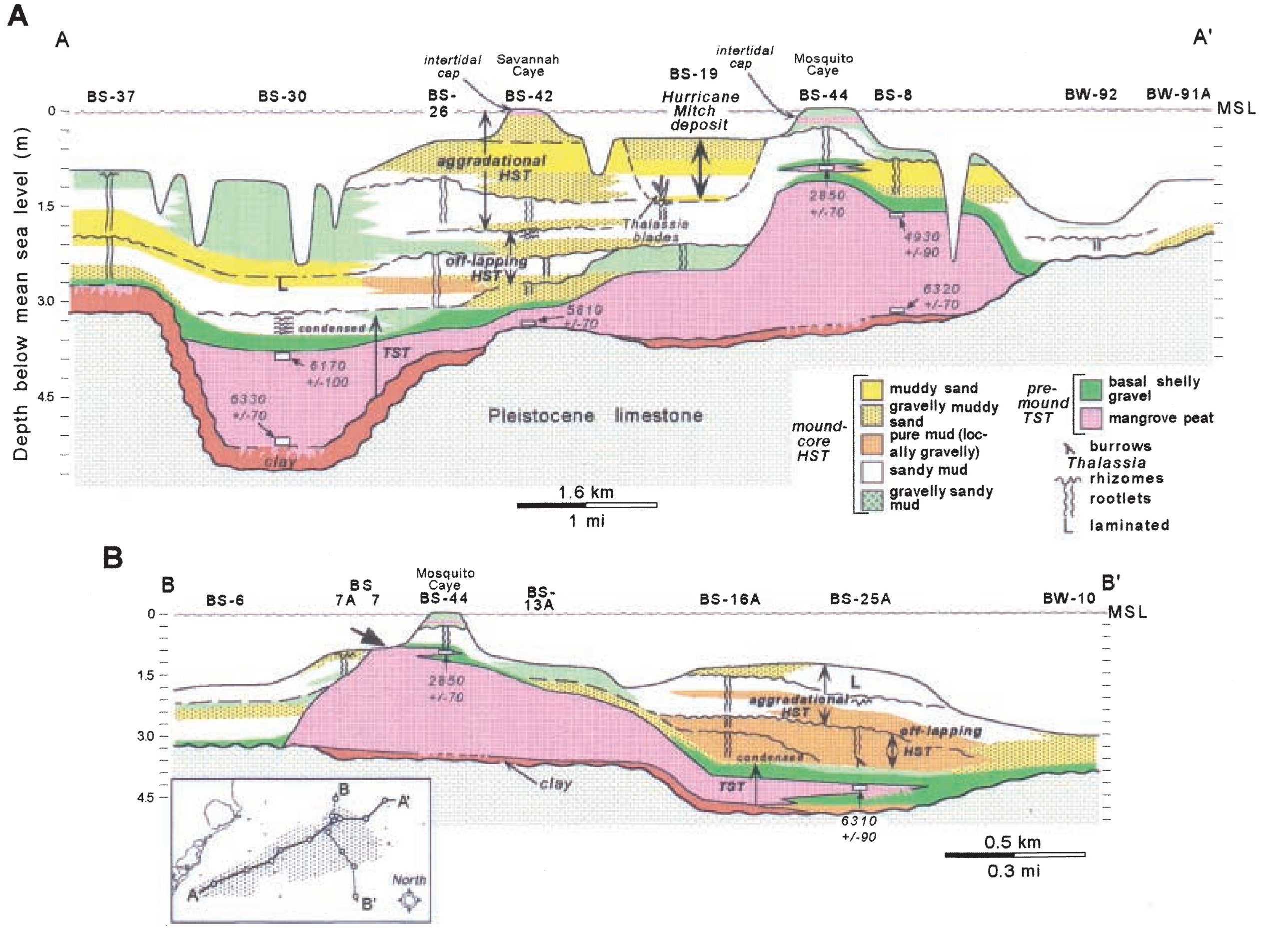


Fig. 10. (A and D) NE–SW cross-sections and (B and C) N–S cross-sections through Bulkhead mud-mound showing sediment lithology, biogenic and sedimentary structures, dated peats and inferred sedimentation units and systems tracts; contacts between sedimentation units as in Fig. 9. Muds include locally gravelly mud, sandy mud and gravelly sandy mud. Basal shelly gravels are mollusc dominated. The bold arrow in (B) at core localities BS-7 and BS-7A points to an area where mangrove peat is being exhumed and eroded. Note aggradational and prograding offlapping geometries of HST sedimentation units, and downlapping of lower HST units onto inferred condensed section.

continuous sections of buried peat are present at Bulkhead. The peat is interpreted as former mangrove cayes or swamps. It locally fills vertical to subvertical root holes and/or burrows in the upper few centimetres of buried soil, and that peat sometimes contains some juvenile pelecypods and gastropods (Fig. 10). Contacts with overlying carbonates are generally sharp.

Variously overlying peat, soil or limestone is a 0·3 to 0·9 m thick section of coarse-grained, locally muddy and/or sandy shell gravel (Figs 9 and 10) with a molluscan-dominated biota and accessory Pleistocene limestone fragments (Figs 7 and 8). Contacts with overlying deposits are sharp to locally gradational, sedimentary and biogenic structures are rare, and the sediments are generally devoid of *Thalassia* rootlets or rhizomes. These characteristics suggest shallow-water environments of shifting sediments on which *Thalassia* could not readily take root. Similar deposits are present today along shallow rocky shorelines in northern Belize, and they are also common as the basal Holocene carbonate sediment present in many cores taken in the area. The gravels are similar texturally and biotically to those underlying Florida Bay mudbanks (e.g. Enos & Perkins, 1979; Wanless & Tagett, 1989; Bosence, 1995), and they and the underlying mangrove peat are similarly interpreted as basal transgressive marine deposits that predate mud-mound development.

Mound-core sediments

Overlying carbonate deposits comprise the bulk of the Holocene sediments at Cangrejo and Bulkhead, although in the latter area, thick peat

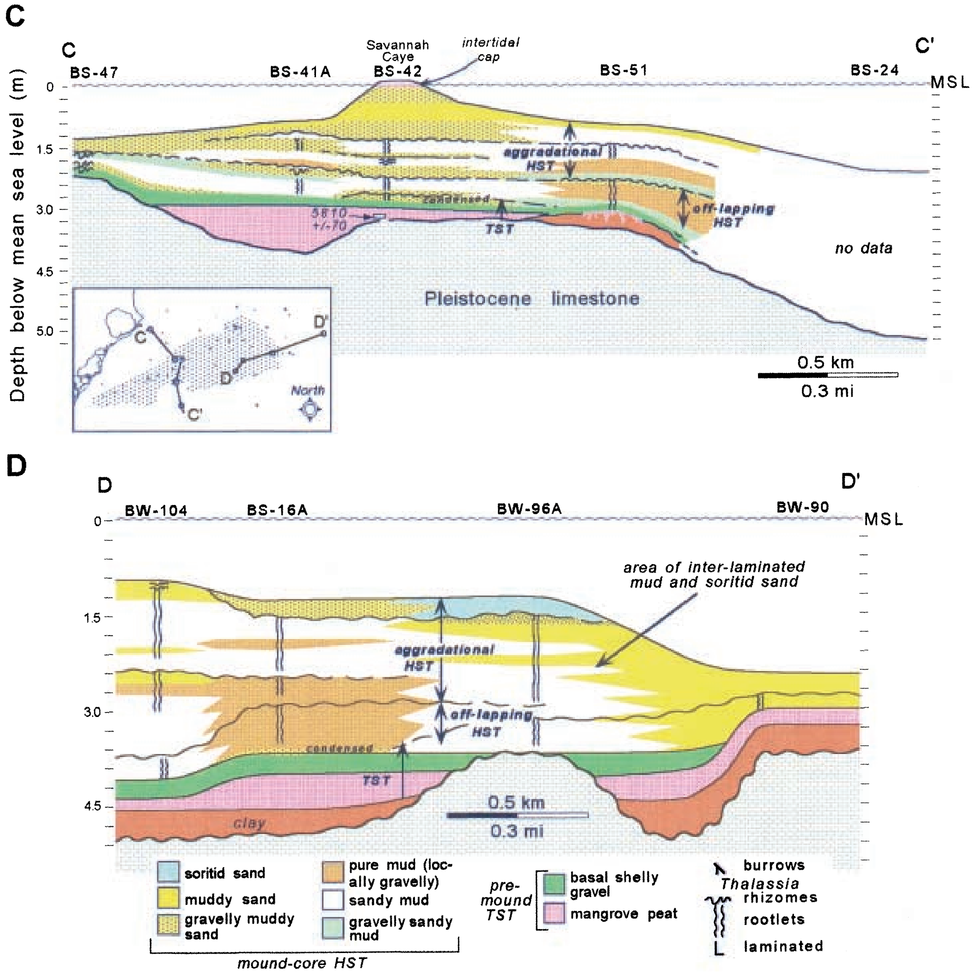


Fig. 10. Continued.

is present locally (Figs 9 and 10). These sediments occupy the same stratigraphic position as the bank (mound)-core facies in Florida Bay mudbanks (Wanless & Tagett, 1989; Wanless *et al.*, 1995). They include gravelly to non-gravelly, very muddy sand, gravelly sandy mud and, at Bulkhead, also locally gravelly and pure mud. Bioturbation by vertical *Thalassia* rootlets and horizontal rhizomes is common, and centimetre-diameter, subvertical burrows are present locally. Fragments of Pleistocene limestone are rare, and textural laminations are present in some of the muds, sandy muds and muddy sands. Conspicuous layers of interlaminated mud and foraminiferal (soritid) sand are present locally along the NE side of Bulkhead (Fig. 10D), where sediments are being deposited in a transition zone between the mud-mound proper and SW-prograding soritid sand shoals N of the ship channel shown in Fig. 5A (Wilhite, 2000).

Conspicuous stacked sediment layers comprise bank (mound)-core deposits in Florida Bay mudbanks and are referred to as sequences by Wanless & Tagett (1989), Tedesco & Wanless (1995) and Wanless *et al.* (1995). Similar deposits, 0·2–1·5 m thick, are recognized at Cangrejo and Bulkhead but, to avoid confusion with current stratigraphic terminology, they are referred to instead as sedimentation units. Four types are recognized, three of which are based on the extent of preserved *Thalassia* rhizomes or rootlets and the fourth by comparative textural and biotic compositional criteria (Fig. 11). In all cases, upper bounding surfaces are considered to be former subaqueous sediment–water interfaces. Some sedimentation units can be correlated across fairly broad areas except where their ready recognition is obscured by intense bioturbation (Figs 9 and 10). The first three types, the terminology of which follows Wanless & Tagett (1989), are those in which there is evidence of *Thalassia* colonization of former

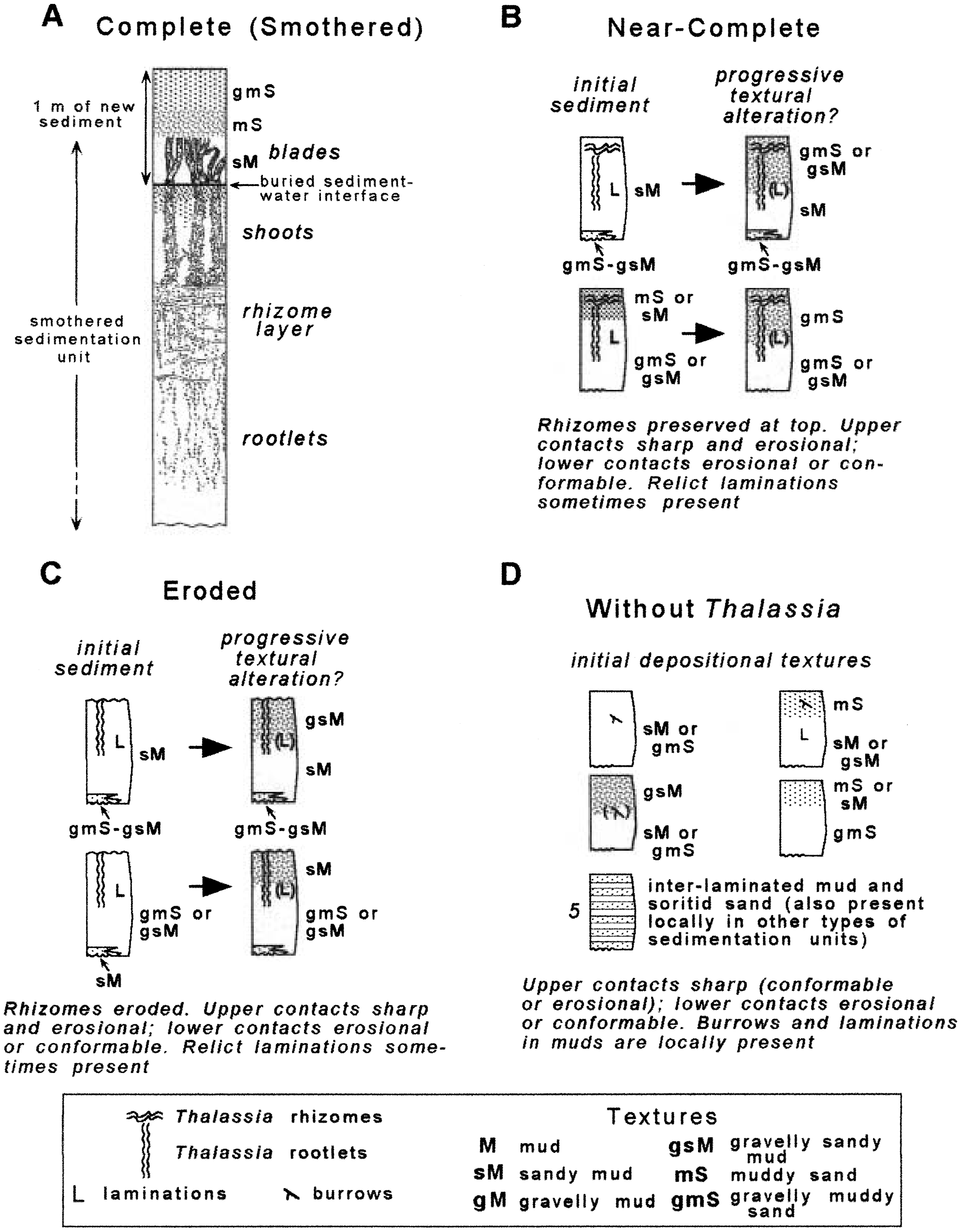


Fig. 11. Sedimentation units and their textural alteration in the mound-core deposits at the Cangrejo and Bulkhead Shoals. Those units with various preserved elements of *Thalassia* include the following types: (A) complete or 'smothered' – found only at core locality BS-19 on the Bulkhead Shoals. New sediment deposited here was 1 m thick. This diagram also illustrates all morphological elements of *Thalassia* discussed in the text (modified from Wanless & Tagett, 1989). Average depth from the sediment–water interface to top of rhizome layer taken at 10 cm; (B) near-complete; and (C) eroded units. Sedimentation units without *Thalassia* are illustrated in (D). Layers of interlaminated mud and soritid sand are locally present in some near-complete and eroded sedimentation units as well.

sediment–water interfaces. Complete or smothered sedimentation units (Fig. 11A) are exceedingly rare, and only one example was recovered at a locality at Bulkhead (BS-19: Fig. 10A) recorded in 1998 1 month after Hurricane Mitch. Water depth was found to be 1 m shallower than it was during the initial survey of the area 6 months earlier. The core recovered 1 m of newly deposited sediment that had buried vertical *Thalassia* blades, below which was a complete profile of

Thalassia shoots, rhizomes and rootlets. The contact between the smothered and underlying sedimentation unit is conformable. These newly deposited sediments were undoubtedly eroded from a nearby area during the storm.

Near-complete and eroded sedimentation units (Fig. 11B and C) are those in which erosion has removed progressively more sediment and *Thalassia* morphological elements below former sediment–water interfaces before deposition of overlying units. Near-complete units are those in which rhizomes are present at or near the top, usually associated with local concentrations of the burrowing pelecypod *Chione*, and are underlain by sediments penetrated by vertical rootlets. Insofar as average depth below the sediment–water interface to the top of rhizome layers in *Thalassia* beds is ≈ 10 cm, that is the average amount of erosion at the tops of such units. Eroded sedimentation units are those in which only *Thalassia* rootlets are present at the top, indicating > 10 cm of erosion. Erosional and near-complete sedimentation units are the most common types at Cangrejo and Bulkhead, and are variously present on both windward and leeward sides of the mud-mounds (Figs 9 and 10).

Inferred sedimentation units that do not contain *Thalassia* elements are more difficult to recognize (Fig. 11D). In sections containing invertebrate burrows, overlying *Thalassia* rootlet and rhizome-bearing sediments may have been present but subsequently eroded insofar as burrows are typically common at or below rhizome layers (Wanless & Tagett, 1989). Significant erosion of the tops of such units would therefore be indicated. Conversely, their tops, whether seemingly conformable or obviously erosional, may actually represent sediment–water interfaces that were devoid of *Thalassia*, which are common at Cangrejo and much more so at Bulkhead in either shallow or relatively deeper water. This interpretation is favoured because experience shows that at least some *Thalassia* rootlets are nearly always preserved in sediments that had grassy bottoms. Superposed sedimentation units without *Thalassia* are tentatively recognized by abrupt increases in the amount of *Chione* towards the tops of such sections (Figs 7 and 8) and concurrent abrupt changes in sediment texture above such horizons (Figs 9 and 10).

Contacts between superposed sediment textures within sedimentation units are mostly gradational, although they are sharp but seemingly conformable in some cases. Post-depositional textural alteration of sediments, particularly those that once had grassy bottoms, is common in Florida Bay mudbanks and was described in detail by Wanless & Tagett (1989), Tedesco & Wanless (1991, 1995) and Wanless *et al.* (1995). In the Belize mounds, such alteration is effected by: (1) burrowing pelecypods, worms, *Thalassia* and, locally at Cangrejo, callianassid shrimp. The pelecypod *Chione*, which besides *Thalassia* is the most common sediment disrupter at Cangrejo and Bulkhead, for example, homogenizes sediments and also contributes a gravel-size shell fraction towards the tops of near-complete and eroded sedimentation units. Storm reworking of surficial coarse sediment fractions into burrows is also evident in some of these deposits; and (2) fine sediment-size fractions can be contributed to original deposits along former sediment–water interfaces by epibionts on *Thalassia*. Altered sedimentation units with *Thalassia* at Cangrejo and Bulkhead variously fine or coarsen upward (Fig. 11B and C), thus making it difficult to determine original depositional textures, especially in the upper parts of such beds.

Sedimentation units without *Thalassia* likewise fine or coarsen upwards and, in some cases, are texturally homogeneous (Fig. 11D). The absence of *Thalassia* and presumably of significant post-depositional alteration suggest that such textures are unmodified depositional attributes. Fining- and coarsening-upward units probably represent depositional events of decreasing and increasing energy respectively. Conversely, coarsening-upward units may be those in which fines have been winnowed after deposition. The presence in many such units of layers of laminated mud and, at Bulkhead, of layers of interlaminated mud and soritid sand are compelling evidence of their physical deposition. Vestiges of similar layers are also locally present in texturally altered, near-complete and eroded sedimentation units (Fig. 11B and C). Eroded tops of units, below which *Thalassia* rhizomes or rootlets are preserved, and the local presence of burrow-escape structures that penetrate into overlying sections (e.g. Wanless & Tagett, 1989) suggest rapid deposition of sedimentation units. Regardless of the specific type of unit in which they occur, the layers of laminated mud may variously represent infilled surficial blowouts, small subaqueous mud dunes (e.g. Enos & Perkins, 1979; Wanless & Tagett, 1989) or suspension deposits. Layers of interlaminated mud and soritid sand are probably micrograded traction/suspension deposits.

Island-cap facies

Present on low-lying intertidal flats at Cangrejo and Bulkhead (Figs 3A, 5A, 9A and 10), such deposits comprise a small portion of total sediment thickness. At these locations, 0·2–0·4 m of desiccated microbial mats and/or gravelly sandy mud, commonly with abundant included tannin-stained mangrove-leaf litter, overlie either mound-core sediments or thin layers of modern to near-modern mangrove peat. Biota are dominated by the salt-marsh pelecypod *Pseudocyrena* sp., batillarids, cerithids and some *Melongena*. A small, narrow beach on the NW shore of Savannah Caye at Bulkhead (Fig. 5A), which adjoins its interior intertidal flat, is composed of a few centimetres of coarse soritid sand.

DEPOSITIONAL DEVELOPMENT OF THE MUD-MOUNDS

Based on the sea-level curve for northern offshore Belize (solid line in Fig. 12), the onset of northward marine transgression was ≈6500–6600 years BP, and only localities where the Pleistocene limestone is deeper than ≈7·5 m below present mean sea level (BPSL) were apparently inundated. At Cangrejo, that would include a small area around Cayo Cangrejo and the bedrock depression to the W (Fig. 1), and no portion of Bulkhead was flooded at this time. Sea level continued to rise rapidly until ≈4500 years BP, whereupon the rate of rise decelerated. Areas on and around present-day Cangrejo and Bulkhead Shoals should have been progressively inundated between 6300 years BP and 5500 years BP, and nearly all the northern shelf was mostly flooded by ≈4000 years BP (Fig. 13).

Early transgressive deposition of premound facies

Mangrove cayes/swamps

Only a few thin layers of basal mangrove peat are present at Cangrejo, the deepest of which is at 6·4 m BPSL in core 25 (Fig. 9). Enough sample for an age date could not be recovered, but its depth suggests a maximum age of perhaps 6400–6500 years (Fig. 12), which would imply devel-

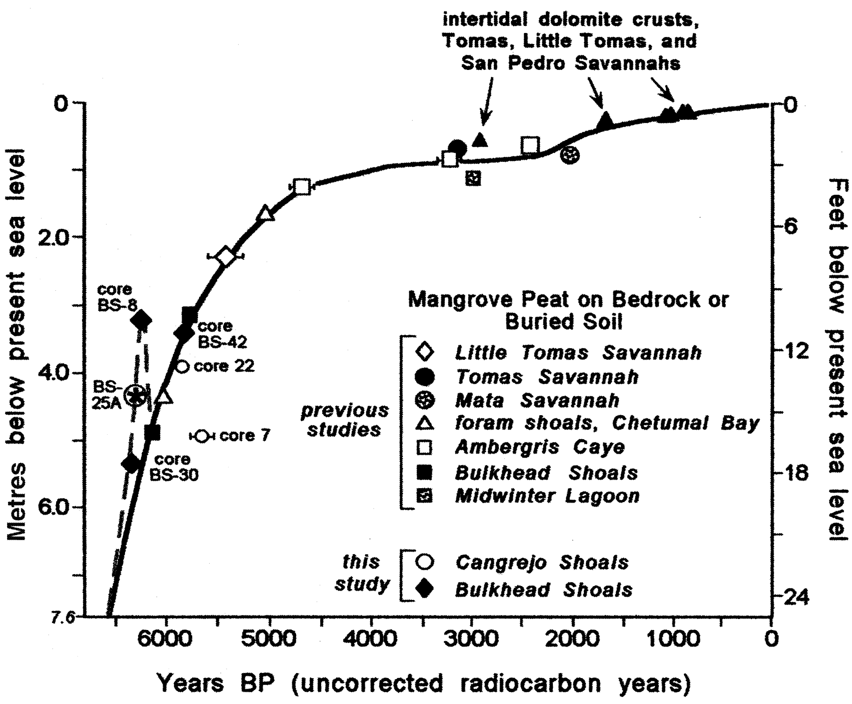


Fig. 12. Sea-level curve for northern offshore Belize (modified from Teal *et al.*, 2000). That portion of the curve older than ≈5500 years BP does not respect the new data points from the Cangrejo and Bulkhead Shoals. The dashed line is the alternative sea-level history discussed in the text. The dated peat in Bulkhead core BS-25A is shown for reference only, and is not part of this sea-level curve because it does not sit directly on bedrock or buried clay soil. Mangrove peats in specific cores discussed in the text are labelled. Sources of previously published peat dates are: Tomas Savannah – Mazzullo *et al.* (1987); foram shoals – Wilhite (2000) and Wilhite & Mazzullo (2000); Ambergris Caye – Ebanks (1967); Bulkhead Shoals – Pusey (1975). Source for dolomite crust dates is Mazzullo *et al.* (1987). Width of symbols encloses ±-values of ^{14}C dates unless otherwise indicated by horizontal error bars.

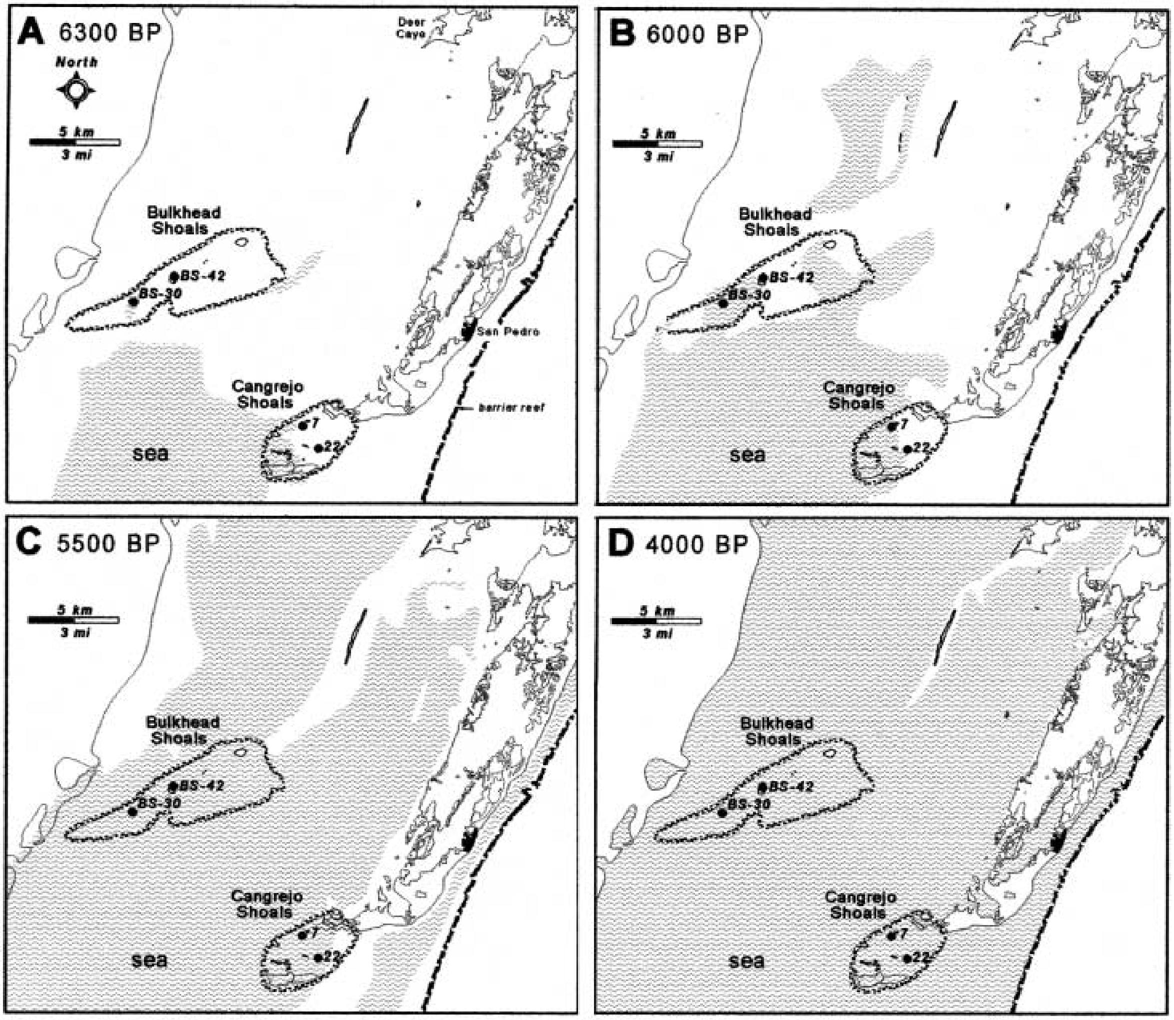


Fig. 13. Progressive Holocene transgression in study area, with extent of marine inundation shown for (A) 6300 years BP – sea level at ≈ 5·5 m below present stand (BPS); (B) 6000 years BP – sea level at ≈ 4 m BPS; (C) 5500 years BP – sea level at ≈ 2·5 m below BPS; and (D) 4000 years BP – sea level at ≈ 1 m BPS. Flooding history reconstructed based on data in Fig. 1 and solid sea-level curve in Fig. 12. Locations of specific cores with dated basal mangrove peats that are discussed in the text are shown. Progressive flooding of adjoining Caribbean Sea not indicated.

opment of some coastal mangrove cayes/swamps in the southernmost part of the mud-mound soon after early flooding. The ages and depths of the basal peats in core 22 (5855 ± 105 years BP at 3·9 m BPSL) at Cangrejo and in cores BS-30 (6330 ± 70 years BP at 5·3 m BPSL) and BS-42 (5810 ± 70 years BP at 3·4 m BPSL) at Bulkhead provide more definitive evidence of the timing of initial mangrove colonization. These radiocarbon ages are consistent with a sea-level history suggested by Fig. 12 (solid-line curve), and the oldest peat at Bulkhead also suggests local development of mangrove cayes/swamps here coincident with early flooding (Fig. 13A). Whereas the scattered mangrove cayes/swamps present at Cangrejo were quickly drowned (Fig. 9), their rapid expansion at Bulkhead instead resulted in swamp environments that persisted for a longer period of time (Fig. 10A and B). But the extent of the swamps diminished progressively as sea level rose, and deposition of the premound coarse shelly gravels ensued. Closely spaced cores indicate a step-like character of near-horizontal contacts of peat and overlying shelly gravels at core localities BS-8 and BS-19 (Fig. 10A) and between localities BS-16A and BS-25A (Fig. 10B) at Bulkhead, which may reflect erosional back-stepping of peat during sea-level rise. Final drowning of mangrove cayes/swamps occurred ≈ 2850 ±70 years BP (at core locality BS-44) in the NE part of Bulkhead (Fig. 10B).

There are, however, some seemingly anomalous age dates relative to the depths of some of the peats. The peat in core 7 at Cangrejo, for instance, is at 4·9 m BPSL, and its determined age (5685 ± 230 years BP) is younger than an extrapolated age of ≈ 6100–6200 years BP based on the solid-line curve in Fig. 12. Assuming its determined age is correct, this disparity may imply that mangrove colonization here began as much as 500 years after initial marine flooding. As at the present day, mangroves do not necessarily colonize all coastal areas and, when they do, colonization is not always coincident with initial flooding. In contrast, the determined age of the peat at 3·2 m BPSL in core BS-8 at Bulkhead is 6320 ± 70 years BP, which is older than it should be at that depth (≈ 5700–5800 years BP). Likewise, the determined age of the peat at 4·3 m BPSL in core BS-25A (6310 ± 90 years BP) is also older than it should be, but only by ≈ 300 years (note: this data point was not included in construction of the sea-level curve because it does not immediately overlie bedrock or clay soil. It is shown in this figure only for reference.) If these determined peat ages are accurate, then they would suggest oscillating rather than smooth sea-level rise from ≈ 6350 years BP to 6250 years BP (dashed line in Fig. 12). Although centennial-scale sea-level fluctuations during the Pleistocene and early Holocene are postulated (e.g. Locker *et al.*, 1996), such a scenario is unlikely at Bulkhead because it would have involved a sea-level oscillation of ≈ 1·7 m in 100 years or less that is evident neither at Cangrejo nor anywhere else in northern Belize. Similar high-frequency oscillation is likewise not reported elsewhere in Belize or the western Atlantic at this time (see Ferro *et al.*, 1999). Tectonic readjustment after peat deposition does not explain the seeming age disparity because the area has been stable since the Pleistocene (Lara, 1993). Until proven otherwise, a smooth rather than oscillating sea-level rise during this period of time is favoured, and the dates of the basal peats in cores BS-8 and BS-25A are considered to be inaccurate.

Shelly gravels

Thin, isolated lenses of *Thalassia* peat recovered in a few cores at Cangrejo are encased within premound shelly gravels (Fig. 9). Shallow-buried *Thalassia*-blade mats, precursors of such peat, are sometimes encountered in Belize and have also been described from Holocene deposits elsewhere (e.g. Enos & Perkins, 1979). Radiocarbon ages of two such peats are 4655 ± 160 years BP and 4565 ± 95 years BP, and are assumed to be the approximate age of the enclosing shelly gravels, at least at those horizons at those core localities (Fig. 9). Because these peats do not directly overlie bedrock or buried soil, their ages were also not included in Fig. 12. At depths of 5·2 m BPSL, however, these peats and associated gravels could be considerably older than the determined ages, perhaps as old as 6200 years BP (Fig. 12). Reworking of older sediment during sea-level rise may account for the disparity in their age relative to their depth. Unfortunately, samples from the shelly gravel here were not available for additional age dates. Samples with which to radiocarbon date the gravel at Bulkhead also are not available, although ages of the tops of underlying mangrove peat in some cores (Fig. 10A and B) suggest that gravel deposition began sometime after 6170 ± 100 years BP (core BS-30), which might imply that the onset of such deposition was approximately coeval at Cangrejo and Bulkhead. In the latter area, however, transgressive deposition of the gravel persisted, at least at some localities, until about 2850 ± 70 years BP (core BS-44) as sea level rose and mangrove swamps were drowned. Hence, the top of the shelly gravel section is diachronous at Bulkhead. At both mud-mounds, the generally onlapping mode of deposition of the shelly gravels and basal mangrove peats (Figs 9 and 10) tracked the high rate of sea-level rise from ≈ 6600 years BP to 4500–4600 years BP (Fig. 12), and several hundred years of lag time are indicated between initial flooding and the onset of deposition of the gravels.

Deposition of mound-cores

Ages of cerithids recovered from several horizons in the mound-core section at Cangrejo range from 2660 ± 180 years BP near the base of the section to < 100 years BP near the top (Fig. 9). It is assumed that these shells represent cerithids living on the mound because the fairly large shells, which are unabraded, could not have been transported easily up onto the shoals if they were derived from surrounding topographically lower areas. In support of this contention is the observation that sample ages from approximately similar depths in three separate cores (7, 14 and 16: Fig. 9) do not vary significantly. At core 16, sediments from the 2660 years BP horizon, which is at the top of a sedimentation unit, to the contact with the basal mound-core sedimentation unit directly overlying premound shelly gravels are thin (≈ 0·8 m), and presumably correlative sections at other core localities are likewise thin (Fig. 9). It appears that relatively little sediment was deposited between the premound gravel at ≈ 4500–4600 years BP and the base of the 2660 years BP horizon sedimentation unit at Cangrejo despite the fact that the area had long since been flooded (Fig. 13C). Although the basal sedimentation unit could be thin because of erosion, it is suggested that it and its correlatives represent a sediment-starved condensed section (Fig. 9) that probably developed at ≈ 4500 years BP or shortly thereafter. In support of this contention is that this time corresponds to the point of inflection on the sea-level curve (Fig. 12). Therefore, based on aforementioned architectural and geometric relationships and radiocarbon ages, the premound basal peats and shelly gravels at Cangrejo are interpreted as deepening-upward transgressive systems tract (TST) deposits. The overlying much thicker mound-core sediments are interpreted as shallowing-upward highstand systems tract (HST) deposits, and these tracts are separated by a condensed section. A similar interpretation is suggested at Bulkhead by virtue of a similar sea-level history. In fact, downlapping of assumed HST deposits onto a condensed section is inferred here (Fig. 10B and D) as well as at Cangrejo (Fig. 9).

Sedimentary architecture and genesis of mound-cores

Offlapping of sedimentation units in the lower part of the HST mound-core, to both the S and W into the deep bedrock depression beneath the shoals, is inferred at Cangrejo (Fig. 9). In turn, overlying HST sedimentation units are mostly aggradational, and their upper bounding surfaces essentially reflect current topography on the shoals. A similar architecture is present at Bulkhead (Fig. 10). The vertical stacking of such geometries, in conjunction with overall shallowing-upward deposition, are consistent with early catch-up sedimentation of the lower HST, which apparently fostered rapid progradational (offlapping) expansion and vertical accretion of the mound-cores. This depositional phase was followed by keep-up sedimentation of the upper HST deposits, which mainly involved continued vertical aggradation (Teal, 1998). Both depositional phases occurred during a period of slow sea-level rise (Fig. 12).

The overall thicker section of Holocene deposits (including peat) at Cangrejo relative to that at Bulkhead (Figs 9 and 10) reflects greater depth to bedrock and, therefore, greater marine accommodation space in the former area. The influx of thick mound-core biodetrital sediments into the Cangrejo Shoals and, by inference, into Bulkhead Shoals since ≈ 4500 years BP is possibly attributed to increased sediment production and thus availability for export to the mud-mounds during sea-level highstand. On the inner shelf, sediment production rate is tied directly to rate of production of soritid and miliolid foraminifera because they are the dominant biota and sediment producers here. Yet, increase over time in the amount of at least soritid foraminifera supplied to Bulkhead is evident in only one core (core 21, Fig. 8), and systematic changes in types of biotic particles supplied to the Cangrejo mound that might be indicative of temporal variations in sediment production rate along the outer shelf are likewise not evident (Fig. 7). Conversely, deposition of thick HST deposits at Cangrejo and Bulkhead can be attributed to changing sediment dynamics after ≈ 4500 years BP instead of sediment production rates, although this contention is even more difficult to prove. Nonetheless, relatively low sediment accumulation rates followed by high accumulation rates are common in TSTs and HSTs, respectively (e.g. Tucker, 1985), although the specific causes of such changes are usually as cryptic as they are in northern Belize.

Significance of storms and depositional models

Monitoring of sediment dynamics in northern Belize for over two decades has shown that little sediment is normally entrained by fairweather tides and currents. Rather, major sediment mobilization and deposition occurs during storms, which are also the most significant agent in the evolution of Florida Bay mudbanks (e.g. Wanless & Tagett, 1989; Bosence, 1995; Tedesco & Wanless, 1995; Wanless *et al.*, 1995) and other shallow-water carbonate deposits (Aigner, 1985; Tucker, 1985). The significance of storms in sediment transport and redeposition in northern Belize is particularly evident in eastern Chetumal Bay. Despite prevailing NE trade winds, for example, most soritid sand shoals here are oriented nearly N–S, which is parallel to winds during northers (Fig. 14). The NE–SW trends of some of the shoals here likely reflect reshaping by exceptionally strong trade winds.

According to Vermeer (1959), Cangrejo Shoals formed as a spit off of the S tip of Ambergris Caye, and sediments were transported to the shoals

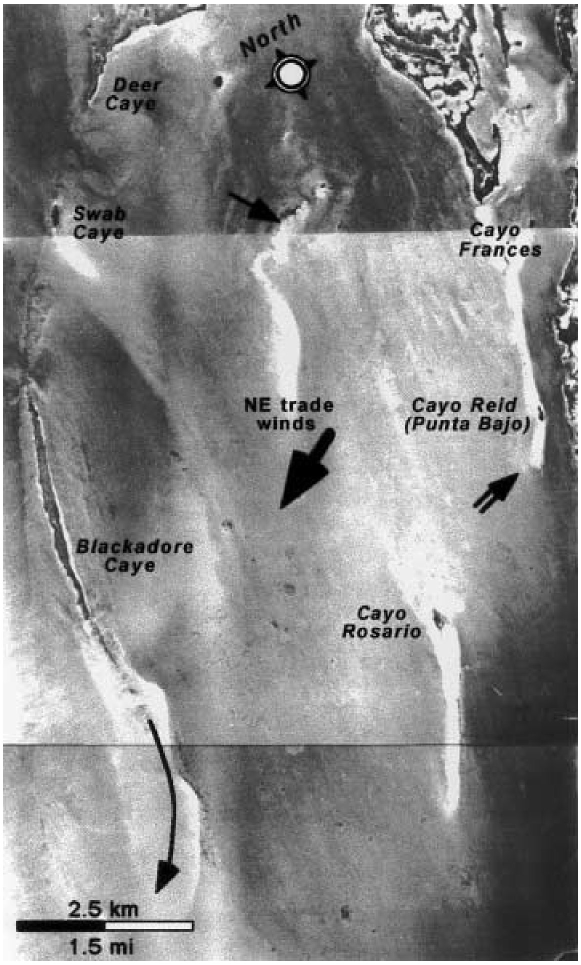


Fig. 14. Composite, high-altitude aerial photograph of a portion of eastern Chetumal Bay showing nearly N–S trends of soritid sand shoals (white areas) off Swab Caye, Cayo Frances, Cayo Reid (Punta Bajo) and the area immediately to the west of it, Cayo Rosario and Blackadore Caye. Some sediment redistribution during SW-moving storms is indicated by NE-trending shoals (small arrow) or recurved spits (small, double-shafted arrow). Note deflection to the SW of soritid sand shoals from the S tip of Blackadore Caye (curved arrow).

from the outer shelf. Pusey (1975) suggested instead that deposition results from a convergence of currents from the inner and outer shelves. The sedimentary architecture of the mound-core (Fig. 9) suggests that a hybrid version of these hypotheses might explain better early mound-core development (Fig. 15A). That is, relatively rapid SW progradation of a large spit may have occurred during the catch-up phase of early HST deposition, with sediments transported to the area mainly during storms. Sediments derived from the inner shelf probably were, and still are, being exported to Cangrejo during northers and occasionally hurricanes such as Keith in 2000, for instance, the strong W winds of which persisted over Chetumal Bay for 36 h (Beven, 2001). In addition, SW longshore drift of sediments along the W coast of Ambergris Caye, and their subsequent deposition at Cangrejo, probably also occurred at times during storms. In fact, sediments directly behind Ambergris Caye are thin (Wilhite, 2000), which suggests that they are being flushed towards the shoals by the latter process today. Export of inner shelf sediments to Cangrejo by exceptionally strong ebb-tidal flow, resulting from the pile-up of waters in Chetumal Bay during the passage of W-moving storms or periods of persistent S winds, occurs today and probably in the past. At the same time, westward offlap (Fig. 9B) occurred as a result of periodic storm washover and, like today, sediments derived from the outer shelf were supplied to the shoals mostly by W-moving storms and also via longshore drift along the E coast of Ambergris Caye (Fig. 15A) during the passage of such storms and strong northers.

The overall NE–SW orientation of Bulkhead (Fig. 1) suggests that deposition occurs mainly during SW-moving storms, including periods of exceptionally strong trade winds. This contention is supported further by the observation that the soritid sand shoals migrating S from Blackadore Caye are deflected to the SW as they approach Bulkhead (Fig. 14). Yet, the existence of the two parallel shoal areas at Bulkhead (western and eastern, Fig. 5A) and the internal architecture of lower mound-core sedimentation units are evidence that deposition was and is slightly more complex. Development of a spit (Fig. 15B) can likewise be invoked for the offlapping, early HST lower mound-core deposits present beneath the western shoal from the lee of the thick mangrove ridge at Mosquito Caye (Figs 6B and 10A and B) to past Savannah Caye. Correlative deposits beneath the eastern shoal also offlap to the south-west. These deposits, and overlying aggradational late HST sediments here, include progressively more surficial soritid sands that have prograded in that direction (Fig. 10D), probably also during storms. The source of these sands is the shoals south of Blackadore Caye (Fig. 14), and the sands are onlapping mud-dominated sediments on the NE part of the mound. Hence, the eastern shoal area is largely a subtidal sediment bar distinct from the western shoal, although they have mostly coalesced to form a single mud-mound complex (Fig. 15B). Local modification of the dominant NE–SW trend in sediment thickness along the eastern shoal to a more NW

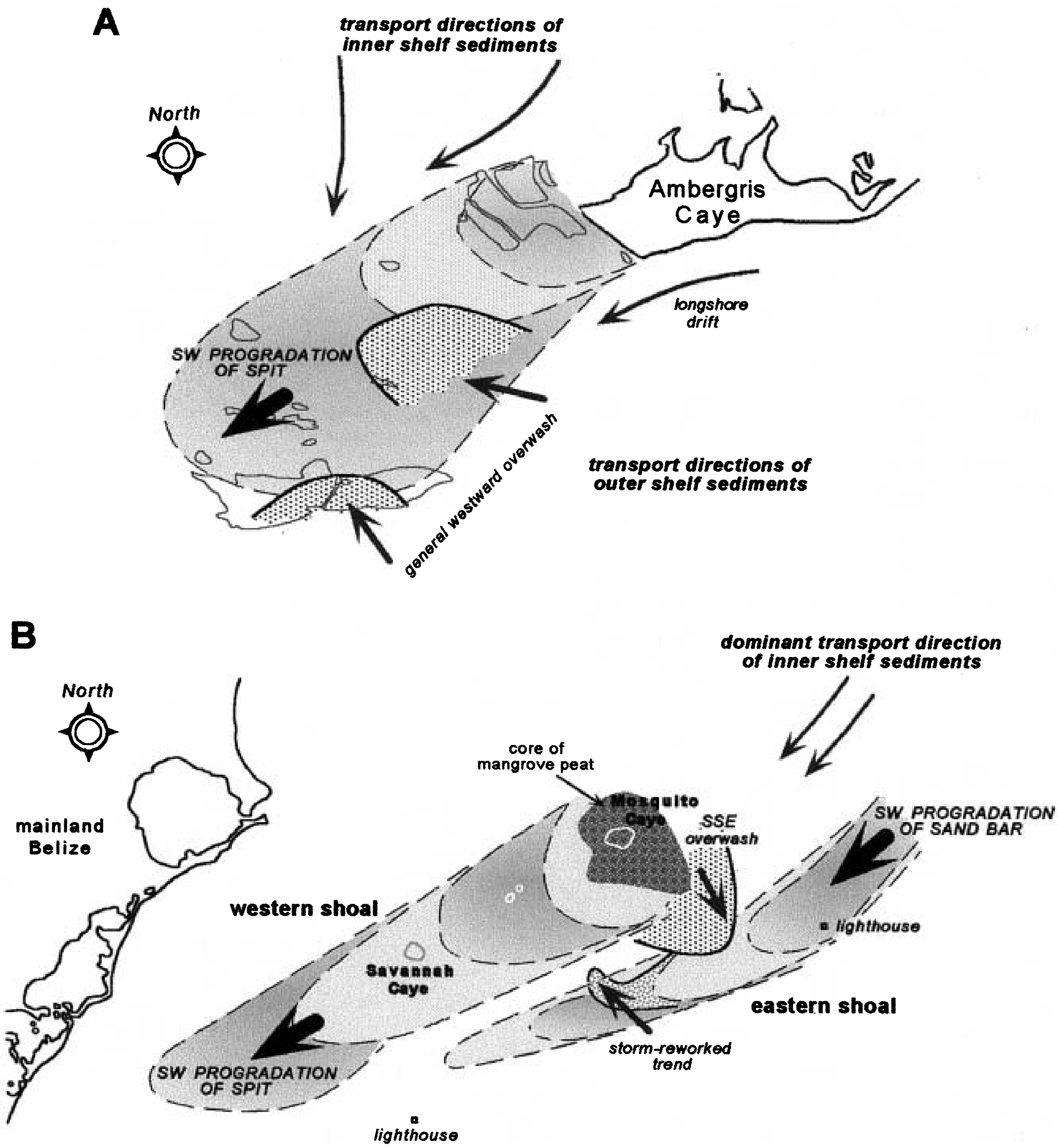


Fig. 15. Depositional models of early highstand systems tract mound-core deposits, and sediment sources, at Cangrejo Shoals (A) and Bulkhead Shoals (B).

orientation (arrow, Fig. 6B) suggests periodic sediment reworking by storms moving in either NW or SE directions. Additionally, some overwash of lower mound-core sediments to the S also occurred along this shoal at times (Fig. 10B).

The succeeding and current aggradational phase of late HST mound-core deposition at Cangrejo and Bulkhead likewise predominantly involves storm deposition and filling of available accommodation space. The surficial mangrove cayes and mangrove-rimmed islands in both areas are young features. At present sea-level stand, continued lateral expansion of the mud-mounds can occur by offlap of sediments into deeper water and, at Cangrejo, by onlap of inner shelf-derived sediments on the leeside of the shoals. The latter process cannot be very effective at Bulkhead because sediments to the W and all along the mainland coast to the N are extremely thin (generally < few centimetres). Lateral expansion and vertical aggradation can also result from further mangrove colonization and trapping of sediment in shallow-water areas.

Origin and significance of mound-core sedimentation units

The Holocene deposits at Cangrejo and Bulkhead constitute part of a eustatically forced, dominantly subtidal cycle with a recognizable TST, condensed section and a HST capped locally by intertidal deposits. The vertical architecture of transgressive onlap by premound facies, followed by offlap and then aggradation of mound-core facies is controlled mostly by the rate of sea-level rise. The HST of this cycle is comprised internally of component lithofacies (i.e. sedimentation units), with thickness and spatial variations in sediment texture that are controlled largely by bedrock topography, rates of influx of biodetrital sediments and physical processes of sediment delivery to, and deposition on, the mud-mounds.

Considering the slow rate of sea-level rise since $\approx$4500 years BP (Fig. 12) and negligible tectonic subsidence since the late Pleistocene (Lara, 1993), individual mound-core sedimentation units are obviously complete to partially eroded, shallowing-upward deposits. As such, they can be considered parasequences that might be recognized in ancient rocks. The characteristics of these assumed parasequences, however, only superficially mimic metre-scale, subtidal parasequences in many Phanerozoic rocks. *Thalassia* grass, morphological elements of which are key components of most of these units, for example is variously present or absent on the shoals today regardless of water depth, and surficial subaqueous sediments are either sandy or muddy, again regardless of depth. Furthermore, sediment textures are mostly altered post-depositionally and, even in unaltered units without *Thalassia*, there are no consistent vertical textural trends (Fig. 11). Hence, not only are criteria lacking for determining relative water depths of the different types of sedimentation units, but there is also no definitive evidence that they each systematically deepen upwards before shallowing upwards as has been interpreted in many ancient parasequences.

The stacked sedimentation units cannot be of forced eustatic origin because there is no evidence of multiple high-frequency sea-level oscillations during the Holocene transgression in Belize. Drummond & Wilkinson (1993) reached the same conclusion for analogous 'sequences' comprising bank (mound)-core deposits in Florida Bay. Autogenic processes such as tidal-flat progradation can also result in the deposition of stacked, shallowing-upward parasequences during a single, uniform sea-level rise (e.g. Ginsburg, 1971; Tucker, 1985), but such is not the case for the sedimentation units at Cangrejo and Bulkhead. Instead, they are autogenic, dominantly subaqueous storm deposits analogous to those comprising bank (mound)-cores in Florida Bay (Wanless & Tagett, 1989) and inferred for some ancient rocks (e.g. Feldman & Maples, 1989; Tedesco & Wanless, 1991). Such units represent single-episode, repetitive but aperiodic events of short duration involving mostly partial erosion of previously deposited units followed by either non-deposition or, during a given or later storm, deposition of new sedimentation units. Although some trapping of sediments by *Thalassia* probably occurs during storms, the Cangrejo and Bulkhead mud-mounds do not owe their origin solely to this process as was originally postulated for some Holocene mudbanks (e.g. Ginsburg & Lowenstam, 1958; Stockman *et al.*, 1967; Scoffin, 1969). The fortuitous discovery of the 1 m thick smothered sequence at Bulkhead attributed to Hurricane Mitch indicates that significant thicknesses of sediment can be deposited during storms, and conversely eroded, in extremely short periods of time. Of the inferred total amount of elapsed time during deposition of the mound-core sections ($\approx$ 4500 years), it is possible that the cumulative amount of time represented by the deposition of all the component sedimentation units might actually be measured in days. Superimposed on this episodic sedimentation is slow background sedimentation effected by *in situ* living organisms although, as discussed above, this process contributes only a minor amount of sediment at Cangrejo and Bulkhead.

Stability of the tidal channels and mud-mounds

Evidence of tidal channel or tidal delta deposits in buried sediments at Cangrejo or Bulkhead is not seen, although admittedly they would be nearly impossible to recognize because sediments within channels today and those in adjoining shoals are similar. However, it is believed that the tidal channels and deltas are relatively young features that formed either late in the offlapping phase of early HST mound-core deposition, because otherwise spits would have been breached, or perhaps coincident with the onset of late HST aggradational deposition.

Pusey (1975) compared aerial photographs of Bulkhead Shoals taken in 1945 and 1963 and concluded that the channels there had not migrated in that period of time. Comparison of aerial photographs of Bulkhead and Cangrejo taken in 1998 with Pusey's photographs (his figs 9 and 25) and with images of Cangrejo taken *c.* 1960 indicates that the positions of the tidal channels on both mud-mounds have not changed significantly in nearly 50 years. Binding of shoal-top sediments by microbial-scum mats and increase in compaction-induced sediment cohesiveness with depth may stabilize channel positions, at least over human life spans. Photographic comparisons indicate that the locations of Cangrejo and Bulkhead have also not changed appreciably in the last 40–50 years, although progressively more shallow-water areas on Cangrejo have been colonized by mangroves. Although minor shoal-margin erosion is observed at Bulkhead, where shallow-buried peat is being exhumed in a small area along the leeward (NW) side of Mosquito Caye (Fig. 10B), sediment deposition on the windward (E) side of the caye is not indicated. Aside from lateral expansion during the early catch-up phase of HST deposition, there is no evidence that either of the mud-mounds has migrated laterally any significant distance since the onset of their aggradational phases of HST deposition.

COMPARISON WITH FLORIDA BAY MUDBANKS

The Belize mud-mounds and Florida Bay mudbanks share many attributes, which is perhaps not surprising considering their similar settings and processes of deposition and post-depositional modification. Both are present, for example, in microtidal settings, and their Holocene sections overall are upward-shallowing, transgressive–regressive cycles deposited during sea-level rise. Basic subdivision of deposits into thin pre-mound/bank sediments overlain by thicker mound/bank-cores, the original textures of which have been altered extensively, is evident in both areas, as is the inferred storm-depositional origin of component sedimentation units. However, inferred temporal change in depositional style within mound-core deposits from early HST catch-up progradational to later HST keep-up aggradational architectures have not been documented in Florida Bay mudbanks. The presence of progradationally offlapping (HST) sedimentation units in Belize is generally similar to that in Florida Bay (Wanless & Tagett, 1989; Wanless *et al.*, 1995), including the local development of spits (e.g. Bosence, 1995). Coalescence of adjoining shoals to form a larger mud-mound complex is indicated at Bulkhead and in Florida Bay (Wanless & Tagett, 1989; Wanless *et al.*, 1995).

Yet, there are significant differences between these occurrences. First, mudbanks in Florida Bay are only 1–3 m thick and are generally no older than 5000 years (Enos & Perkins, 1979), and some of the banks in the central and eastern segments of the bay are considerably younger than that (Quinn & Merriam, 1988; Wanless & Tagett, 1989). In contrast, the Belize mounds began to form $\approx$6300–6500 years ago, and the greater depth below sea level of the Pleistocene limestone resulted in greater accommodation space during Holocene sea-level rise and, consequently, thicker sediments (i.e. 4·5–7·6 m). Secondly, there is no definitive evidence of significant lateral migration of the Belize mounds in response to windward erosion and leeward deposition, as is indicated within many of the mudbanks in Florida Bay (Enos & Perkins, 1979; Enos, 1989; Wanless & Tagett, 1989). Consequently, relatively steeply dipping, erosionally truncated sequences comprising bank (mound)-core deposits in Florida Bay are not recognized in Belize (Figs 9 and 10). The cross-sectional profile of Cangrejo is asymmetrical and steeper on its leeward side, which is bordered by relatively deep water (Fig. 9A). Although Bulkhead is somewhat more symmetrical, it also tends to be slightly steeper on its eastern flank as the shoals pass into deeper water (Fig. 10A). Rather than being of erosional origin, these steepened margins appear instead to be controlled by topography on the underlying bedrock limestone, which in turn controls off-shoal sediment thickness and water depth. Thirdly, there are no pronounced trends of leeward fining of sediments or consistent textural trends either along the longitudinal axes of the mounds or vertically within the mound-core deposits at Cangrejo or Bulkhead (Figs 9 and 10) as there is in Florida Bay (e.g. Enos & Perkins, 1979; Quinn & Merriam, 1988; Enos, 1989; Wanless & Tagett, 1989; Bosence, 1995; Wanless *et al.*, 1995). Lastly, whereas long-lived supratidal island facies form the core and capping deposits of some Florida Bay mudbanks (Enos & Perkins, 1979; Wanless & Tagett, 1989; Wanless *et al.*, 1995), surficial intertidal deposits are only minor components of the Belize mounds. Thick deposits of buried mangrove peat at Bulkhead, however, are analogous to long-lived swamp deposits present within some Florida Bay mudbanks.

Although these attributes may not be particularly useful in distinguishing mud-mounds deposited on an open shelf such as in Belize and those in a restricted setting such as Florida Bay, three aspects of the Belize occurrences might serve to do so. The first is their greater areal extent, which is analogous to the mudbanks in the less physically restricted, western part of Florida Bay (Enos & Perkins, 1979; Enos, 1989;

Wanless & Tagett, 1989) and to those seaward of the Florida Keys (e.g. Ebanks & Bubb, 1975; Turmel & Swanson, 1976; Bosence *et al.*, 1985; Tedesco & Wanless, 1995; Wanless *et al.*, 1995) rather than to the sinuous banks elsewhere in the bay. Secondly, whereas mud dominates in central-eastern Florida Bay (e.g. Enos & Perkins, 1979; Wanless & Tagett, 1989), sand-size fractions seem to constitute a relatively high proportion of the mound sediments in Belize. Lastly, the presence of skeletal particles of outer-shelf derivation, at least at Cangrejo, indicates proximity to an open shelf. Mudbanks in south Florida deposited in less restricted environments than those in central-eastern Florida Bay likewise include considerable quantities of skeletal sand and gravel and relatively abundant biotic particles and *in situ* living biota (e.g. corals and calcareous algae) typical of more open-shelf environments (Basan, 1973; Turmel & Swanson, 1976; Wanless, 1981; Bosence *et al.*, 1985; Wanless & Tagett, 1989; Bosence, 1995; Tedesco & Wanless, 1995; Wanless *et al.*, 1995). In this regard, an abundance of at least soritid foraminifera such as at Bulkhead, if not miliolids as well, in other Cenozoic mud-mounds may suggest deposition on similarly relatively wide (inner) shelves leeward of platform barriers such as Ambergris Caye.

CONCLUSIONS

Cangrejo and Bulkhead Shoals are areally extensive, Holocene biodetrital mud-mounds. They encompass areas of 20 km^2 and 35 km^2, and maximum sediment thicknesses are 7·6 m and 4·5 m respectively. Deposition is on a wide, shallow-water shelf that is much less restricted than in Florida Bay, and where storms are likewise the dominant process of transport and redeposition of sediments. Overall shallowing-upward deposition occurred during Holocene marine flooding of emergent Pleistocene bedrock limestone beginning ≈6500–6600 years BP. Locally preserved soils on the bedrock limestone are overlain by basal transgressive, premound *Rhizophora* mangrove peat and thin sections of coarse shelly gravel. Deposition of these facies tracked the rapid rate of sea-level rise from about 6400–6500 years BP to 4500 years BP. Whereas mangrove caye/swamp environments were established early but quickly drowned at Cangrejo, they kept pace with early sea-level rise at Bulkhead, where resulting thick sections of buried peat are present. After deposition of a thin condensed section, overlying HST mound-core deposits are thick and were deposited during slow sea-level rise in the last ≈4500 years. Component sedimentation units are autogenic storm deposits, and their upper surfaces mostly represent eroded sediment–water interfaces, the depositional textures of which have largely been overprinted by bioturbation and the presence of former *Thalassia*-colonized surfaces. Vertical stacking of these deposits imparts a texturally complex, quasi-cyclic architecture to the section that only superficially mimics metre-scale, eustatic parasequences in ancient rocks. An early highstand phase of mound-core development is recognized to comprise progradationally offlapping sediments deposited in rapid catch-up fashion, whereas the later (and current) highstand phase mainly involves keep-up aggradational deposition. Mound-core deposits are overlain locally by young intertidal islands, characterized by a few centimetres of desiccated carbonate sediments and/or microbial laminites, and mangrove cayes/swamps. The channels on the mud-mounds also appear to be young features that formed during highstand. The locations of the mud-mounds and channels that transect them appear to be fairly stable at least over human life spans.

Sedimentary facies and internal architectures of the Belize mud-mounds are similar to those attributes in mudbanks in central-eastern Florida Bay. Possibly the only characteristics that might distinguish mud-mounds deposited in more open-marine environments from those deposited in restricted settings are their broad areal extent, higher proportion of sand- and gravel-size sediment fractions and relatively abundant component biotic particles derived from adjoining open shelves.

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