

Late Pliocene to Holocene platform evolution in northern Belize, and comparison with coeval deposits in southern Belize and the Bahamas

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ABSTRACT

Lithostratigraphy, depositional facies architecture, and diagenesis of upper Pliocene to Holocene carbonates in northern Belize are evaluated based on a *ca* 290 m, continuous section of samples from a well drilled on Ambergris Caye that can be linked directly to outcrops of Pleistocene limestone, and of overlying Holocene sediments. Upper Pliocene outer-ramp deposits are overlain unconformably by Pleistocene and Holocene reef-rimmed platforms devoid of lowstand siliciclastics. Tectonism controlled the location of the oldest Pleistocene platform margin and coralgall barrier reef, and periodically affected deposition in the Holocene. A shallow, flat-topped, mostly aggradational platform was maintained in the Holocene by alternating periods of highstand barrier-reef growth and lowstand karstification, differential subsidence, and the low magnitude of accommodation space increases during highstands. Facies in Pleistocene rocks to the lee of the barrier reef include: (i) outer-shelf coralgall sands with scattered coral patch reefs; (ii) a shoal–water transition zone comprising nearshore skeletal and oolitic sands amidst scattered islands and tidal flats; and (iii) micritic inner-shelf deposits. Four glacio-eustatically forced sequences are recognized in the Pleistocene section, and component subtidal cycles probably include forced cycles and autocycles. Excluding oolites, Holocene facies are similar to those in the Pleistocene and include mud-mounds, foraminiferal sand shoals in the inner shelf, and within the interiors of Ambergris and surrounding cayes, mangrove swamps, shallow lagoons, and tidal and sea-marginal flats. Meteoric diagenesis of Pliocene and Pleistocene rocks is indicated by variable degrees of mineralogic stabilization, generally depleted whole-rock $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values, and meniscus and whisker-crystal cements. Differences in the mineralogy and geochemistry of the Pliocene and Pleistocene rocks are attributed to variable extent of meteoric alteration. Dolomitization in the Pliocene carbonates may have begun syndepositionally and continued into the marine shallow-burial environment. Positive dolomite $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values suggest precipitation from circulating, near-normal marine fluids that probably were modified somewhat by methanogenesis. Sedimentologic and diagenetic attributes of the Pliocene–Pleistocene rocks in the study area are similar to those in the Bahamas with which they share a common history of sea-level fluctuations and climate change.

Keywords Belize, dolomitization, platform evolution, Pliocene to Holocene, rimmed platform, tectonics.

INTRODUCTION

Sedimentologic analysis of extant carbonate platforms provides critical comparative models for understanding ancient platforms (Read, 1985; Schlager, 1992), and perhaps the most extensively studied modern platform from the viewpoint of its evolution and development is the Bahama Banks (Ginsburg, 2001a). Belize, Central America, is also a major carbonate platform in the western hemisphere, and it has been the site of lowstand-punctuated, platform carbonate deposition since the Cretaceous (Vinson, 1962; Bishop, 1980; Salvador, 1987; Rao & Ramanathan, 1988; Morán-Zenteno, 1994). There are many sedimentological studies of Holocene shallow-marine and upper fore-reef deposits on the Belize platform (e.g. Ebanks, 1975; High, 1975; Purdy *et al.*, 1975; Pusey, 1975; James & Ginsburg, 1979; Wilhite & Mazzullo, 2000; Mazzullo *et al.*, 2003; Purdy & Gischler, 2003; Yang *et al.*, 2004). In contrast, much less is known about its platform evolution, and what has been published has focused mainly on subsurface upper Quaternary deposits in the central and southern shelf areas of the country (Fig. 1). Early studies (Choi, 1981; Choi & Ginsburg, 1982; Choi & Holmes, 1982) evaluated lithostratigraphy, facies patterns and platform development based on analysis of seismic profiles

coupled with some drill logs and shallow cores. Subsequent research, including high-resolution seismic sequence-stratigraphic studies (Westphall, 1986; Esker *et al.*, 1998; Ferro *et al.*, 1999), described inter-relationships among mixed carbonate–siliciclastic facies architecture, development of incised valleys and valley-fill systems, sea-level fluctuations, and tectonics. Although these studies provided a carefully documented view of upper Quaternary platform and fore-platform evolution in Belize, they encompassed only part of the extensive Belize platform and only that of Late Quaternary age. Whether their conclusions are applicable to the northern shelf area as well is uncertain, however, especially considering known along-strike (N–S) variations in antecedent topography, water depth, proximity to a siliciclastic source and inferred tectonic influence on deposition in these areas (Purdy, 1974b; Purdy *et al.*, 1975, 2003; Purdy & Gischler, 2003).

The present study of the sedimentary architecture and evolution of upper Pliocene to Holocene depositional systems in northern offshore Belize generates a more complete synthesis of platform evolution here. It also contributes to the knowledge of controls on platform evolution in the geologic record (Tucker, 1985; Schlager, 1992; Handford & Loucks, 1993; Read *et al.*, 1995) and to concepts useful in petroleum exploration (e.g. Bishop, 1980; Pindell, 1991). The approach of this paper is threefold. First, it defines the lithostratigraphic and temporal framework of pre-Holocene strata based on integration of a 284 m thick section of cut samples of Late Pliocene to Pleistocene age from a well drilled on Ambergris Caye (the ‘Airstrip well’), and a *ca* 4.7 m thick outcrop section of Pleistocene limestone. Secondly, it interprets the pre-Holocene depositional environments, and their geochemical evolution in terms of dolomite occurrence and stable oxygen and carbon isotope stratigraphy. Thirdly, these data and interpretations serve as the basis for evaluating platform evolution from the Late Pliocene to the Holocene, and for comparing such to platform development in central to southern Belize and to coeval deposits in the Bahama Banks – the latter area commonly considered to be the ‘type locality’ of western hemisphere platforms.



Fig. 1. Location of study area in northern offshore Belize. Seismic line APE 84-08 (shown in Fig. 9C) is from Purdy *et al.* (2003) after Ferro *et al.* (1999).

GEOLOGICAL SETTING

The geological setting and general stratigraphy of Belize were summarized most recently by Lara

(1993), Purdy *et al.* (2003) and King *et al.* (2004). Belize is located at the southern end of the Yucatan Peninsula, which is a low-relief area of highly karsted, undeformed Tertiary and Quaternary carbonates. The oldest rocks exposed on the mainland are in the Maya Mountains (Fig. 1), the primary source of siliciclastics in the region. Silurian to Devonian granites are overlain by Upper Carboniferous to Middle Permian sedimentary, meta-sedimentary and volcanic rocks that, in turn, were deformed and intruded by granite during the Triassic. Surrounding the Maya Mountains are largely undeformed Jurassic siliciclastics, and Cretaceous to upper Tertiary carbonates with some evaporites. Pleistocene carbonate rocks are present mainly in low-lying areas along the coast, and are associated with siliciclastics in the central and southern parts of the country.

Belize lies atop the North American Plate in a passive-margin setting. Rifting in the area began during the Late Triassic and continued into the Cenozoic as the Caribbean Plate migrated eastwards (Bishop, 1980; Salvador, 1987; Pindell, 1991). Cenozoic tectonism in Belize involved faulting (left-lateral and transtensional strike-slip), uplift and compressional folding, and development of the major structural features of the area (Dillon & Vedder, 1973), including the fault-bounded, modern reef-rimmed platform edge (Fig. 1). Tectonic activity diminished after the Oligocene (Bishop, 1980), and although northern offshore Belize is now seemingly tectonically quiescent, there is offshore subsidence and documented movement along some of the faults in central to southern Belize and on some of the offshore atolls (Dillon & Vedder, 1973; Lara, 1993; Purdy *et al.*, 2003).

STUDY AREA, SAMPLES AND METHODS

The study area is centred on and around Ambergris Caye on the northern shelf, distal from a current source of siliciclastics in the Maya Mountains (Fig. 1). Bedrock within the shallow marine (< 5 m) environment around the cayes is locally overlain by buried soil and/or mangrove peat, and in turn, by Holocene carbonate sediments, the study of which (Fig. 2, inset; Mazzullo *et al.*, 2003; Yang *et al.*, 2004) forms the basis for interpreting pre-Holocene rocks. The bedrock is highly karsted limestone that rises to a maximum elevation, on Ambergris Caye, of ca 2.4 m above sea level. One hundred and sixty samples com-

prising a total of ca 4.7 m of section were collected from outcrops on Ambergris and adjoining cayes, from sea-floor exposures in shallow marine areas, and from blocks of limestone brought to the surface during commercial excavation or dredging activities (Fig. 2). Samples were described in the field and laboratory, and representative samples were examined via thin-section petrography. Three seemingly unaltered samples of the fossil coral *Montastrea annularis* were dated by U–Th series by Ken Rubin (SOEST/University of Hawaii), and two unaltered samples of the gastropod *Strombus gigas* were dated by amino acid racemization by Colin V. Murray-Wallace (University of Wollongong, Australia). These specimens were collected from limestone exposed at Reef Point and along the Basil Jones transect on Ambergris Caye, respectively (Fig. 2), and their mineralogy was 100% aragonite as confirmed by X-ray diffraction (XRD).

A 284 m deep well – the ‘Airstrip well’ – was drilled in 1991 by the Belize Water and Sewer Authority (WASA) adjoining the airstrip south of San Pedro Town on Ambergris Caye, ca 1.1 km leewards of the platform margin (Fig. 2). It spudded in Holocene beach sand and penetrated the top of the limestone bedrock of the cayes at –2 m, which coincides with mean sea level (MSL). Except for some sections of no recovery, cuttings were collected every 3 m during drilling, and they were later described via binocular microscopy and thin-section petrography. The upper 2.3 m of samples in this well correlate to the basal 2.3 m of shallow-subsurface Pleistocene limestone that were sampled (Fig. 3A), thus providing a critical and uninterrupted link between deeper samples in the Airstrip well and outcrops in the study area. Wire line logs were not run on the well, and bore-hole fluids (described by the drillers as ‘salty water’) were not sampled by WASA. A subset of cuttings was sent to Barbara Lidz (US Geological Survey) for identification and age assignment of benthic foraminifera. Dolomite was identified in the well samples, and it was isolated following the procedure in Teal *et al.* (2000). Only samples that were shown by XRD to comprise 98% or more dolomite were sent to the Stable Isotope Laboratory, University of Michigan–Ann Arbor for stable isotope analysis. A subset of whole-rock samples from the well was also analysed for O and C isotopic composition. External reproducibility for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analyses (PDB) is less than 0.1‰; corrections are not applied for dolomite–phosphoric acid fractionation in dolomite $\delta^{18}\text{O}$ values.

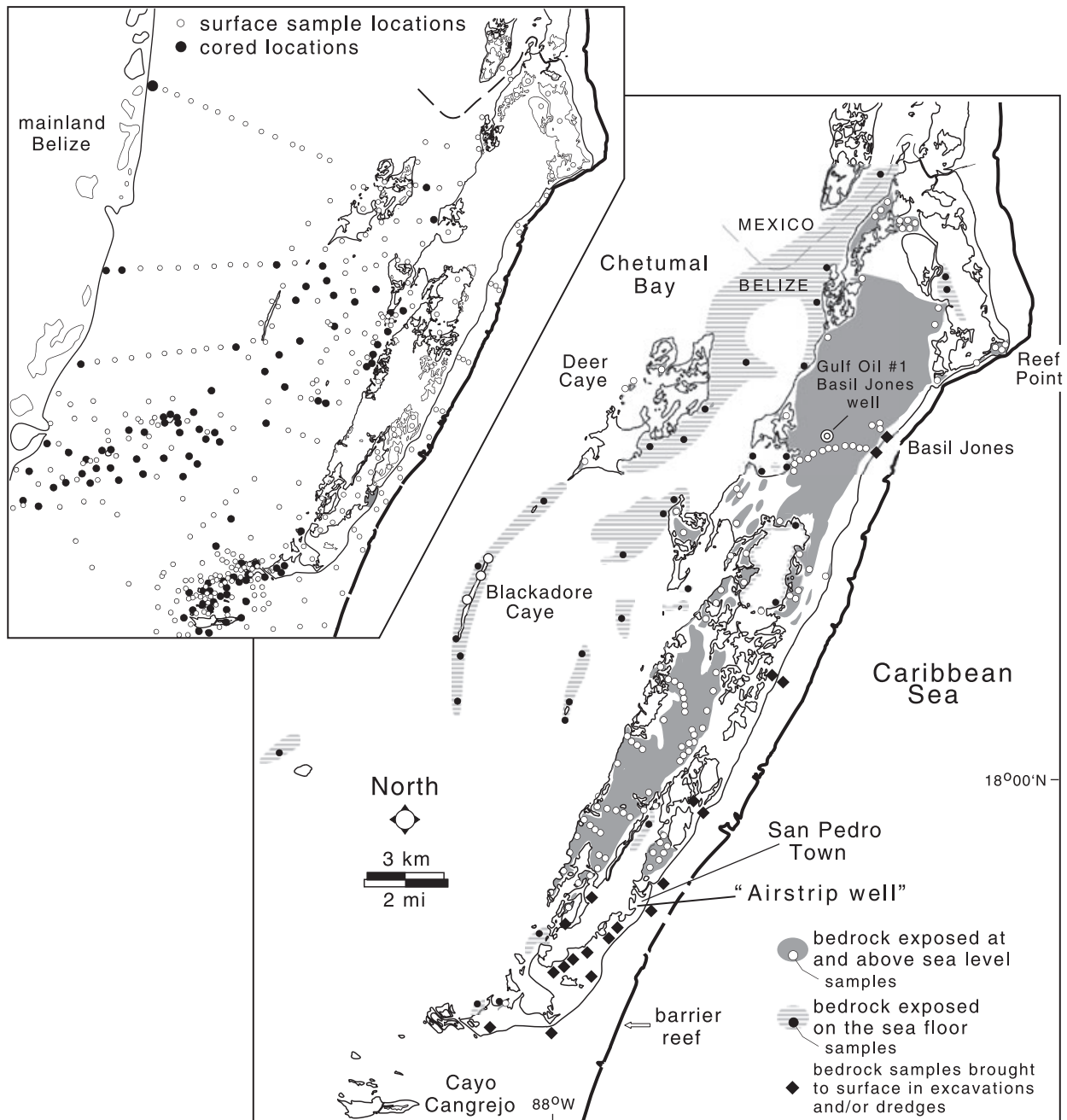
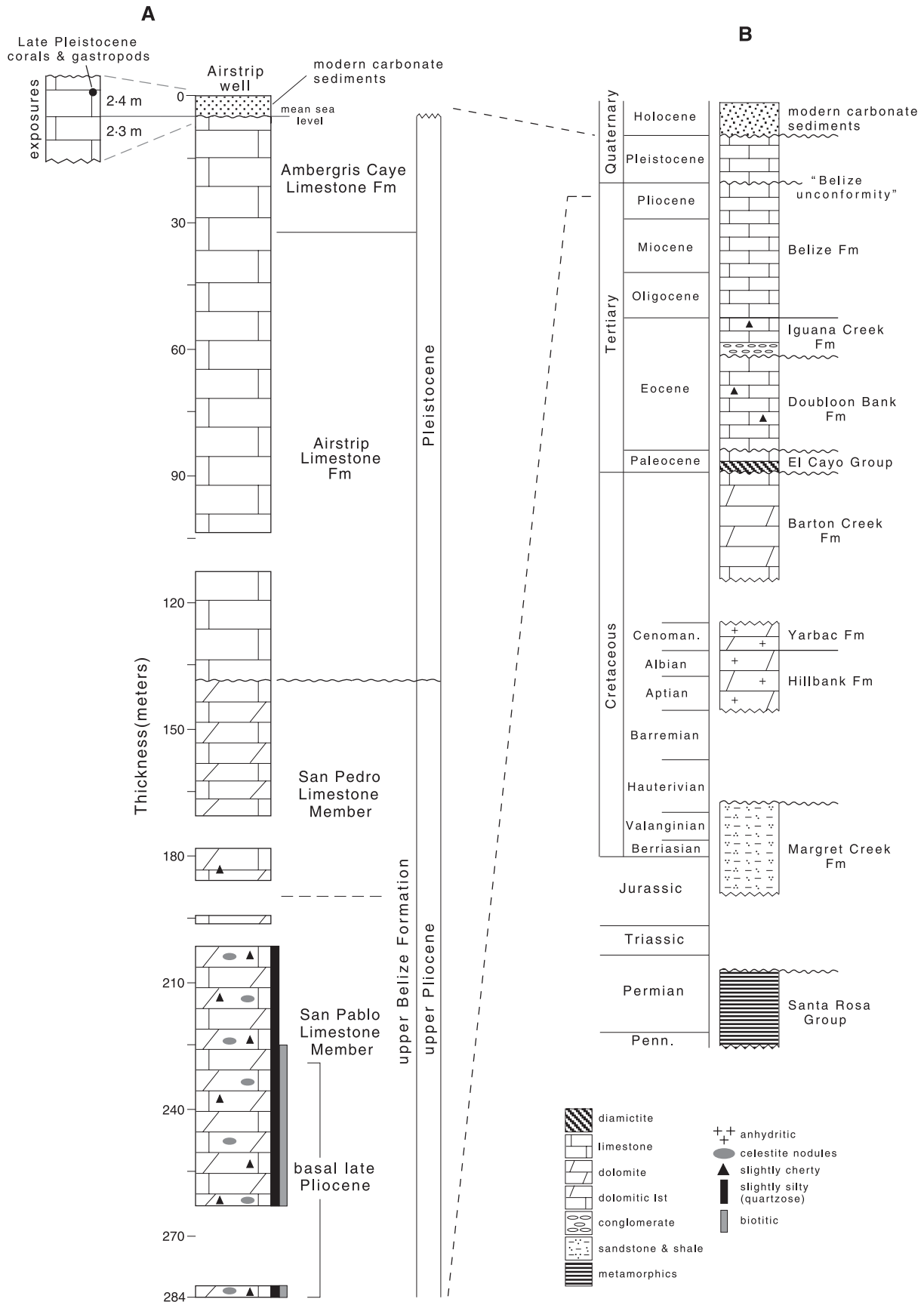


Fig. 2. Distribution of bedrock limestone exposed on and around Ambergris Caye, sample locations, and locations of the Airstrip well and the Gulf Oil no. 1 Basil Jones well. Inset – locations of samples of Holocene carbonate and associated sediments (from Mazzullo *et al.*, 2003 and Yang *et al.*, 2004).

X-ray diffraction of Holocene sediments and surface and subsurface rocks was carried out on a Phillips 3100XRG diffractometer utilizing Cu-K

alpha radiation with internal quartz standards added. Mol.% MgCO₃ in calcite and dolomite was determined by the [1 0 4] peak shift method

Fig. 3. (A) Composite stratigraphic section in northern Belize based on the Airstrip well and exposures on and around Ambergris Caye, proposed stratigraphic terminology, and vertical range of basal Late Pliocene benthic foraminifera. Uppermost beds of the Ambergris Caye Limestone exposed on Ambergris Caye contain age-dated corals assigned to Late Pleistocene (Sangamon) oxygen isotope stage 5e. (B) Stratigraphy of northern Belize (Corozal Basin), no vertical scale, from Purdy *et al.* (2003), who placed upper beds in the Gulf Oil no. 1 Basil Jones well on Ambergris Caye (shown in Fig. 2) within the Eocene Doubloon Bank Formation. Note the prominent ‘Belize unconformity’ at the top of the Pliocene, which correlates to the unconformity at the top of the Pliocene in the Airstrip well.



following Mackenzie *et al.* (1983) and Lumsden & Chimahusky (1980), respectively. Radiocarbon dating of Holocene mangrove peat and associated samples was carried out by Geochron Laboratories, and the ages reported are uncorrected for reservoir effect.

STRATIGRAPHY OF PRE-HOLOCENE SUBSURFACE AND EXPOSED ROCKS

The section in the Airstrip well, together with the exposed and near-surface limestones present on and around Ambergris Caye, has a total thickness of nearly 290 m of pre-Holocene strata (Fig. 3A). This section is divided into the following lithologic units in ascending stratigraphic order. Formal names are proposed to clarify the vague and poorly documented stratigraphic assignments and terminology in this part of the section.

San Pablo Limestone

This unit, the base of which was not encountered in the well, consists of 95 m of greyish light tan, silty (maximum 10% by weight of detrital quartz, and in the basal 83 m of section, also detrital biotite) and slightly cherty, soft and 'chalky', non-porous, dolomitic limestone with scattered nodules of replacive celestite. The replacive dolomite is finely crystalline (mean size 15 μm), and the unit coarsens upwards slightly from mudstones with miliolids and diatoms to wackestones with similar allochems and rare coral and thin-shelled bivalve fragments.

San Pedro Limestone

This unit consists of 55 m of light grey to greyish tan, non-porous, dolomitic limestone with red algae, echinoid spines, minor to rare corals, miliolids and rare soritids, abundant pyritized peloids in upper beds, and scattered fragments of crab carapaces. Ramose and encrusting red algae are particularly abundant in the upper 15–20 m. Texture coarsens upward, and the replacive dolomite is finely crystalline (mean size 15 μm). Minor chert nodules are present towards the base.

Airstrip Limestone

This section comprises 105 m of white and some yellowish-tan, porous limestone with corals, red algae, *Halimeda*, *Homotrema*, soritid and miliolid foraminifers, and gastropod and pelecypod frag-

ments. Ramose and encrusting red algae are abundant in the basal 25–30 m. Texture coarsens upwards from packstones with thin interbeds of grainstone in the lower half, to overlying packstones and grainstones.

Ambergris Caye Limestone

The uppermost unit in the Airstrip well is 28 m thick, and consists of mostly white and light tan, porous limestones that generally coarsen upwards from wackestones/packstones to packstones/grainstones. Constituent particle size and the amount of corals and associated coralline algae, *Halimeda*, *Homotrema* and thick-shelled pelecypods and gastropods increase upwards. Of the total vertical section of ca 4.7 m of limestones that was compiled from exposures and excavated and/or dredged samples on and around Ambergris Caye, the basal 2.3 m correlate to the limestone section of the same thickness at the top of the Airstrip well (Fig. 3A). These rocks and the overlying 2.4 m of exposures on and around the caye are included within the Ambergris Caye Limestone to give it a total thickness of ca 30 m. Flores (1952) referred to exposures of coral-rich rocks along the north-eastern coast of Ambergris Caye (e.g. at Reef Point: Fig. 2) as the 'Ambergris reef limestone', from which the name of the present formation is derived.

AGES AND CORRELATION OF PRE-HOLOCENE ROCKS IN BELIZE

In the Airstrip well, samples of unaltered skeletal material, mud matrix, or marine cements suitable for radiometric dating or $^{87}\text{Sr}/^{86}\text{Sr}$ isotope analyses were not available, and absence of cores precludes magnetostratigraphic dating. Only bank-top (shallow-water) foraminifers that are not age-diagnostic are present in well samples in the Ambergris Caye Limestone down to the upper San Pedro Limestone. Biotic particles are poorly preserved in the middle to lower San Pedro Limestone and upper San Pablo Limestone, but the lower half of the San Pablo Limestone (232–286 m depth: Fig. 3A) contains basal Late Pliocene planktic foraminifers assignable to biozone N20 (3.5 to 2.5 Ma) of Bolli & Saunders (1985). Based on lithologic similarity of the San Pablo and San Pedro dolomitic limestones and the abrupt change to limestone above, the top of the Pliocene is placed at the top of the dolomite. Lara (1993) documented a similar mineralogic

relationship between Pliocene and Pleistocene rocks in the subsurface in southern Belize. The inferred unconformity at the top of the San Pedro Limestone therefore probably correlates to: (i) the 'Belize unconformity' recognized in subsurface central and southern Belize (Esker *et al.*, 1998; Ferro *et al.*, 1999; Purdy *et al.*, 2003); (ii) the unconformity at the top of the Pliocene recognized in subsurface southern Belize (Choi & Ginsburg, 1982; Choi & Holmes, 1982); and (iii) to the global sea-level lowstand at the top of the Pliocene (Haq *et al.*, 1988).

The limestone exposed on and around Ambergris Caye, which encompasses the top 4.7 m of the Ambergris Caye Limestone, has long been regarded as Pleistocene (e.g. Flores, 1952; Ebanks, 1975; Pusey, 1975). A Sangamon age was suggested by Tebbutt (1975) based on apparent correlation to *ca* 125 000 year old deposits in the Bahamas and elsewhere. In the present study, a sample of *M. annularis* in limestone at 0.5 m above MSL at Reef Point (Fig. 2) yielded a U–Th age of 135 800 ± 900 cal yr BP (Table 1). Thorium content is at the high end of the normal range for corals, which may account for a U–Th age slightly older than the age of 128 280 ± 1330 cal yr BP obtained from a fossil *Acropora palmata*, collected from 0.3 m above MSL also at Reef Point by Gischler *et al.* (2000). Together, however, these age dates establish that at least the upper part of the Ambergris Caye Limestone is within oxygen isotope stage 5e (Sangamon highstand) of Late Pleistocene age. Preliminary amino acid racemization results (D/L ratios for the total acid hydrolysate: Table 1) suggest that two samples of *Strombus gigas* in limestone at 1.2 m above MSL along the Basil

Jones traverse (Fig. 2) likewise are within stage 5e. The other sample of *M. annularis* that was U–Th age-dated was from limestone dredged from 2.3 m below the surface on southern Ambergris Caye. Its U–Th age of 165 500 ± 1100 cal yr BP is considered unreliable given the relatively high Th content (Table 1).

The Pleistocene age of the Airstrip Limestone in the well and all but the top 2.3 m of Sangamon-age Ambergris Caye Limestone remains equivocal. This section correlates to the upper part of the subsurface Belize Formation, above and immediately below the 'Belize unconformity', as is recognized in the northern part of the country (Fig. 3B). Accordingly, previous assignments of outcropping and relatively shallow subsurface strata in northern offshore Belize as Eocene (e.g. Dillon & Vedder, 1973; Bishop, 1980), undivided Tertiary (Purdy, 1974a,b; Ferro *et al.*, 1999, their fig. 2), or undivided Quaternary (Rao & Ramanathan, 1988), and likewise, their correlation to the Barton Creek Formation (Rao & Ramanathan, 1988), are not warranted. Assignment of at least shallow (to *ca* 450 m depth) subsurface strata in the Gulf Oil no. 1 Basil Jones well on Ambergris Caye to the Eocene Doubloon Bank Formation (Purdy *et al.*, 2003, their fig. 3A) likewise is not justified. It is proposed that the Belize Formation in northern Belize be restricted to pre-Pleistocene strata, with the San Pablo and overlying San Pedro limestones comprising its upper members (Fig. 3A). The overlying Airstrip and Ambergris Caye limestones are thus considered to be formations that correlate to strata (unnamed in Purdy *et al.*, 2003, their fig. 2) above the Belize unconformity, and to Pleistocene carbonate and siliciclastic deposits in the subsurface

Table 1. Age-dated samples from bedrock limestone exposures on Ambergris Caye (this study). U–Th series dates from Ken Rubin, University of Hawaii, and amino acid racemization data from Colin V. Murray-Wallace, University of Woolongong, Australia. Elevations are with respect to mean sea level.

Sample	Location	Elev	$^{230}\text{Th}/^{238}\text{U}$	Age	Detrital Correction	Remarks
U–Th Series Dating						
<i>M. annularis</i> (KW-90)	Reef Point	+0.5 m	0.800 ± 0.004	135,800 BP ± 900	0.1% 450 yr	Reliable
<i>M. annularis</i> (KW-111)	Dredge, so. Ambergris Caye	–2.3 m	0.897 ± 0.005	165,500 BP ± 1100	1% 4600 yr	Unreliable
Sample	Location	Elevation	D/L LEU (leucine)	D/L ASP (aspartic acid)	Remarks	
Amino Acid Racemization						
<i>S. gigas</i> (KW-30A)	Basil Jones	+1.2 m	0.44 ± 0.01	0.56 ± 0.04	Likely O isotope stage 5e	
<i>S. gigas</i> (KW-30B-1)	Basil Jones	+1.2 m	0.42 ± 0.01	0.60 ± 0.05	IBID	

of central and southern Belize (Choi, 1981; Choi & Ginsburg, 1982; Choi & Holmes, 1982; Esker *et al.*, 1998; Ferro *et al.*, 1999).

DEPOSITIONAL FACIES AND DIAGENESIS OF PRE-HOLOCENE STRATA

Sediments and biota of Holocene age in northern offshore Belize have been examined by many researchers, including Ebanks (1975), High (1975), Pusey (1975), Mazzullo *et al.* (1987, 1992, 2003), Dunn (1990), Birdwell (1992), Mazzullo & Bischoff (1992), Lowe (1995), Burke *et al.* (1998), Teal (1998), Teal *et al.* (2000), Wilhite (2000), Wilhite & Mazzullo (2000), Dimmick-Wells (2002), Purdy & Gischler (2003), Gischler & Hudson (2004), and Yang *et al.* (2004). Accordingly, Holocene facies in northern Belize are well known among sedimentologists. The sedimentologic and biotic attributes of these deposits are summarized in Table 2, and they provide the analogues for interpreting Pliocene and Pleistocene environments in outcropping and subsurface limestones in the study area.

Depositional environments and geochemistry of rocks in the Airstrip well

Upper Pliocene outer-ramp deposits

Upper Pliocene strata in the basal part of the Airstrip well are lithologically and biotically distinct from overlying Pleistocene coral-rich limestones (Fig. 4). The basal San Pablo Member, for example, is slightly cherty and silty (10–15% detrital quartz and biotite) dolomudstone with sparse miliolids and diatoms. This section coarsens upwards to include interbedded dolopackstones and grainstones in the upper part of the San Pedro Member, with increasing amounts of ramose and encrusting coralline algae and pyritized peloids, and lesser amounts of echinoid spines, miliolids, soritids, bivalves, and minor sand- to fine gravel-size coral fragments. The packstones and grainstones are typically fine-grained and generally contain particles that are smaller than coarse sand to fine gravel. Muds and fine-grained sands similarly are present in deep water, fore-reef slope settings surrounding, but somewhat distal from, extant carbonate platforms (e.g. Coniglio & Dix, 1992). The San Pablo and San Pedro limestones cannot be considered fore-reef deposits adjoining a reef-rimmed platform, however, given that coeval platform-marginal

coral reef deposits of Pliocene age have not been identified either in the study area or in up-dip locations on the Belize mainland to the west (Wright *et al.*, 1959). Rocks possibly of this age on the mainland are mainly nearshore sands and marls (King *et al.*, 2003, 2004). Secondly, coarse-grained coral and *Halimeda*-rich rocks that typically comprise upper fore-reef lithologies in Belize (e.g. James & Ginsburg, 1979) and elsewhere are not present in the Airstrip well section. Instead, the San Pablo and San Pedro Members are interpreted as shallowing-upward, outer-ramp deposits based on: (i) the biota present; (ii) rarity of corals, (iii) the fine-grained lithology of the rocks; and (iv) the supposition that the Pliocene and Pleistocene sections are disparate depositional systems separated by an unconformity. These rocks have no facies counterpart in the Pleistocene (Sangamon) limestones or Holocene sediments in the study area.

A major unconformity at the top of the Pliocene is recognized in outcrops over much of the Yucatan Peninsula (Wright *et al.*, 1959; Vinson, 1962). In contrast, Pliocene rocks are present in the subsurface in northern offshore Belize (this paper) and central to southern Belize (Purdy, 1974a,b; Choi & Ginsburg, 1982; Lara, 1993; Esker *et al.*, 1998; Ferro *et al.*, 1999; Purdy *et al.*, 2003), which indicates that these areas were subsiding at the time. The quartz–biotite silt in the San Pablo and San Pedro Members was ultimately derived from the Maya Mountains to the south-west, and its presence supports Purdy *et al.*'s (2003) contention that this source area was unroofed at least by early Late Pliocene. An unconformity at the top of the upper Pliocene San Pedro Member in the Airstrip well (Fig. 3A) is suggested by a pronounced facies disparity between coral-poor packstones/grainstones in slope strata of the upper San Pedro Member and the interbedded wackestones/packstones with relatively abundant corals and other shallow-water biota in inferred platform strata of the overlying basal Airstrip Formation. Alternatively, it is possible that this contact is a correlative conformity down-dip of the major unconformity recognized on the mainland. Additional unconformities that are not readily identifiable in the well samples by lithic evidence (such as is present in the Pleistocene section) may also be present in the Pliocene rocks, particularly at the base of sections where there is an abrupt increase in the amount of MgCO₃ in component calcites (e.g. at ca 155, 220 and 270 m; Fig. 5A). A shift to lower whole-rock $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values at 155 m and 270 m depths

Table 2. Characteristic lithology and biota of Holocene surficial and shallow-buried depositional environments, excluding the barrier reef (facies 1 – see Fig. 7B).

Environment	Facies ¹	Lithology and common biota
Outer-shelf facies		
Marine sand tract	2	Generally gravelly sand, more gravelly towards barrier reef and finer-grained toward land. Aside from coral fragments and sponges, accessory common biota are <i>Halimeda</i> spp., <i>Neogoniolithon</i> spp., <i>Penicillus</i> spp. and <i>Udotea</i> spp.; <i>Homotrema rubrum</i> ; <i>Strombus gigas</i> , <i>S. pugilis</i> , <i>S. costatus</i> and <i>S. raninus</i> , <i>Turbinella angulata</i> , <i>Vasum muricatum</i> , various tritons, cowries, cone shells, top shells, star shells, helmet shells and limpets; <i>Apolymetis intastriata</i> , <i>Macoma constricta</i> , various lucines including <i>Codakia</i> spp., various tellins, cockles, ark shells and thorny oysters; various urchins and sea stars (e.g. <i>Diadema</i> , <i>Meoma</i> , <i>Brissus</i> and <i>Oreaster</i>); grassy areas with <i>Thalassia</i> and <i>Syringodium</i>
Beach	2	Relatively fine-grained sand with biota as above
Storm rubble ridge at Robles Point	–	Coarse gravel to boulder-size particles, dominantly stony corals (e.g. <i>M. annularis</i> , <i>M. cavernosa</i> , <i>Diploria</i> spp., <i>Agaricia</i> spp., <i>Acropora palmata</i> , <i>A. cervicornis</i> and <i>Porites</i> spp.), gastropods (e.g. <i>S. gigas</i> and <i>T. angulata</i>), gorgonians; various sponges; and organisms listed above
Sponge bioherm	2a	Sand and gravelly sand with <i>Ircinia campana</i> and other sponges; algae, gastropods and pelecypods as in facies 2; <i>Caulerpa</i> spp. and some <i>Thalassia</i> ; <i>Porites</i> spp., <i>Manicina areolata</i> , and <i>Siderastrea siderea</i> ; <i>Pinna carnea</i>
Facies on Ambergris and other cayes		
Intra-caye lagoons	3 & 4	Sandy and slightly gravelly mud (facies 3) and muddy molluscan gravel (facies 4) with miliolids and soritids; <i>Chione</i> spp., <i>Anomalocardia</i> spp., various tellins, lucines and mussels; <i>M. melongena</i> , murex shells, various cerithids, batillarids and horn shells, <i>Fasciolaria tulipa</i>
Mangrove swamps	–	Peats with <i>Pseudocyrena floridana</i> , <i>Melongena melongena</i> , and various cerithids, batillarids and mangrove oysters (<i>Isognomon alatus</i>)
Tidal and sea-marginal flats	–	Mud, mainly slightly gravelly and sandy mud, and some muddy and slightly gravelly sand with biota as in facies 3 and 4 and as in mangrove swamps
Transitional outer to inner shelf	–	Buried on southern Ambergris Caye – mainly skeletal gravel with mixture of biota listed above in outer-shelf, intra-caye lagoon, mangrove swamp, and tidal- and sea-marginal flat facies
Mud mounds	5	Inner-shelf (Bulkhead Shoals) and transitional outer shelf–inner shelf (Cangrejo Shoals): dominantly mud, sandy mud, and muddy sand dominantly with soritids and miliolids and accessory <i>Chione</i> spp., various cerithids, tellins, <i>Thalassia</i>
Inner-shelf facies		
Muddy gravel	4	Muddy gravel dominantly with pelecypods and gastropods listed below in facies 7, and some miliolids and soritids
Miliolid facies	6	Dominantly mud with miliolids
Foraminiferan sand shoals & inter-shoal deposits	7	Dominantly soritids, accessory miliolids; pearl oysters (<i>Pinctada imbricata</i>), mussels (e.g. <i>Brachidontes</i> spp.), <i>Chione</i> spp., scallops and <i>Anomalocardia</i> spp.; <i>Bulla striata</i> , murex shells, <i>F. tulipa</i> , <i>M. melongena</i> and various cerithids and batillarids; various tellins and egg cockles
<i>Brachidontes</i> gravel	8	Muddy sand and gravel with abundant <i>Brachidontes</i> spp., soritids, and accessory biota as listed under facies 7
Muddy sand to sandy mud	9	Muddy sand to sandy mud dominantly with soritids, miliolids, accessory <i>M. melongena</i> , <i>Chione</i> spp., <i>Anomalocardia</i> spp. and fragments of thin-shelled pelecypods; and various cerithids and batillarids
Sandy mud	10	Sandy mud dominantly with peloids, miliolids and some soritids; ostracodes; and fragments of thin-shelled pelecypods
Mainland beach	11	Fine sand dominantly with miliolids and molluscs as listed in facies 9

¹In reference to numbered facies in Fig. 7B.

Some facies are not shown in Fig. 7B, and hence, are not numbered here.

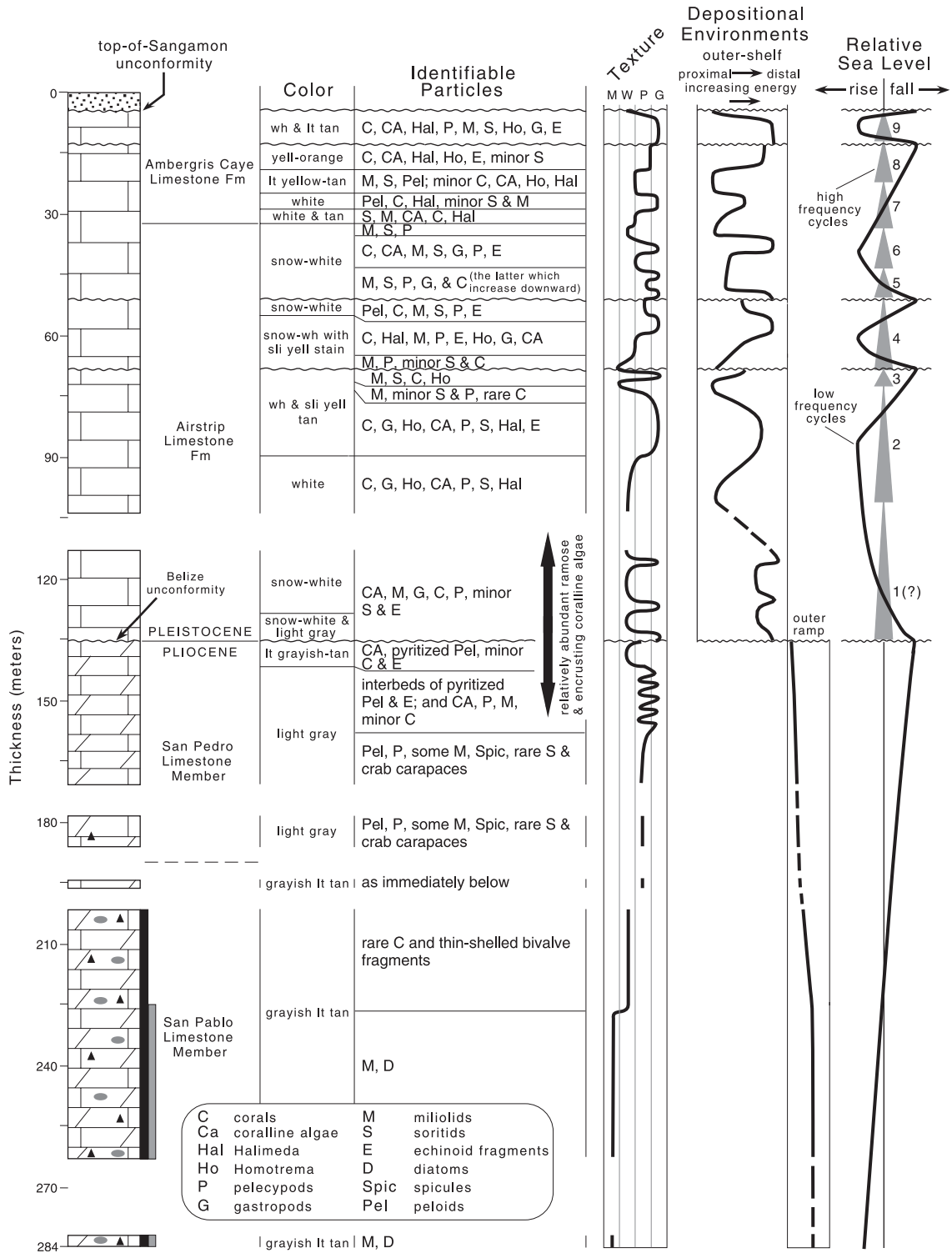


Fig. 4. Lithologic and biotic attributes of subsurface Pliocene and Pleistocene rocks in the Airstrip well (excluding surface exposures), and inferred unconformities, depositional environments, and hierarchal cycles; refer to Fig. 3 for lithologic legend. Particles are listed in order of decreasing abundance; and under 'Texture', M-W-P-G refers to mudstone, wackestone, packstone and grainstone, respectively. See Fig. 7A for continuation of sea-level cyclicality into the Holocene.

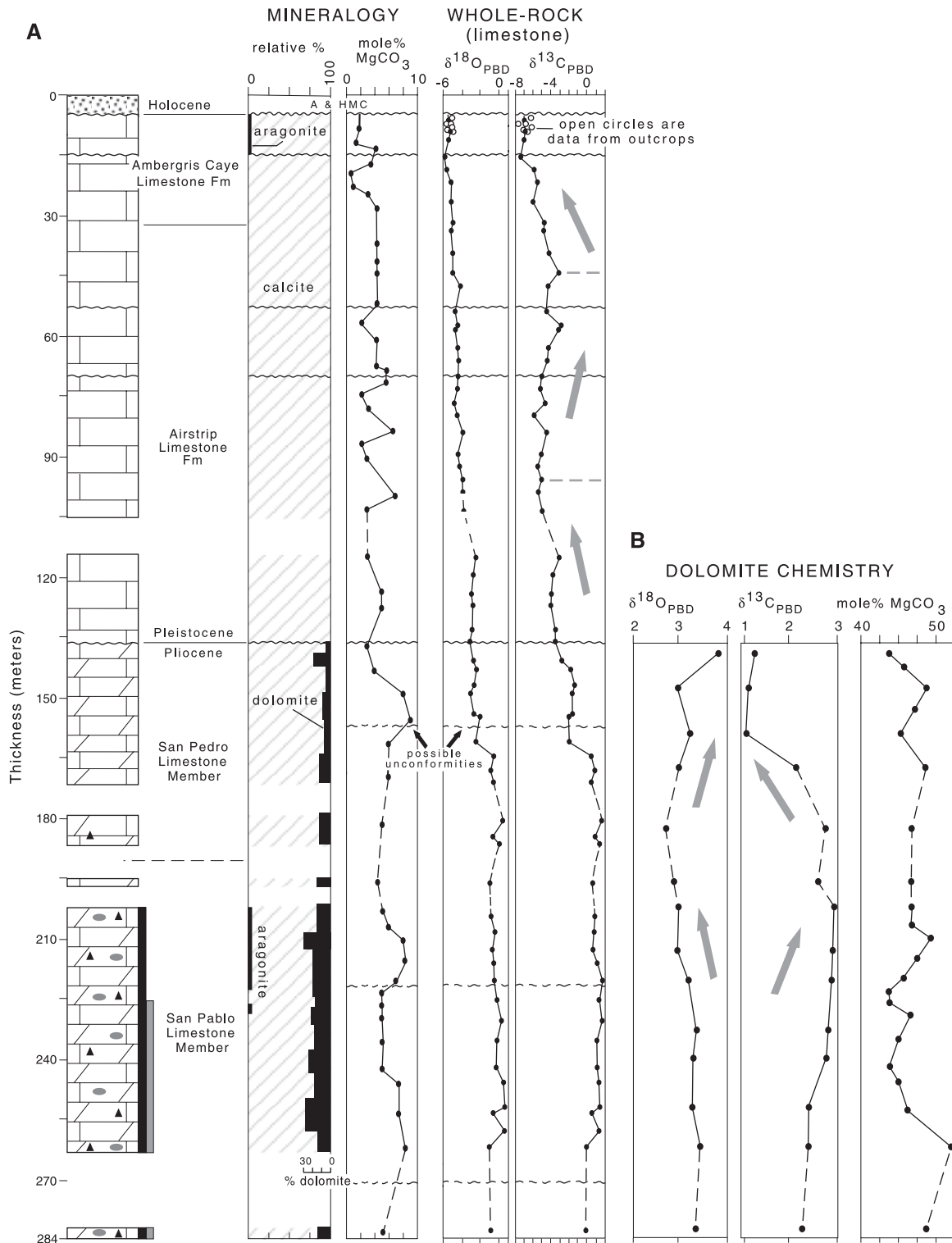


Fig. 5. (A) Mineralogy of subsurface limestones and dolomitic limestones, excluding Pleistocene outcrops (see Fig. 6B for those data); and whole-rock $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in the Airstrip well (black circles) and exposed Sangamon limestone (open circles). Short-term trends in ^{13}C values are indicated by arrows. (B) $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values and Mg concentrations in dolomite in Pliocene rocks. Short-term trends in isotopic composition are indicated by arrows.

may reflect the presence of such unconformities. The rarity, in the rocks, of petrographic features indicative of subaerial exposure, such as meniscus and whisker-crystal interparticle cements, reflects the fine-grained texture of the rocks.

With the exception of < 1% residual aragonite near the top of the San Pablo Member, upper Pliocene rocks are dominantly low-Mg calcite with minor high-Mg calcite (4–9 mol.% MgCO_3). As much as 30% replacive dolomite is present, the amount of which increases downwards in the section (Fig. 5A). Whole-rock $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values co-vary and show little significant variation below 165 m depth (mean values of 0‰ and +1‰, respectively). $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values decrease (–3.0‰ and –3.6‰, respectively) in overlying deposits to the top of the Pliocene. If there are additional unconformities in the Pliocene section, then their presence is not reflected in isotope values. The dolomite in the rocks is uniformly finely crystalline and calcic (43–49 mol.% MgCO_3), and only one generation can be discerned petrographically. Oxygen and carbon isotope values of dolomite separates range from +2.7 to +3.8‰ and +1.0 to +2.95‰, respectively. Oxygen isotope values decrease (from +3.3 to +2.7‰) from 284 to ca 180 m as carbon values correspondingly increase (from +2.3 to a maximum of +2.9‰). These trends reverse from 180 m to the top of the Pliocene, and $\delta^{18}\text{O}$ values increase to +3.8‰ whereas $\delta^{13}\text{C}$ values correspondingly decrease to 1.2‰ directly beneath the unconformity. There are no obvious correlations between dolomite stoichiometry and C and O isotopic values, amount of dolomite, or depth. However, dolomite stoichiometry roughly tracks the amount of MgCO_3 in associated limestones. Celestite is ubiquitous in the San Pablo Member, but not abundant volumetrically. It occurs as small nodules that replace matrix and particles, and rarely, as cement that occludes intraparticle pores.

Outer-shelf, reef-rimmed platform deposits of inferred Pleistocene age

Most of the Pleistocene rocks in the Airstrip well are interpreted to be of shallow-water origin and to include proximal (landward) to distal (basinward) outer-shelf and barrier reef-flat deposits. Specifically, the section from ca 27 m above the base of the Airstrip Formation to the top of the Ambergris Caye Formation (Fig. 4) consists of thick units (5–15 m) of coarse-grained packstones/grainstones with abundant corals, *Homotrema*, *Halimeda*, thick-shelled gastropods

and pelecypods, coralline algae, and accessory soritids, miliolids and echinoid fragments. These rocks are interbedded with generally thinner units (2–5 m) of wackestones/packstones with variable amounts of *Halimeda*, echinoderm fragments, some *Homotrema* and coralline algae, thick- and thin-shelled pelecypods and gastropods, relatively abundant miliolids, soritids and peloids, and generally only minor coral. They are interpreted as representing a mosaic of: (i) mostly aggradational but slightly basinward-prograding, medial outer-shelf sands and associated patch reefs; (ii) finer-grained sediments deposited in more proximal (leeward) outer-shelf locations; and (iii) just above the basal 27 m of the Airstrip Formation, probably some barrier reef-flat deposits on the distal part of the outer-shelf. Such a facies architecture is inferred in subsurface Quaternary platform strata in central Belize (Ferro *et al.*, 1999; Purdy *et al.*, 2003). The basal ca 27 m in the Airstrip Formation comprises fine-grained, relatively coral-poor wackestones with interbeds of packstones/grainstones with more abundant corals and accessory thick-shelled gastropods and pelecypods. These rocks may be either proximal fore-reef sediments or distal outer-shelf facies deposited at a time when a barrier reef had not yet been fully established. As in immediately underlying strata in the San Pedro Member, these rocks contain particularly abundant encrusting and ramose coralline algae.

The Pleistocene limestones in the Airstrip well are dominantly low-Mg calcite, with some high-Mg calcite that contains lower average Mg contents (0.5–7.0 mol.% MgCO_3) than calcites in subjacent Pliocene strata (Fig. 5A). Whole-rock $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are all negative and considerably lower than in most of the Pliocene limestones. Both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values define relatively long-term trends of decreasing values ($\delta^{18}\text{O}$ from –3.0 to –5.9‰ and $\delta^{13}\text{C}$ from –3.5 to –7.0‰, respectively) upwards to the top-of-Sangamon unconformity. There is no correlation, however, between $\delta^{18}\text{O}$ values and position relative to any of the unconformities in the section, and no marked excursions to more negative oxygen values. In detail, $\delta^{13}\text{C}$ values are more variable than $\delta^{18}\text{O}$ values and define shorter-term trends wherein values become more negative from the base of the Pleistocene to about 90 m depth (from –3.5 to –5.0‰), then increase to 45 m depth (to –3.8‰), and ultimately progressively more negatively (to –7.0‰) towards the top-of-Sangamon unconformity. A negative carbon isotope excursion,

from -5.8 to -7.0% , occurs in the top *ca* 10 m immediately beneath the unconformity.

Three additional unconformities are inferred in the Pleistocene succession below the top-of-Sangamon unconformity in the well (Figs 4 and 5A) based on: (i) an abrupt increase in the amount of coarse crystalline calcite spar in samples; (ii) the presence of brown, porous, unfossiliferous, laminated mudstone interpreted as soilstone crust (such a lithology is not common or readily recognizable); and (iii) abrupt appearance of strongly red and/or reddish yellow-stained limestone. Immediately below these unconformities, and below the top-of-Sangamon unconformity, are fairly marked decreases in mol.% MgCO_3 in limestones. There is no obvious covariance between mol.% MgCO_3 and pronounced negative stable isotope excursions (Fig. 5A). Hence, although similar decreases in MgCO_3 concentration are present in the section, additional unconformities were not inferred at those levels when the above-listed lithic criteria were absent.

Exposed Late Pleistocene (Sangamon) limestone

The lower half of the 4.7 m of limestone exposed on and around Ambergris Caye overlaps upper beds of the Ambergris Caye Formation in the Airstrip well, whereas the upper half of exposures supplements the section in the well (Fig. 3A). The characteristic lithologies and biota of inferred depositional environments in these Sangamon-age deposits are summarized in Table 3, and facies are illustrated in Fig. 6. These rocks represent a continuation of the depositional facies in the upper part of the Airstrip well in that they similarly define a marginal reef-rimmed platform. Barrier reef deposits are exposed at Reef Point on northern Ambergris Caye and on a dredge-spoil island along the modern barrier reef south-east of San Pedro Town (Fig. 6A). The exposures at Reef Point were previously considered to be outer-shelf patch reefs, although in the present paper and other studies (e.g. Tebbutt, 1975; Gischler & Hudson, 2004) they are considered to be barrier-reef facies based on their location (i.e. along the edge of the platform) and biota. These rocks include, for example, abundant *in situ* and dislodged *A. cervicornis*, *A. palmata* and *Agaricia* spp., and encrusting coralline algae and *Homotrema*. In contrast, Holocene outer-shelf patch reefs in the study area (Burke *et al.*, 1998), and Sangamon-age patch reefs exposed on Ambergris Caye (Table 3 and Fig. 6A), are dom-

inated by *M. annularis* and contain few to none of these other corals, only minor encrusting coralline algae, and generally no *Homotrema*. Maximum exposed thickness of the barrier reef facies at Reef Point is *ca* 0.6 m.

The thickness of the Sangamon barrier reef at the dredge-spoil island could not be determined. This originally 2.3 m high island was formed in the mid-1970s during dredging operations, and it was nearly completely eroded during Hurricane Mitch in 1998. It consisted of blocks of coral-rich limestone with *A. palmata*, *A. cervicornis*, *M. annularis*, *Diploria* spp., *Agaricia* spp., *Homotrema*, encrusting coralline algae, and other biota (in barrier reef and reef-flat facies, Table 3). Some blocks are Holocene based on their aragonitic and unaltered high-Mg calcite composition and presence of still-red *Homotrema rubrum*. Associated denser limestones with similar fossils, abundant pore-filling calcite cements and predominantly of low-Mg calcite composition that are similar lithologically and biotically to the rocks at Reef Point are considered to be Pleistocene (Sangamon). Accordingly, there appears to be vertical superposition of Sangamon and Holocene platform-marginal barrier reefs in the study area.

The outer-shelf during the Late Pleistocene was about twice as wide as today (see Figs 6A and 7B), and similarly included scattered coral patch reefs whose exposed areal dimensions vary from a few square decimetres to several hundred square metres; the maximum exposed thickness is *ca* 0.5 m. These patch reefs are typically surrounded by porous coralline sand as in Holocene deposits. To the immediate lee of the outer-shelf there was a fairly wide transition zone into a mollusc-dominated inner-shelf lagoon. Over most of northern and central Ambergris Caye, this transition zone was a shoal-water area with scattered bioclastic and/or superficial-oid shoals, beaches that adjoined small islands and/or tidal flats, and local areas of fine-grained miliolid sand deposited in sheltered areas (e.g. 'pocket beaches'). Maximum exposed thickness of these transition-zone deposits is 1–1.5 m. Other than this Sangamon-age shoal-barrier facies tract, there is no evidence for an exposed island-barrier like present-day Ambergris Caye. The transitional shoal-barrier tract area may have been located on a mostly submerged antecedent high, and in turn, it remained as the present topographically high bedrock foundation of Ambergris Caye after post-Sangamon subaerial exposure. Areal wide-spread foraminiferal sand shoals like those in the Holocene inner-shelf (Fig. 7B) are not identi-

Table 3. Characteristic lithology and biota of inferred depositional environments in Late Pleistocene (Sangamon) limestones exposed on and around Ambergris Caye (after Weed & Mazzullo, 2002).

Environment	Lithology	Common biota
Outer-shelf facies		
Barrier reef and reef-flat ¹	Gravelly packstone and grainstone	Mostly <i>in situ</i> reefs with <i>Acropora palmata</i> , <i>A. cervicornis</i> , <i>Montastrea annularis</i> , <i>M. cavernosa</i> , <i>Diploria</i> spp., <i>Agaricia</i> spp., <i>Porites</i> spp., <i>Dichocoenia stokesii</i> , <i>Strombus gigas</i> and other thick-shelled gastropods, lucine and tellins (including <i>Apolymetis</i> sp.), <i>Homotrema rubrum</i> , <i>Halimeda</i> , encrusting coralline algae, soritid and miliolid foraminifers. Reef-flat facies – dislodged corals as above, thickets of broken <i>A. cervicornis</i> , and abundant lucines and tellins (including <i>Macoma</i> sp.)
Patch reefs	Gravelly packstone and grainstone	Mostly <i>in situ</i> reefs with <i>M. annularis</i> , <i>Diploria</i> spp., <i>Porites</i> spp., <i>Halimeda</i> , rare to no <i>H. rubrum</i> and coralline algae; <i>S. gigas</i> and other thick-shelled gastropods, tellins and lucines (including <i>Apolymetis</i> sp.), echinoid debris, rare <i>A. cervicornis</i> and <i>Eusmilium fastigiata</i>
Outer-shelf sands	Locally gravelly packstone and grainstone	<i>Halimeda</i> -rich with accessory coral fragments, <i>Codakia</i> spp., tellins and lucines (including <i>Apolymetis</i> sp.), some <i>S. gigas</i> and other thick-shelled gastropods, <i>Marginella</i> spp., <i>Fasciolaria tulipa</i> , miliolid and soritid foraminifers
Transitional outer-shelf to inner-shelf facies		
Nearshore and beach	Gravelly packstone and grainstone	<i>Halimeda</i> , <i>Chione cancellata</i> , accessory <i>B. striata</i> , <i>Codakia</i> spp., <i>Arca</i> spp., lucines and tellins, coral fragments, tellins, superficial ooids, miliolid and soritid foraminifers; locally some tritons, <i>S. gigas</i> , <i>Marginella</i> spp., coralline algae
Islands/tidal flats	Wackestone to grainstone	As above, and relatively abundant cerithids and batillarids
Restricted shoals	Wackestone to grainstone	Abundant miliolids and some accessory grains as above
Inner-shelf facies		
Lagoon	Gravelly wackestone and packstone	<i>C. cancellata</i> , <i>B. striata</i> , <i>Melongena melongena</i> , cerithids, batillarids, some <i>Arca</i> spp., <i>Anomalocardia</i> spp., mussels, local murex shells

¹Present at Reef Point and the dredge-spoil island (location shown in Fig. 6A).

fied in the Sangamon limestones. The areal distribution of inferred Sangamon environments and facies tracts differs considerably from those described by Tebbutt (1975), whose study was based on a much smaller sample data set.

Post-depositional karsting (Purdy, 1974a; Purdy *et al.*, 2003) during *ca* 110 000 years of subaerial exposure from the Late Pleistocene (*ca* 115 000 cal yr BP according to the Shackleton, 1987 curve) into the Early Holocene sculpted the topography of the limestone bedrock on top of which Holocene sediments in the study area were deposited. In addition to sinkholes and caves, many of which are now submerged, surficial outcrop features along the top-of-Sangamon unconformity include rillenkarren, lapies, carbonate-cemented

breccias composed of blackened grains (*sensu* Shinn & Lidz, 1988), dissolution-enlarged root holes, and soilstone crusts. Mineralogically, although the limestones are dominantly low-Mg calcite with < 4 mol.% MgCO₃, they locally contain considerable amounts of higher-Mg calcite (5–16 mol.% MgCO₃). Furthermore, they contain much more aragonite than in subjacent Pleistocene strata (Fig. 6B). Whole-rock δ¹⁸O and δ¹³C values overlap those in correlative strata of the upper Ambergris Caye Formation in the Airstrip well (Fig. 5A). Diagenetic features are similar to those in Pleistocene rocks in the well, and include fabric and not fabric-selective dissolution pores, pore-filling calcite cements in interparticle and dissolution pores, meniscus cements, minor whisker

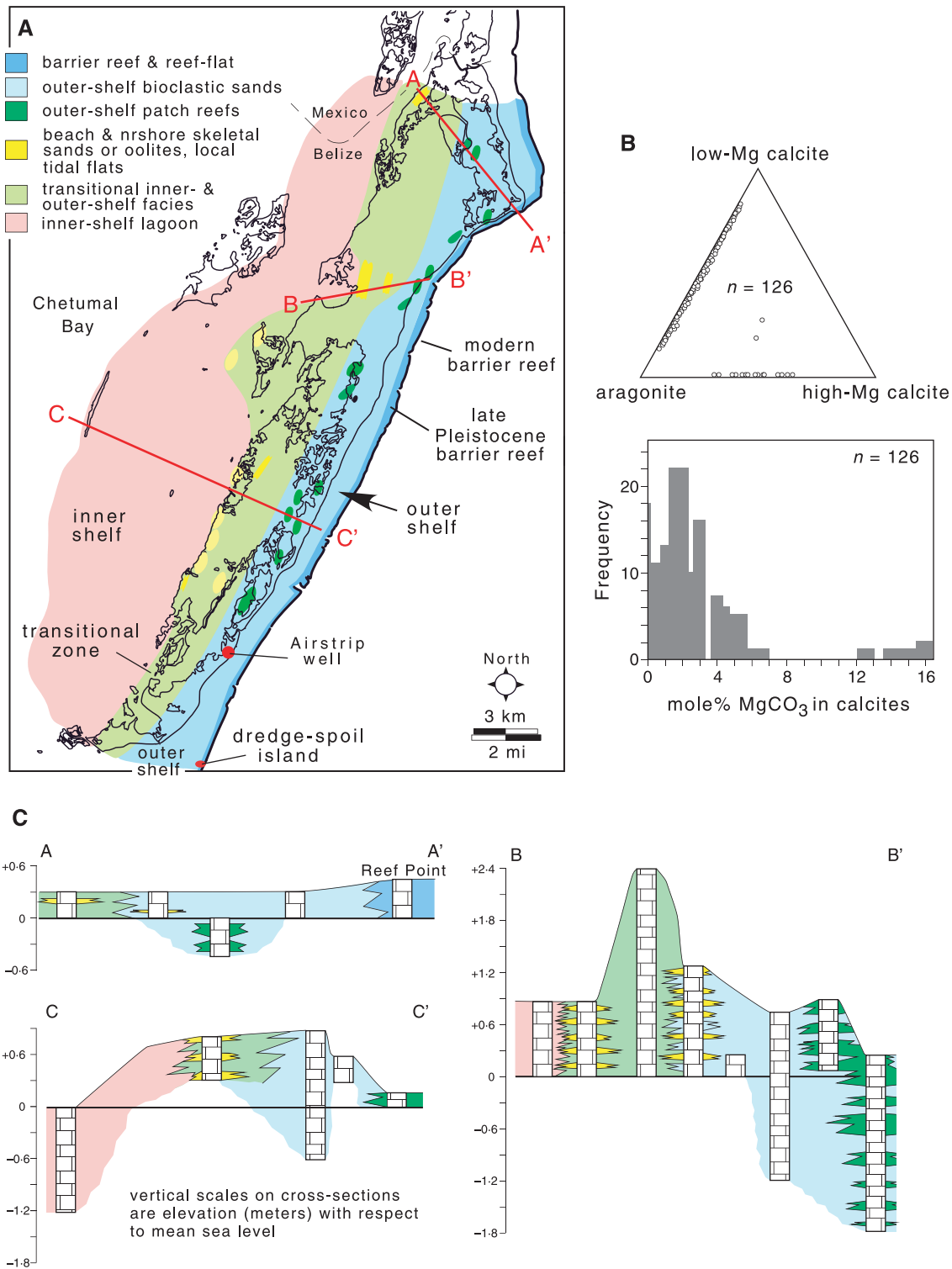


Fig. 6. (A) Inferred facies in Late Pleistocene–Sangamon (oxygen isotope stage 5e) limestones exposed in the study area (refer to Fig. 2 for details). Platform-margin barrier reef facies are exposed at Reef Point and at an artificial dredge-spoil island (now mostly eroded) SE of San Pedro Town. (B) Mineralogy and mol.% $MgCO_3$ contents in calcites in Sangamon limestones exposed on and around Ambergris Caye. (C) Cross sections illustrating stratigraphy and inferred environments compiled from outcrops and dredged or excavated samples.

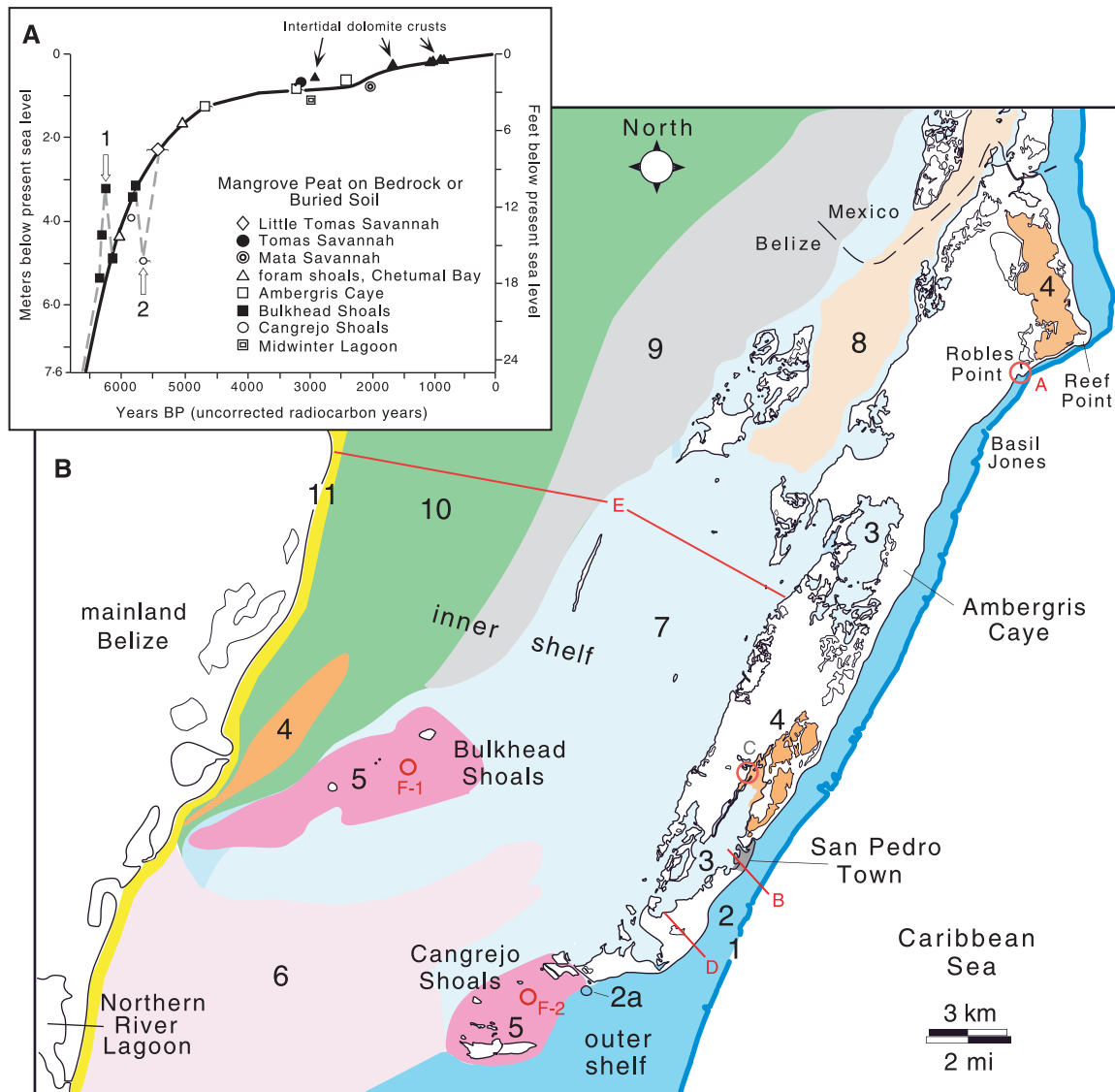


Fig. 7. (A) Holocene sea-level curve in study area based on radiocarbon ages. Arrows point to suspect age-dated peats: 1 – from -3.2 m in core BS-8 on Bulkhead Shoals, dated at 6320 ± 70 cal yr BP; 2 – from -4.9 m in core 7 on Cangrejo Shoals, dated at 5685 ± 230 cal yr BP. See Fig. 10A and B for stratigraphic context of these dated samples. Dashed line between 5500 and 6500 cal yr BP is an alternate sea-level curve discussed in the text. (B) Surficial Holocene inner- and outer-shelf facies around Ambergris Caye; beaches, tidal flats, and mangrove swamps cannot be shown at this scale (Mazzullo *et al.*, 1987, 2003; Teal *et al.*, 2000; Wilhite & Mazzullo, 2000; Yang *et al.*, 2004). Legend for numbered facies belts: 1 – barrier reef-flat, reef-crest, and upper fore-reef biolithite and associated sand and bioclastic gravel; 2 – outer-shelf corallgal sand and bioclastic gravel, scattered patch reefs, and beach sand along the eastern coast of Ambergris Caye; 2a – sponge ‘reef’; 3 – miliolid–soritid–*Chione* mud; 4 – muddy molluscan gravel; 5 – mud-mounds (see Mazzullo *et al.*, 2003); 6 – miliolid mud; 7 – locally gravelly, soritid–miliolid–*Chione* sand and mud; 8 – *Brachidontes*–foraminifer–molluscan muddy sand and bioclastic gravel; 9 – soritid–miliolid–molluscan muddy sand to sandy mud; 10 – peloid–miliolid–pelecypod–ostracod sandy mud; and 11 – miliolid–molluscan sand. Sample locations from which this facies map was compiled are shown in Fig. 2 inset. Letters A–F and associated red lines and circles correspond to the sections shown in Fig. 8.

calcite crystals, syntaxial low-Mg calcite overgrowths on echinoid fragments, calcitization of skeletal aragonite and rare marine aragonite cement, and partial replacement of some pelecypod fragments by microcrystalline quartz.

Holocene reef-rimmed platform facies

Surficial Holocene facies are shown in Fig. 7B and their characteristics are summarized in Table 2. The following section discusses only

the most salient aspects of Holocene deposition that are relevant to the evolution of the northern Belize platform. Holocene marine carbonate sedimentation began *ca* 6500 cal yr BP based mainly on radiocarbon dates of buried mangrove peats (Fig. 7A) that directly overlie either Sangamon limestone or buried soil atop this limestone (Fig. 8).

Outer-shelf facies

The outer-shelf seawards of Ambergris Caye is narrow, and maximum water depth is 3 m. The barrier reef (facies 1) has not been the focus of previous sedimentologic studies (e.g. Mazzullo *et al.*, 1992; Burke *et al.*, 1998), and relative to the barrier in central and southern Belize it has received little attention (Miller & MacIntyre, 1977; James & Ginsburg, 1979; Burke, 1982; Perkins & Carr, 1985). Coralgal sand and gravelly sand (facies 2) overlie limestone bedrock on the outer shelf, and sediments coarsen to dominantly sandy, coral-fragment gravel towards the barrier reef. Sediments are generally thin (0.5 m), and commonly thicken landwards (Fig. 8A, B and D). This thickness trend reflects bedrock topography and dominant on-platform sediment transport caused by prevailing onshore, north-east trade winds. *M. annularis*-dominated patch reefs included within facies 2 are present locally, especially north of the latitude of San Pedro Town. They attain a maximum thickness of 2.4 m (Mazzullo *et al.*, 1992; Burke *et al.*, 1998). An area that contains relatively abundant loggerhead (*Ircinia campana*) and other sponges is present at the southern tip of Ambergris Caye (Fig. 7B). Associated biota include various non-framebuilding corals, ramose red and green algae, and thick-shelled gastropods (facies 2a: Table 2). Similar spongal deposits were not identified in exposed Pleistocene rocks.

At Robles Point and just north of Basil Jones (localities shown in Fig. 7B), and other localities along the eastern coast of northern Ambergris Caye, coralgal beach sands comprising storm washover, landward-dipping berm and seaward-dipping shoreface sub-facies are thin (1–2 m) where bedrock is close to the surface. A prominent 4 m high ridge comprising boulder-size coral-gastropod rubble overlying gravelly coralgal beach sand is present at Robles Point (Fig. 8A). These storm deposits, which had been modified and/or added to during Hurricanes Mitch and Keith in 1998 and 2000, respectively, trend north-eastward along the shore nearly to Reef Point, where they thin out.

Bedrock is considerably deeper along the seaward coast of Ambergris Caye south of Basil Jones, and accordingly, thickness of coralgal beach sands and component sub-facies is greater – usually 4–4.5 m (Fig. 8B and D). Locally, beach sands are muddy and relatively organic-rich where they are, or recently were, present in heavily *Thalassia*- and/or mangrove-colonized areas. Beach accretion is evident at several places along the seaward coast of Ambergris Caye. Radiocarbon dating of buried, unaltered *Strombus gigas* shells in northern San Pedro Town, for example, indicates accretionary deposition of 1.2 m of sand and *ca* 30 m of corresponding shoreline advance in the last 750 years (Fig. 8B, inset 1). At several localities south of San Pedro Town, as much as 40 m of shoreline advance in the last *ca* 500–750 years is indicated by the presence of Maya Late Classic conch middens that originally accumulated along a beach but which now are 40 m behind the modern beach (Fig. 8B, inset 2). Depending on location, beach sands either pinch-out against exposed limestone on the caye or they pass landwards variously into organic-rich swamp deposits of red mangrove (*Rhizophora mangle*) peat and/or peaty carbonate mud, or intra-island lagoonal facies 3 and 4 (Figs 7B, 8A and B), described below.

Facies on Ambergris and other cayes

In addition to seaward-facing beach sands, a variety of other environments are present on Ambergris and surrounding cayes, but they are not shown in Fig. 7B because of the limited scale. Intra-caye lagoonal deposits, for example, include mangrove swamp peats and/or dominantly foraminiferal (miliolids and soritids)–*Chione* (pelecypod) sandy and slightly gravelly mud (facies 3) and muddy mollusc gravel (facies 4). Such sediments usually average 1.2 m in thickness. Sea-marginal flats adjoining intra-caye lagoons, including tidal flats, are present locally. Sediments are typically are ≤ 1 m thick, component particles are dominated by molluscs and soritid foraminifers, and textures include some mud, mainly slightly gravelly and sandy mud and some muddy and slightly gravelly sand; all such sediments are derived from adjoining shallow lagoons (Fig. 8C). Microbial laminites produced by *Scytonema* or *Schizothrix*, desiccation cracks, flat-pebble mud clasts, root holes, and fenestrae are common in the upper parts of many such deposits, which locally contain abundant syndepositional dolomite (Mazzullo *et al.*, 1987; Gregg *et al.*, 1992; Mazzullo, 2000). Narrow beaches composed dom-

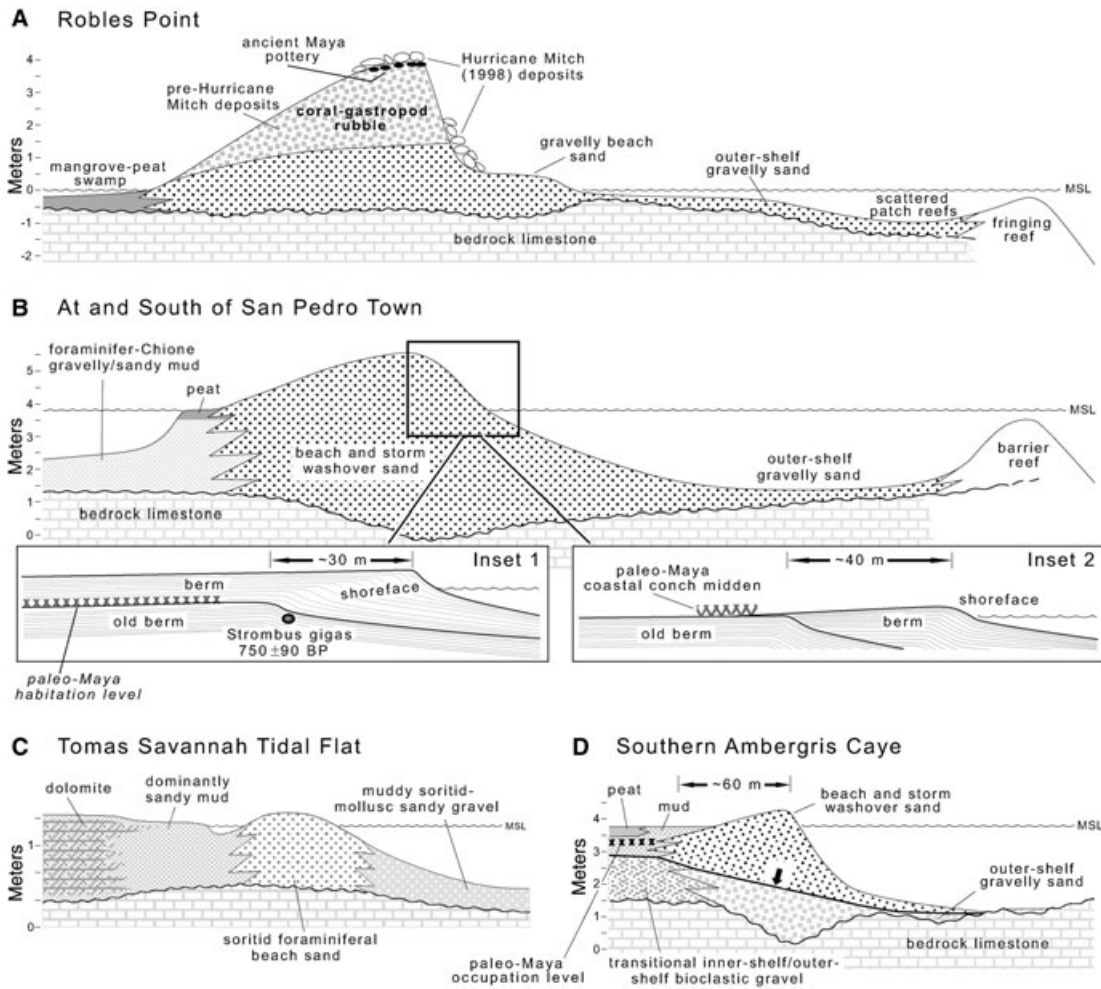


Fig. 8. Holocene facies; vertical scale exaggerated. (A) Coarse-grained offshore and beach deposits at Robles Point. Maximum 4 m-high ridge along shore capped by storm rubble. The barrier reef becomes a fringing reef here. Note palaeo-Maya artifacts. (B) Typical offshore and thick beach deposits at and south of the latitude of San Pedro Town. Inset 1 illustrates beach accretion and progradation in the last 750 years, concurrent with palaeo-Maya habitation, in northern San Pedro Town. Youngest beach sediments are 1.2 m thick. Inset 2 illustrates beach accretion associated with Maya Late Classic conch middens that originally accumulated along an older beach at a locality south of San Pedro Town. (C) Dolomitized tidal flat deposits adjoining foraminifer sand beach and intra-island gravelly bioclastic lagoonal sediments. (D) Deposition of earliest Holocene, transitional outer-shelf–inner-shelf deposits on southern Ambergris Caye was terminated, at the horizon indicated by the arrow, by accretion of beach ridge *ca* 500–750 years ago, resulting in shallowing-upward deposition of swamp peat deposits behind the beach. (E) Facies transect in inner-shelf, from back-side of Ambergris Caye to the Belize mainland. (F-1 and F-2) Carbonate sediments and associated deposits at the Bulkhead and Cangrejo Shoals mud mounds.

inantly of soritid foraminifer sand are present locally along the margins of flats adjoining shallow lagoons. Local beaches along the back side of Ambergris Caye (Fig. 8E) are composed of ≤ 1 m of coarse-grained mollusc- and soritid foraminifer-dominated sandy bioclastic gravel.

Buried Holocene sediments in swampy areas on the southern part of interior Ambergris Caye to the immediate lee of the outer-shelf beach ridge typically are 2.0–2.4 m thick. They comprise a shallowing-upward section of very coarse, mollusc-dominated skeletal gravel, with mixed inner-

shelf and outer-shelf biota (Table 2), that is capped by *Rhizophora* mangrove peat (Fig. 8D). This transitional facies tract, which is not present in surficial Holocene deposits, existed until deposition of beach sand along the seaward coast of southern Ambergris Caye isolated the inner- and outer-shelf areas about 500–1000 years ago (Dunn & Mazzullo, 1993).

Inner-shelf facies

North-east-trending soritid foraminifer sand shoals (water depth 0–1 m) and adjoining deeper

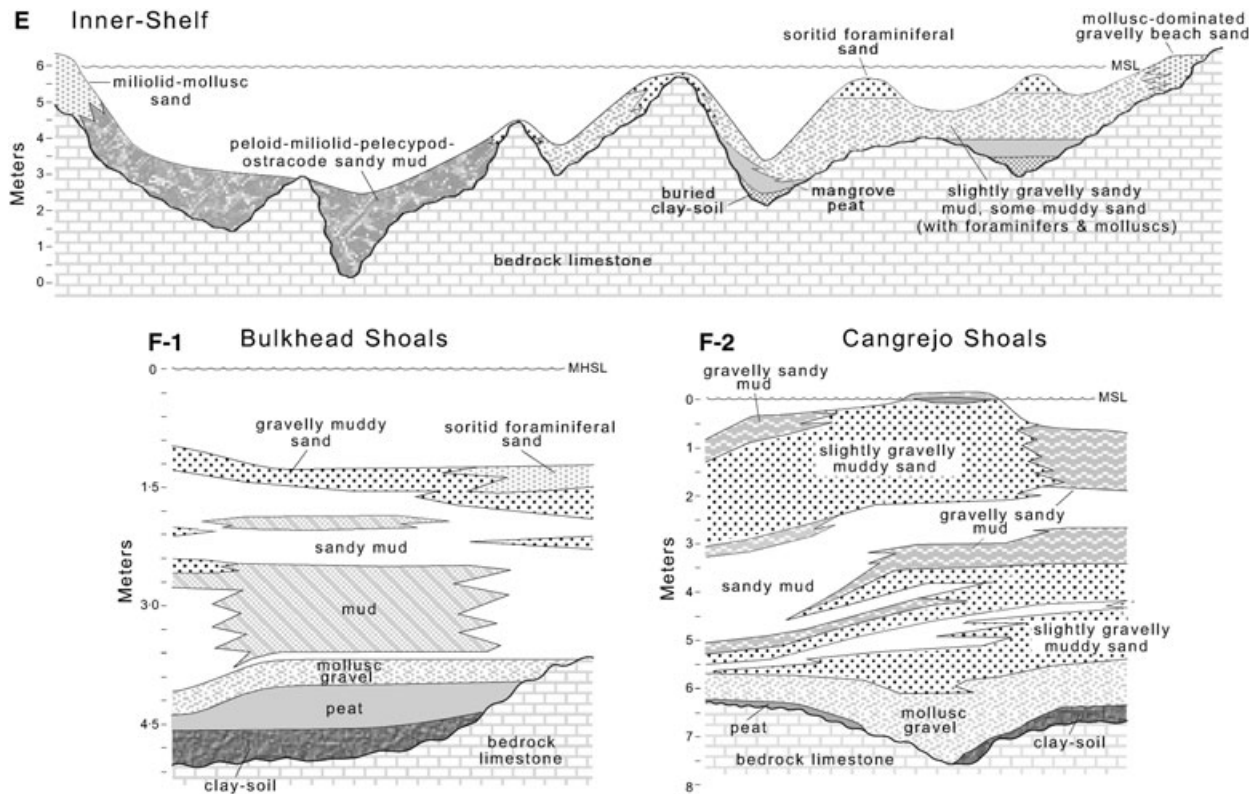


Fig. 8. Continued

water (maximum 1.8 m) areas of organic-rich, soritid–miliolid–molluscan sandy/gravelly mud and gravelly sandy mud are present behind Ambergris Caye in the eastern part of the inner shelf (Fig. 8E). These sediments (facies 7: Fig. 7B) variously overlie limestone bedrock, buried clay-soil (of post-Sangamon but pre-6500 cal yr BP age: Mazzullo *et al.*, 2003), and/or Holocene mangrove peat. Maximum ^{14}C ages of underlying mangrove peats are 6000 cal yr BP in the south and 5000 cal yr BP in the north (Wilhite & Mazzullo, 2000), and reflect northward marine transgression during the Holocene. As sea level reached close to the present stand a few thousand years ago (Fig. 7A), Holocene carbonate facies mainly have prograded to the south–south-west under the influence of dominant north-east trade winds and northers (Yang *et al.*, 2004). Thickness of carbonate sediments varies from a few centimetres on bedrock highs to a maximum of *ca* 3 m elsewhere. The foraminiferal shoal area passes north-east into water 1.2–1.8 m deep, where bedrock is locally mantled by only a thin veneer (a few centimetres) of *Brachidontes*–foraminiferan–molluscan muddy sand and bioclastic gravel (facies 8). Sediments pass progressively westwards within the inner shelf (Fig. 8E) from foraminiferal–molluscan muddy sand and sandy mud

(facies 9: *ca* 0.6 m thick), to relatively deep-water (maximum depth 4.5 m) peloid–miliolid–pelecypod–ostracod mud and sandy mud (facies 10: 0–2.4 m thick). Narrow beach sands locally are present along the mainland coast and comprise fine-grained, miliolid foraminifer and mollusc-dominated sand (facies 11: maximum 1.2 m thick). Towards the south, inner-shelf facies are generally < 1 m of miliolid mud (facies 6) deposited in water depths of 6.0–7.6 m.

Mud-mound facies

The lithology, biota and stratigraphic architecture of surficial (facies 5) and buried Holocene sediments comprising the Cangrejo and Bulkhead Shoals mud mounds were recently described by Teal *et al.* (2000), Mazzullo *et al.* (2003) and Yang *et al.* (2004). These mud mounds encompass areas of 20 and 35 km², respectively, along the outer-shelf to inner-shelf transition (Cangrejo) and within the inner-shelf (Bulkhead). Buried clay soils of post-Sangamon but pre-6500 cal yr BP age locally overlie deeply submerged Pleistocene limestone in these areas, and in turn, they are overlain locally by Holocene mangrove peat (Fig. 8F-1 and F-2). Overlying carbonate sediments on the mud mounds are believed to be mainly storm deposits (Mazzullo *et al.*, 2003).

They are organic-rich, mud-dominated, and contain relatively abundant syndepositional dolomite (Teal *et al.*, 2000; Dimmick-Wells, 2002). Maximum thickness of Holocene deposits at Cangrejo and Bulkhead mud mounds is 7.6 and 4.5 m, respectively. Approximately 1 m or less of coarse-grained, muddy molluscan gravel (facies 4) atop bedrock is present to the immediate west of Bulkhead Shoals, where water depth is 2 m (Fig. 7B).

DISCUSSION

Late Pliocene-to-Holocene facies architecture

Samples from the Airstrip well are critical in that they link subsurface and outcrop sections and allow extension of the history of carbonate platform evolution in northern Belize into the Late Pliocene. In contrast, previous studies of platform development in central and southern Belize focused primarily on seismic study of the Late Pleistocene and Holocene deposits (Choi, 1981; Choi & Ginsburg, 1982; Choi & Holmes, 1982; Westphall, 1986; Esker *et al.*, 1998; Ferro *et al.*, 1999). Based on depositional environments inferred from the present study, the northern shelf changed abruptly from a shallowing-upward ramp during the Late Pliocene to a coral reef-rimmed platform in the Pleistocene and Holocene (Fig. 9A). A similar history is suggested farther to the south, at least locally, based on seismic study (Fig. 9C). This seismic section shows Pliocene strata in the upper part of the Belize Formation, including unconformity-capped upper Pliocene beds, correlative to the San Pablo and San Pedro Limestones in the Airstrip well. The inference is that these rocks represent a ramp rather than a rimmed platform. Purdy (1974a,b) reported shaly limestone in subsurface Miocene and Pliocene rocks in central to southern Belize that may be counterparts of the silty, shaly lime mudstone/wackestone ramp deposits comprising the San Pablo Limestone in the Airstrip well (Fig. 4).

In the study area and perhaps elsewhere in Belize, the change from an unconformity-capped ramp to a rimmed platform may have been largely structurally controlled insofar as: (i) the seaward edge of the platform is fault-bounded (e.g. Purdy *et al.*, 2003); and (ii) Late Neogene to Recent tectonic activity is documented in offshore Belize (Dillon & Vedder, 1973; Mazzullo & Bischoff, 1992; Lara, 1993; Ferro *et al.*, 1999; Purdy *et al.*, 2003). Among other possibilities, it is reasonable

to suggest that movement along that fault system during the latest Pliocene and Early Pleistocene may have established a structural hinge along which Early Pleistocene barrier reef growth was focused and a rimmed platform initially developed (Fig. 9A). Once formed, this platform may have steepened over time as a result of a combination of processes such as: (i) karst accentuation of the platform-to-basin profile during sea-level lowstands (e.g. Purdy, 1974b); (ii) renewed reef growth along the platform edge during highstands; and (iii) differential subsidence between the platform and adjoining basin. Such processes also are believed to have exerted control on the deposition of Holocene platform carbonates and the barrier reef in central and southern Belize (Choi, 1981; Choi & Ginsburg, 1982; Choi & Holmes, 1982; Westphall, 1986; Lara, 1993; Esker *et al.*, 1998; Purdy, 1998; Ferro *et al.*, 1999; Purdy *et al.*, 2003). A shallow, flat-topped platform behind the barrier reef in the study area probably was maintained because of relatively low magnitudes of accommodation-space increase during highstands as are typical of icehouse states (Read *et al.*, 1995), coupled with relatively low rates of platform subsidence. Yet, rates of subsidence were substantially high enough that platform and platform-marginal reef growth during the Pleistocene and Holocene mainly were aggradational, with only a minor component of basinward progradation (Fig. 9A). Aggradation is also suggested locally in central Belize (e.g. Fig. 9C), but farther south, progradation occurred instead (Esker *et al.*, 1998; Ferro *et al.*, 1999). Pleistocene and Early Holocene siliciclastics are present in central to southern Belize, where subsidence rates were higher than to the north (Gischler & Hudson, 2004). Whether the 'shingled' model of platform-margin accretion suggested by James & Ginsburg (1979) for post-Sangamon highstand deposits (Fig. 9B) is also applicable in the present study area cannot be evaluated based on currently available data.

If one assumes a Late Pliocene duration of 1.35 Myr (the average age of Pliocene N20 biozone of Bolli & Saunders, 1985) and the beginning of the Pleistocene at 1.65 Ma, then the sediment accumulation rate of the 150 m of ramp deposits in the Airstrip well might have been as much as 110 m Myr⁻¹. Likewise, assuming Pleistocene rocks older than Sangamon age are present in this well and that the top-of-Sangamon unconformity formed *ca* 125 ka, then the duration of Pleistocene rimmed-platform deposition here was 1.5 Myr. If so, then the sediment accumulation

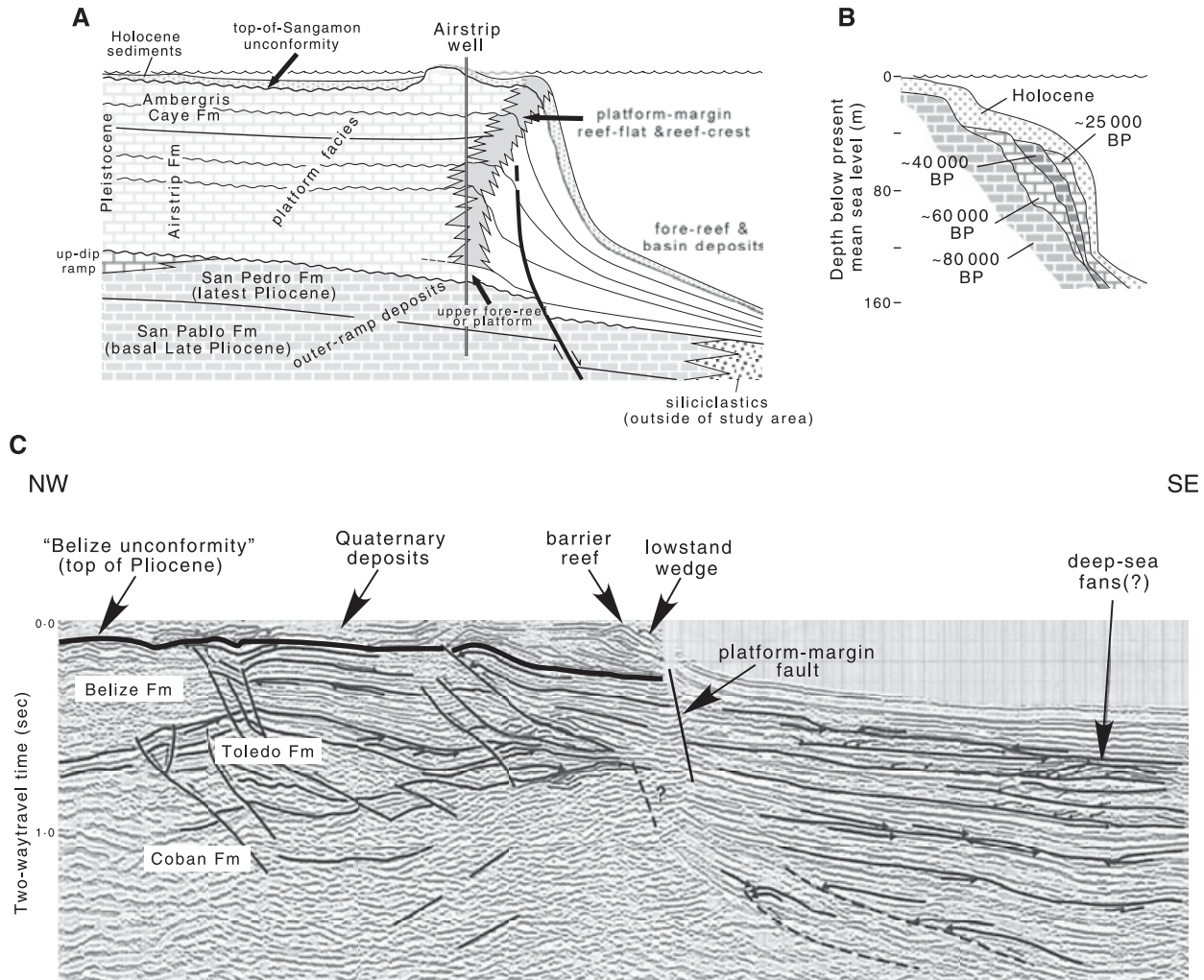


Fig. 9. (A) Depositional evolution in study area. The platform section in the Airstrip well (Fig. 4) includes inferred proximal to distal outer-shelf and barrier reef-flat deposits, whereas limestone exposures include both outer- and inner-shelf deposits, depending on location. Renewed faulting in the latest Pliocene to Early Pleistocene created a structurally defined platform margin along which Pleistocene barrier-reef growth was focused. Miocene and younger distal fore-platform deposits to the south-south-east of the study area include siliciclastics (Case *et al.*, 1984). (B) Shingled model of Belize platform-margin accretion in the last 80 000 years (after James & Ginsburg, 1979). Lithologic units denoted by time are those presumably deposited during sea-level highstands since the Sangamon. (C) Seismic section APE 84-08, which is the closest such data to the study area (see Fig. 1). Section and interpretations from Purdy *et al.* (2003) after Ferro *et al.* (1999). Note the slightly progradational Quaternary reef-rimmed platform margins, and absence of obvious reef-rimmed platforms in subjacent Pliocene strata in the upper part of the Belize Formation.

rate was about 87 m Myr^{-1} , which is an order of magnitude less than that of the upper Pliocene ramp deposits. Platform sedimentation rates, however, typically are greater than those on deeper-water ramps (Schlager, 1992). The seemingly anomalous Pleistocene rate may suggest that not all of the Pleistocene is in fact present in the Airstrip well, and/or that the total amount of time represented by unconformities here is substantial. Regardless, these rates are less than the range of short-term (10^2 – 10^5 years) rates reported in the

Caribbean and elsewhere (Schlager, 1992, 1999), which suggests the relatively limited amount of subsidence and accommodation space increase that occurred in the study area since the Late Pliocene.

Pleistocene cyclicality

The sea-level drop and top-of-Pliocene unconformity inferred in the Airstrip well (Figs 3 and 4) are also recognized in central and southern Belize

(Choi & Ginsburg, 1982; Choi & Holmes, 1982; Esker *et al.*, 1998; Ferro *et al.*, 1999; Purdy *et al.*, 2003) and elsewhere in the world (e.g. Haq *et al.*, 1988) suggesting that they record a glacio-eustatic lowstand. Above the top-of-Pliocene unconformity, the Pleistocene section in the study area comprises four recognizable, relatively low-frequency cycles punctuated by unconformities, including the top-of-Sangamon unconformity (Figs 4 and 9A). These cycles, interpreted as depositional sequences, almost certainly are also of glacio-eustatic origin. Choi & Holmes (1982) and Ferro *et al.* (1999) likewise identified four and five unconformity-bounded seismic sequences in subsurface Pleistocene strata in southern and central Belize, respectively. In contrast, Esker *et al.* (1998) identified 11 such sequences in subsurface Pleistocene strata in southern Belize. Specific correlation of the sequences identified by these workers to those in the study area is not possible.

At least nine component higher-frequency, subtidal cycles are recognized in the Pleistocene section in the Airstrip well (Fig. 4), which probably include autocycles and eustatically forced cycles; such cycles and unconformities could not be resolved in the Pliocene beds. The cycles include: (i) those that shallow and fine upwards (1, 2, 6, 7 and 9) from coarse-grained, relatively coral-rich rocks (medial to distal outer-shelf) to fine-grained rocks (somewhat protected, near-shore outer-shelf); (2) cycle 5, which shallows upwards from coral-rich to carbonate sand-rich; and (3) those punctuated by unconformities (3, 4 and 8). The study area was far from the mainland during the Pleistocene. Hence, these cycles probably represent local shallowing-upward deposition of scattered patch reef-cored or carbonate sand-cored islands in an outer-shelf setting rather than prograding coastal deposits. Reduction in thickness of cycles 1 to 9 reflects a decreasing rate of accommodation space as the location of the Airstrip well shallowed in the Early Pleistocene (Fig. 9A).

Holocene sedimentation and tectonics

Some movement along faults that involve Sangamon-age limestone appears to have affected Holocene marine deposition in the study area as it has elsewhere in offshore Belize (Purdy *et al.*, 2003). Evidence for such includes the two buried, radiocarbon-dated peats directly overlying Pleistocene limestone at localities BS-8 at Bulkhead Shoals and 7 at Cangrejo Shoals

(locations denoted by arrows in Fig. 7A). These dates are anomalous relative to their depth in that at 3.2 m and 4.9 m below MSL, the peats should be younger than their determined ages of 6320 ± 70 and 5685 ± 230 cal yr BP, respectively. Assuming these ages are accurate, they could be interpreted as suggesting rapidly fluctuating sea level from between *ca* 6500 to 5500 cal yr BP (dashed line in Fig. 7A). Although Late Pleistocene to Holocene centennial-scale fluctuations have been suggested elsewhere in the world (e.g. Locker *et al.*, 1996; Neumann & Hearty, 1996; Baker & Haworth, 2000a,b), they have not been identified on other Belize sea-level curves (e.g. Ferro *et al.*, 1999; Gischler & Hudson, 2004). An alternative explanation is that there has been some Holocene, post-depositional movement along faults at these localities, with cores BS-8 and 7 being on the up-thrown sides of normal faults. If so, then the maximum amount of throw along the faults is as much as 2 m (Fig. 10A and B). It is possible that these two areas are located along a single fault system that trends north-west-south-east across southern Chetumal Bay and which may be the extension of a fault offshore of southern Ambergris Caye (Fig. 10C). Periodic discharge of meteoric fluid along a postulated arcuate fault that trends northeast from Blackadore Caye to southern Deer Caye in Chetumal Bay (Fig. 10C) has resulted in nearly pervasive alteration to low-Mg calcite of Holocene sediments of original high-Mg calcite composition (Mazzullo & Bischoff, 1992). Whether there has been movement along that fault during the Holocene, however, is not known.

The bedrock topography of much of Ambergris Caye south of the latitude of Basil Jones, and in surrounding offshore areas, is a series of north-east-trending ridges and swales (Figs 10D and 11A). The highest linear ridge on Ambergris Caye is *ca* 1.8 m above sea level. Exposed bedrock to the north is more or less uniformly high, and distinct ridges and swales are not readily obvious. The easternmost linear bedrock swale along the seaward coast of Ambergris Caye (Fig. 8B and D) is a maximum of 4.3 m below MSL. It extends nearly uninterruptedly in a south-west direction, and is the terminus of a west-sloping topographic surface on the Sangamon limestone. The eastern side of this surface is a known fault that defines a raised rim (*sensu* Purdy, 1974a,b) on which the Holocene barrier reef has developed (Fig. 11B). A ridge of bedrock limestone close to and/or exposed above sea level is present to the immediate

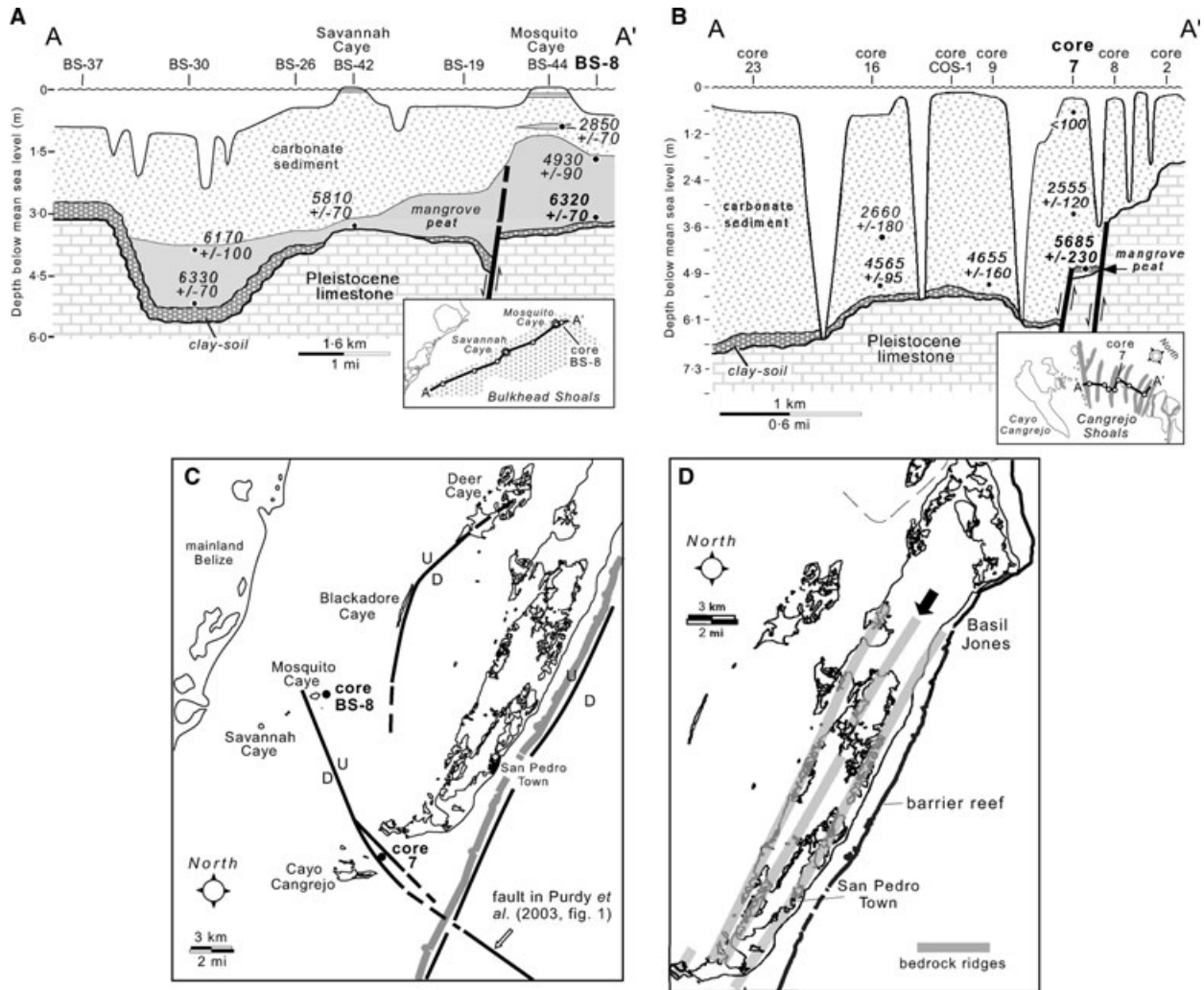


Fig. 10. (A, B) Stratigraphy, radiometric dates, and inferred Holocene faulting around core localities BS-8 on Bulkhead Shoals and 7 on Cangrejo Shoals (after Mazzullo *et al.*, 2003). (C) Some inferred post-Sangamon faults (bold black lines) in study area. The southernmost fault may be the landward extension of an offshore fault shown in Purdy *et al.* (2003). See fault along seaward side of Ambergris Caye in Fig. 12A. (D) Prominent bedrock ridges on Ambergris Caye, the highest of which is denoted by an arrow. Except for north of Basil Jones and locally along the central-eastern part of the caye, the easternmost ridge is mostly below sea level and buried beneath Holocene sediment.

west of the swale (Fig. 10D), and is separated from it by a low scarp. Similar topographic configurations are present elsewhere in the study area (Fig. 11A). The uniform westward slope of the bedrock surface between such ridges, the presence of a fault along the seaward side of the barrier reef (Fig. 9A and C), and the existence of inferred faults in Chetumal Bay (Fig. 10C) suggest that the bedrock foundation of the study area comprises slightly tilted fault blocks (Fig. 12A). Such an interpretation is consistent with the transtensional rifted-margin setting of the area (e.g. Dillon & Vedder, 1973; Bishop, 1980; Lara, 1993), and is similar to the structural fabric farther south in

Belize (e.g. fig. 1 in Purdy *et al.*, 2003). Purdy (1974a,b) rightfully considered that the top-of-Pleistocene topography in northern Belize resulted largely from post-Sangamon karsting, but he also recognized the possible structural origin of bedrock ridges on Ambergris Caye. Structure, be it related to faults and/or fractures, has clearly influenced karsting and subsequent Holocene deposition in the study area by controlling the locations of the Pleistocene and Holocene barrier reefs, the location and thickness of inner-shelf deposits (Fig. 8E), and the distribution of corallgal beach and marine sands on the outer shelf (Fig. 8A, B and D).

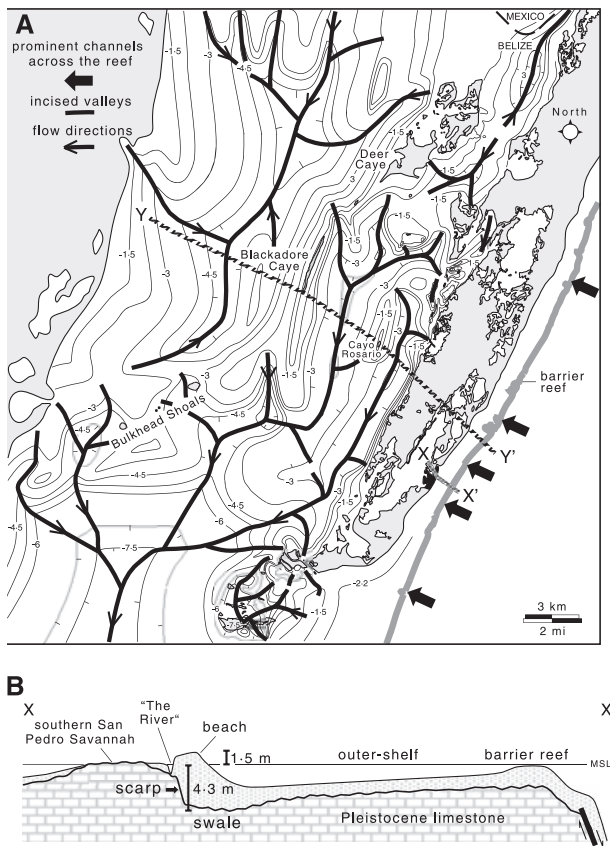


Fig. 11. (A) Depth to top of karsted Pleistocene limestone below mean sea level, topographic ridges, and post-Sangamon–pre-6500 cal yr BP exposure incised valleys; contour interval 0.75 m. The many small sinkholes present in this area are not shown. Western Chetumal Bay was an area of internal drainage. Some of the deeper channels that cut the Holocene and Pleistocene barrier reefs are indicated by bold arrows. Not shown are incised stream valleys parallel to bedrock ridges on Ambergris Caye (Fig. 10D) that flowed to the southwest. (B) Section illustrating typical bedrock topography and sediment thickness across the outer shelf to Ambergris Caye. The conspicuous furrow beneath the seaward beach may be a fault as shown in Fig. 12A.

Pleistocene to Holocene highstand–lowstand facies and incised valleys

Alternating periods of highstand carbonate and lowstand valley incision and associated fluvial siliciclastic deposition are suggested for subsurface upper Pleistocene to Holocene deposits in central and southern Belize (Choi, 1981; Choi & Ginsburg, 1982; Choi & Holmes, 1982; Esker *et al.*, 1998; Ferro *et al.*, 1999). Despite a similar history of sea-level fluctuations, there are essentially no siliciclastics in upper Pliocene and Pleistocene rocks (Figs 4 and 5 and Table 3) or

in Holocene sediments (Table 2) in the study area. Minor detrital quartz and biotite in Pliocene limestone in the Airstrip well (Figs 3 and 4), and <1% quartz silt in Holocene sediments (Teal *et al.*, 2000; Wilhite, 2000; Dimmick-Wells, 2002), represent the only siliciclastic influx into the area. The closest siliciclastics are present along the mainland coast to the southwest, in and around Midwinter Lagoon and Northern River Lagoon (Fig. 1) (High, 1975; Burke *et al.*, 1992; Lowe, 1995; Lowe & Mazzullo, 1995; Purdy *et al.*, 2003). The paucity of siliciclastics in the study area reflects: (i) distance from the Maya Mountains source; and (ii) since at least the Pliocene, regional drainage from the mountains has been mostly to the east–south-east, rather than towards the study area. This is probably a result of progressive subsidence and tilting of the Belize platform to the south since at least the Pleistocene (e.g. Ferro *et al.*, 1999). The lateral change from carbonate deposition to mixed carbonate-siliciclastic deposition is a common pattern in the stratigraphic record (e.g. Doyle & Roberts, 1988; Budd & Harris, 1990; and Lomando & Harris, 1991). Because of the absence of siliciclastics, the stratigraphic architecture in northern Belize instead comprises superimposed couplets of highstand carbonates and lowstand unconformities.

In addition to dolines, caves and caverns, limestone karsting in the study area resulted in conspicuous incised valleys along the top-of-Sangamon unconformity (Fig. 11A). Similar valleys may be present along older unconformities here, but they are not readily recognizable. Structural control on valley occurrence, which is also indicated to the south (Esker *et al.*, 1998; Ferro *et al.*, 1999), is suggested by the parallelism of most valleys and structural ridges (Figs 8B, D and 11). Moreover, whereas the drainage pattern in most of Chetumal Bay is somewhat dendritic, there is a strong overprint of rectilinear drainage, particularly on and around Ambergris Caye. Such a pattern reflects the dominant north-east and approximately east–west structural grain of the area. Whereas valley-fill deposits to the south are believed to be fluvial to estuarine siliciclastics overlain transgressively by lagoonal siliciclastics and carbonates (Esker *et al.*, 1998; Ferro *et al.*, 1999; and earlier studies cited therein), such is not the case in northern Belize. Instead, incised valleys are partly filled variously by clay-soil, mangrove peat and marine carbonate sediments. It is *possible* that siliciclastics *may* have been present during the latest Pleistocene and Early Holocene, and they either completely by-passed

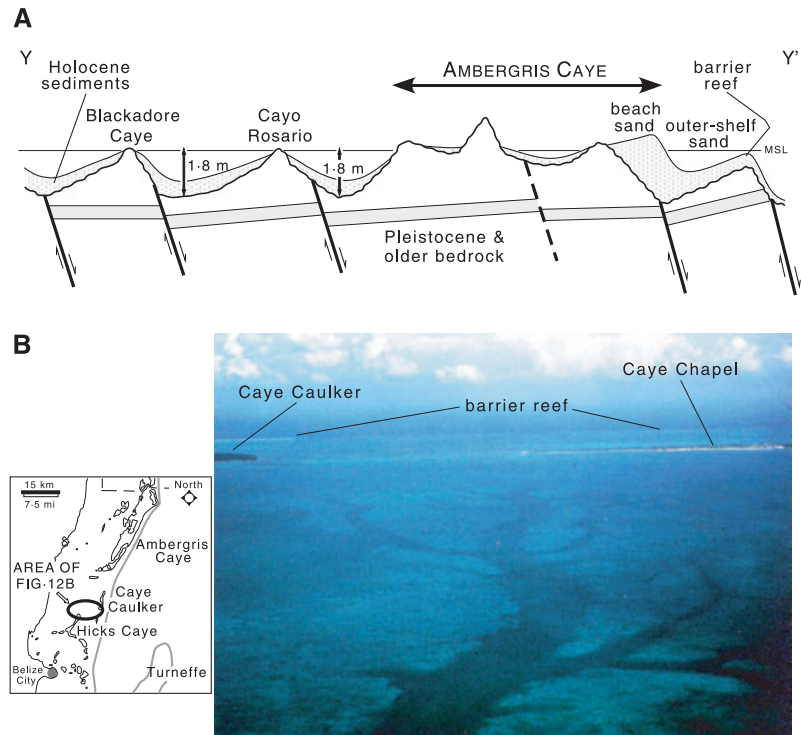


Fig. 12. (A) Schematic section illustrating postulated karst-modified bedrock structure and relationship to Holocene sediments in the study area. (B) Aerial photo of a valley incised into bedrock limestone just south of the study area; view is to east, with the Holocene barrier reef in the background. Note that the pattern of tributaries entering the trunk stream suggests that flow was from east-to-west rather than in a seaward direction across the platform.

the platform during lowstand or were transported westwards during Holocene transgression. Such an interpretation might be tenable only if at least *some* siliciclastics had been encountered in any of the hundreds of samples collected (Fig. 2) over the last 25 years. Moreover, most of the valleys do not flow into the study area from the mainland. Rather, most valley heads are rooted in limestone bedrock, including those streams that flowed *westward* from the topographic high that now is Ambergris Caye (Fig. 11A); this terrain does not include any siliciclastics. A notable example of westward rather than eastward stream flow across the exposed Sangamon carbonate platform, denoted by tributary–junction angles, is a large incised valley immediately south of the study area (Fig. 12B). Westward stream flow generally followed the slope of underlying tilted fault blocks (Fig. 12A).

The incised valleys in the study area dominantly have U-shaped cross-sectional profiles (Fig. 11A). In contrast, incised valleys in central and southern Belize have V- or U-shaped profiles, which Ferro *et al.* (1999) ascribed to erosion by streams transporting dominantly relatively coarse-sediment bed-loads and suspended loads, respectively. Because of the absence of siliciclastics, it is suggested that the valleys in the study area formed solely as a result of dissolution during post-Sangamon lowstand. Purdy

(1974a,b) recognized such dissolution-carved, U-shaped valleys in central Belize (e.g. English Caye Channel; Fig. 1). Depth of valley incisement, valley gradients, and topographic relief are considerably less in the study area than in subsurface central to southern Belize. These parameters probably reflect the development of only shallow doline-karst in northern Belize relative to more intense karstification to the south (Purdy, 1974a,b; Purdy *et al.*, 2003). Notwithstanding caverns, <20 m of relief is indicated by the sum of the maximum elevation of outcrops on Ambergris Caye and maximum depth below sea level of top-of-Sangamon bedrock. In contrast, subsurface topographic relief to the south is as much as 80 m (Ferro *et al.*, 1999).

Diagenesis of Pliocene and Pleistocene rocks

Marine diagenesis in the Pliocene and Pleistocene limestones in the study area included micritization of grains and the precipitation of some aragonite and high-Mg calcite cements in reef deposits in the Pleistocene rocks. Assuming a mean Belize shelf sea water $\delta^{18}\text{O}$ value of *ca* 1.4‰ as today (Teal *et al.*, 2000), the positive $\delta^{18}\text{O}$ values of the Pliocene dolomite in the Airstrip well (mean of *ca* 3‰; Fig. 5B) could suggest that dolomitization began syndepositionally in marine pore fluids of near-normal composition. Early

dolomitization of relatively deep-water, muddy, organic-rich deposits is common in Tertiary and Holocene sediments (Mazzullo, 2000). The general trend of increasing dolomite $\delta^{13}\text{C}$ values with depth (Fig. 5B) may suggest increasing involvement of bacterial methanogenesis during dolomitization. Such reactions are common in many organic-rich sediments as pore-water chemistry evolves from sulfate reduction into the methanogenic realm (Mazzullo, 2000; Teal *et al.*, 2000). The dolomite stable isotope data alternatively could imply that dolomitization began syndepositionally and then continued in the marine shallow-burial environment, or that conversely it was initiated solely within the latter environment. In either case, the dolomite was precipitated from circulating marine pore fluids of near-normal composition based on dolomite $\delta^{18}\text{O}$ values. Increased dolomite stoichiometry roughly tracks the presence of calcites with relatively high residual Mg content (Fig. 5). It is possible that the main phase of dolomitization occurred during the Pleistocene mainly in the marine-burial environment and subsequent to end-of-Pliocene subaerial exposure.

Dolomite $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values increase slightly (up to +3–8‰) and are considerably lighter (mean of *ca* +1‰), respectively, above the middle of the San Pedro Member (at *ca* 165 m depth) in the Airstrip well (Fig. 5A). Dolomite formed interstitially in circulating sea water suggests that $\delta^{18}\text{O}$ enrichment may record global sea water cooling and the onset of glaciation during the Late Pliocene to Early Pleistocene (e.g. Williams, 1988). It is also possible, but not resolvable based on the current sample set, that the stable isotope compositional field of the dolomite above 165 m depth defines a population that is distinct in terms of timing from the dolomite below that depth. The short-term fluctuations of dolomite $\delta^{13}\text{C}$ values up-section in the well, but below 165 m, are matched by very subtle but opposite trends in $\delta^{18}\text{O}$ values (Fig. 5B). Such data may suggest slight temporal fluctuation of pore-water chemistry during dolomitization, which mostly affected $\delta^{13}\text{C}$ values, related possibly to variations in the extent and type of microbial activity in the sediments (e.g., Teal *et al.*, 2000). Alternatively, these $\delta^{13}\text{C}$ trends may reflect variations in the relative contribution of different sources of carbon during dolomitization.

Subaerial diagenesis of the Pliocene and Pleistocene limestones attending multiple periods of exposure to meteoric fluids resulted in: (i) dissolution of aragonitic particles; (ii) variable degree

of stabilization of high-Mg calcite to low-Mg calcite; (iii) the generation of mostly light whole-rock $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values; and (iv) in the Pleistocene limestone, the local precipitation of calcite whisker crystals and meniscus cements. In the Pliocene rocks there is some higher-Mg calcite than in overlying subsurface Pleistocene rocks (4–9 mol.% versus maximum of 7 mol.%; Fig. 5A). Moreover, there is minor residual aragonite in the Pliocene rocks, but none in the Pleistocene except for at the top of the section (Fig. 4). Although slight, these mineralogical and geochemical differences may reflect somewhat less extensive meteoric alteration of dominantly micritic and otherwise fine-grained, lower-permeability Pliocene rocks than in the coarser-grained Pleistocene limestones. In contrast, there is more higher-calcite (with as much as 16 mol.% MgCO_3) in exposed Sangamon-age limestones than in subsurface Pleistocene rocks, and these exposed limestones contain some aragonite (Figs 5A and 6B). Obviously, only one episode of nearly 110 000 years of meteoric exposure was not sufficient to diagenetically alter these rocks as much as subsurface strata, whose relatively greater degree of alteration probably reflects multiple episodes of sea-level lowstand and subaerial exposure (Fig. 4). Within the subsurface rocks there is a relatively long-term trend of decreasing whole-rock $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values upwards in the section, at least from above *ca* 165 m depth if not throughout the entire section (Fig. 5A). Mean whole-rock $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in the Pliocene rocks of 0‰ and +1‰, respectively, may partly reflect a mixture of original components in the limestone and isotopically more positive dolomite stable isotope values. There is no petrographic evidence to support or deny a contention that whole-rock stable isotope values in these rocks might indicate diagenetic alteration in the marine-burial environment (e.g. Melim *et al.*, 1995, 2001a,b). The availability of only cuttings samples, however, limits the detail to which diagenesis can be evaluated. The observed $\delta^{18}\text{O}$ trend is counter to that compiled from deep-sea records, and there is no such trend recognized in $\delta^{13}\text{C}$ data (e.g. Williams *et al.*, 1988). Hence, the whole-rock stable isotope data in the Airstrip well are interpreted to reflect: (i) the presence of more extensively altered (Pleistocene) rocks upwards in the section; and (ii) the overall diagenetic significance of the top-of-Sangamon unconformity. The shorter-term $\delta^{13}\text{C}$ signal within the data parallel essentially invariant $\delta^{18}\text{O}$ values, and with the exception of the most negative $\delta^{13}\text{C}$

values immediately beneath the top-of-Sangamon unconformity, they do not coincide with the stratigraphic locations of any of the other unconformities in the section (Fig. 5A). The significance of these short-term signals is not immediately apparent.

The celestite in the Pliocene San Pablo Limestone may have formed in the shallow-burial diagenetic environment, after dolomitization, with Sr supplied from up-dip dissolution of aragonite, and sulfate derived from circulating pore water and/or an up-dip source of evaporites (e.g. Scholle *et al.*, 1990; Taberner *et al.*, 2002; Hanor, 2004). Gypsum is present in Cretaceous and Tertiary strata exposed on the Belize mainland (King *et al.*, 2004).

COMPARISON WITH BAHAMIAN PLATFORM EVOLUTION AND DIAGENESIS

Despite the great distance between the two areas, upper Pliocene to Pleistocene depositional facies and sedimentological evolution in northern off-shore Belize are very similar in several respects to those parameters in two deep cores (Unda and Clino, Fig. 13) taken on the western Great Bahama Bank (Lidz & McNeill, 1998; Westphal, 1998; Westphal *et al.*, 1999; Ginsburg, 2001a; Kenter *et al.*, 2001; Manfrino & Ginsburg, 2001; McNeill *et al.*, 2001). Carbonate deposition dominated in both areas, and upper Pliocene ramps similarly shallowed upwards and were replaced by rimmed

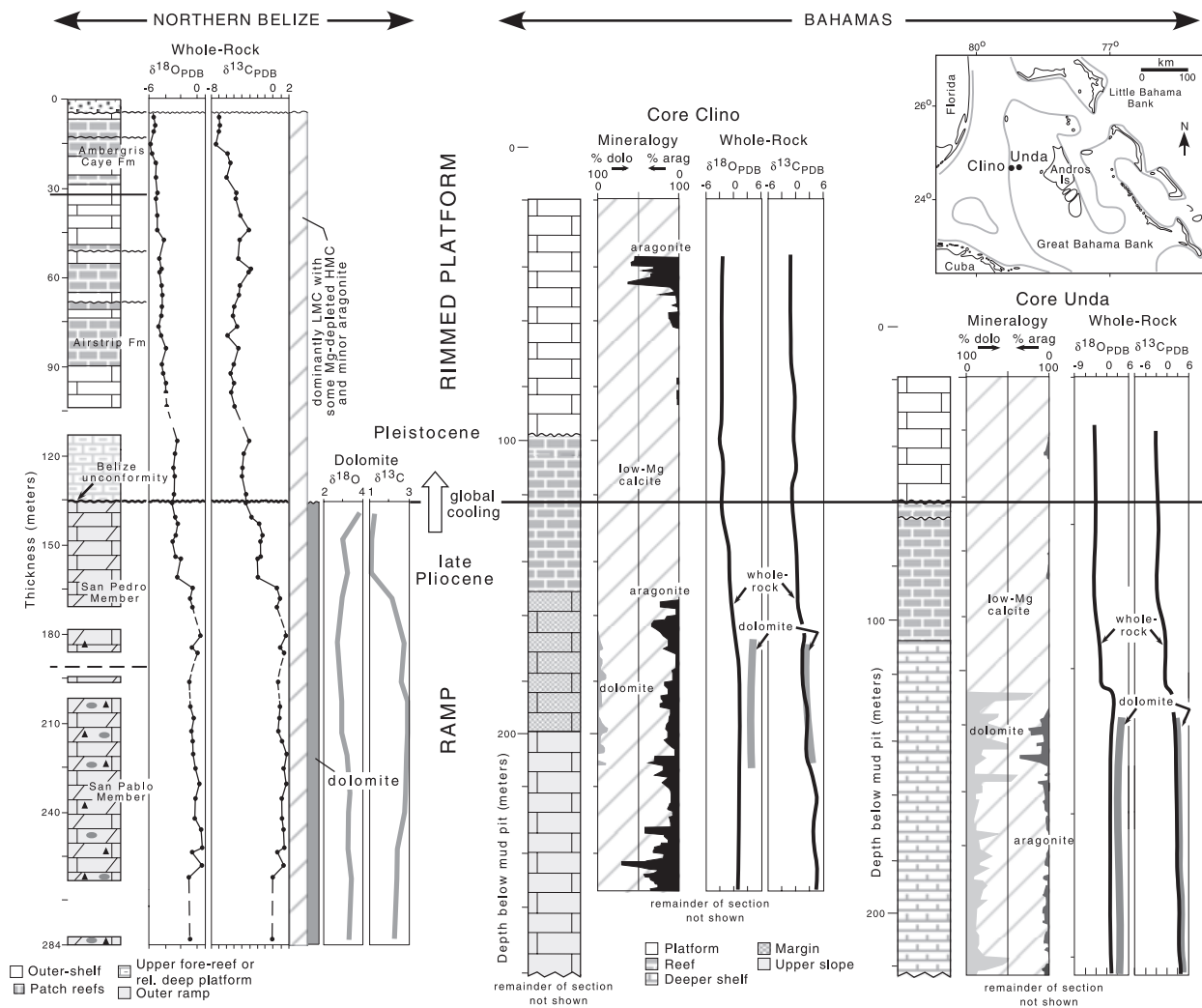


Fig. 13. Comparison of stratigraphy, depositional environments, and mineralogy and whole-rock stable isotope geochemistry in the study area (combined outcrop and subsurface) and in the Clino and Unda cores on Great Bahama Bank. The Clino core is more off-bank facies during the Pliocene than the Unda core (Ginsburg, 2001a,b). Lithologies and ages in the Bahamian cores are from Kenter *et al.* (2001), Manfrino & Ginsburg (2001), and McNeill *et al.* (2001), mineralogy and stable isotope data are from Melim *et al.* (2001a,b), and location map is after Manfrino & Ginsburg (2001).

platforms across the Pliocene–Pleistocene boundary. That boundary also is an unconformity in the up-dip Unda core. Such architectural change coincided with the onset of Northern Hemisphere glaciation during the Pliocene (Cronin & Dowsett, 1991; Raymo, 1994). Whether there was a causal relationship between these events cannot be determined. However, these areas experienced a similar history of decreasing accommodation into the Pleistocene concurrent with a change to successively lower-amplitude sea-level fluctuations (e.g. Beach & Ginsburg, 1980) as is common during icehouse times (Read *et al.*, 1995). Encrusting and ramose red algae are abundant in Pliocene–Pleistocene boundary strata in both areas, which may reflect postulated relatively deeper-water upper Pliocene and earliest Pleistocene environments, and/or slight ocean cooling at this time. Whereas platform sedimentation in northern Belize was dominantly aggradational since the Pleistocene, it was mostly progradational on Great Bahama Bank with the exception of a period of aggradation during the middle to Late Pleistocene (McNeill *et al.*, 2001). Pleistocene deposits similarly include glacio-eustatically forced cycles. Correlation of the 10 to 13 unconformity-bounded cycles in the Clino and Unda cores, respectively, to either the four unconformity-bounded cycles or nine component higher-frequency cycles in northern Belize (Fig. 4) is not possible because of lack of specific age assignments in the latter section. A notable difference between the two areas is that tectonism apparently has significantly influenced Pleistocene and Holocene sedimentation in Belize.

The similarity of diagenetic processes and products in the upper Pliocene and Pleistocene rocks in Belize and on Great Bahama Bank (in the latter area described by Kenter *et al.*, 2001; Melim *et al.*, 2001a,b; and Swart *et al.*, 2001), is even more striking (Fig. 13). Evidence exists in both areas for marine-burial diagenesis (mainly involving dolomitization in Belize) and multiple periods of subaerial meteoric diagenesis (e.g. Melim *et al.*, 1995, 2001b; Kenter *et al.*, 2001). Such a motif is a first-order response to similar histories of largely glacio-eustatically controlled sea-level fluctuations. Trends of whole-rock $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are almost identical in both areas, although the Belize samples are somewhat more depleted in $\delta^{18}\text{O}$ and particularly in $\delta^{13}\text{C}$. The Bahamian Pliocene rocks contain considerably more aragonite than their Belize counterparts, particularly in the Clino core. Melim *et al.* (2001b) attributed aragonite preservation to diagenetic alteration

mainly in the marine-burial environment, which corresponds to increasing stable isotope values relative to those in overlying Pleistocene rocks which instead were altered mainly by meteoric fluids. In the Belize samples, preservation of relatively high Mg contents in calcite and only minor aragonite in the Pliocene rocks instead is attributed to less extensive meteoric alteration of dominantly low-permeability micritic rocks. In contrast, diagenetic alteration was more extensive in the coarser-grained, presumably higher-permeability Pleistocene rocks. That Belize is located in an area of greater average annual rainfall than Great Bahama Bank may influence the relative extent of meteoric alteration in these areas, and may at least partly explain the slight differences in the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of Pleistocene whole-rock samples.

Significant amounts of dolomite are present in both areas and only in Pliocene rocks. The mean $\delta^{18}\text{O}$ value of the Bahamian dolomite likewise is *ca* +3‰, and it similarly is interpreted as having precipitated from circulating sea water of near-normal composition. Mean $\delta^{13}\text{C}$ values in both areas cluster around 2.5–3‰. A similar dolomite origin may reflect the open-ocean facing setting of both areas, and their consequent exposure to normal-marine sea water. Dolomite abundance and its analogous timing of formation strengthen the contention that shallow-burial dolomitization via circulating marine pore fluids (e.g. Saller, 1984; Simms, 1984; Vahrenkamp & Swart, 1994; Whitaker *et al.*, 1994) is a common process within carbonate platforms. Possible bacterial involvement in Bahamian dolomite formation was not addressed by Melim *et al.* (1995, 2001a,b) or others (e.g. Vahrenkamp & Swart, 1994; Whitaker *et al.*, 1994). Both areas share the common presence of celestite in the Pliocene rocks (see Melim *et al.*, 2001a,b). Despite the distance between Belize and the Bahamas, the similarities between the two areas in terms of platform evolution and diagenesis reflect fundamental control on these parameters by glacio-eustasy, climate change and sea water chemistry during the Late Pliocene and Pleistocene.

CONCLUSIONS

The lithostratigraphy, depositional facies and architecture, diagenesis, and nature and extent of inferred sea-level fluctuations and tectonic controls on the deposition of upper Pliocene to Holocene carbonate deposits in northern offshore

Belize are evaluated based on strata in the Airstrip well on Ambergris Caye, limestone exposed on and around the cayes, and Holocene marine sediments. The basal part of the subsurface section in the Airstrip well includes *ca* 150 m of dolomitic, slightly silty and siliceous, fine-grained limestone of upper Pliocene age. These rocks are overlain unconformably by *ca* 133 m of dominantly coarse-grained, coralgal limestone of Pleistocene age. The youngest strata in the Airstrip well partly overlap with and are overlain by additional section of Pleistocene limestone that is exposed on and around Ambergris Caye. A sample of exposed limestone is radiometrically dated at 135 800 years and is assigned to oxygen isotope stage 5e (Sangamon interglacial).

Pliocene rocks in the Airstrip well comprise relatively deep-water ramp deposits that shallowed upwards and which are capped by an unconformity. Depositional architecture changed abruptly across the Pliocene–Pleistocene boundary to a progressively shallower reef-rimmed platform, which has persisted into the Holocene, coincident with the onset of northern Hemisphere glaciation. Similar depositional history and architecture are indicated farther south in Belize based on seismic data, and also along the western side of Great Bahama Bank. Pleistocene facies in the well and in outcrops include: (i) platform-marginal, coralgal barrier-reef deposits composed of framebuilding corals such as *A. palmata*, *A. cervicornis*, and *Agaricia* spp. and associated with relatively abundant *Homotrema* and encrusting coralline algae; and to their lee; (ii) a wide outer-shelf tract of coralgal sand with scattered patch reefs, the latter dominated by *M. annularis*, with little to no *Homotrema* or coralline algae; (iii) a wide outer-shelf to inner-shelf transition zone that comprises nearshore coralgal and some oolitic sand, coarse skeletal beach sands fringing small islands and/or tidal flats, and locally, fine-grained foraminiferal sands; and (iv) a micritic, molluscan-dominated, inner-shelf lagoon. Four unconformity-bounded depositional sequences of probable glacio-eustatic origin are recognized in the Pleistocene section. Component higher-frequency, shallowing-upward cycles are of subtidal character, and probably include such forced cycles and autocycles. With the exception of oolites, the facies present in Pleistocene rocks are represented in Holocene deposits, which also include mud-mounds, inner-shelf foraminiferal sand shoals, and within the interior of Ambergris

and surrounding cayes, *Rhizophora* mangrove swamps, shallow lagoons, and tidal and sea-marginal flats.

The initial development of a flat-topped, reef-rimmed platform during the Pleistocene was structurally controlled, and platform-to-basin topography was maintained and accentuated into the Holocene by barrier reef growth, lowstand karstification, differential platform-to-basin subsidence, and low magnitude of eustatic accommodation-space increases during highstands. Subsidence rate during Pleistocene and Holocene deposition was less than in central to southern Belize, but high enough that a dominantly aggradational style of platform accumulation developed. Syndepositional and post-depositional faulting locally affected Pleistocene and Holocene deposition. Unlike central and southern Belize, there was no siliciclastic influx during Pleistocene lowstands. The drainage pattern of incised valleys along the top-of-Sangamon unconformity was largely controlled by bedrock structure, and these channels are believed to have formed by karst dissolution.

Positive dolomite $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in Pliocene rocks suggest formation in the early post-depositional shallow-burial environment, in contact with circulating marine pore fluids of near-normal composition. Pore-water chemistry, however, was probably modified by bacterial methanogenesis. Recurrent subaerial exposure during lowstands resulted in more intense meteoric alteration of Pleistocene limestones than in the finer-grained Pliocene rocks. Such diagenesis is suggested by aragonite dissolution, variable degree of high-Mg calcite stabilization, up-section trends of more depleted whole-rock $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values, and locally, precipitation of meniscus and whisker-crystal calcite cements. The diagenetic, mineralogic, and stable isotopic attributes of the Pliocene and Pleistocene rocks in the study area are remarkably similar to those in the western Great Bahama Bank with which they share a common history of platform evolution, climate change and sea-level fluctuations, and similar ocean-water oxygen isotope chemistry.

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