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Holocene development of the Belize Barrier Reef

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Abstract

Previously, knowledge of the Holocene development of the Belize Barrier Reef (BBR)—the largest reef system in the Atlantic Ocean—was limited to one location (Carrie Bow Cay). We present new data from 11 rotary drill cores taken at 9 locations and 36 radiometric ages that indicate that the BBR was established from >8.26 to 6.68 ky BP on Pleistocene reef limestones, presumably deposited during oxygen isotope stage 5. The nonsynchronous start of Holocene reef growth was a consequence of variation in elevation of antecedent topography, largely controlled by underlying NNE-trending structures. From north to south, Pleistocene elevation decreases along these structural trends, probably reflecting differential subsidence and variations in karst topography. Reef anatomy is characterized by three facies. In order of decreasing abundance, these facies are represented by corals (mainly *Acropora palmata* and members of the *Montastraea annularis* group), by unconsolidated sand and rubble, and by well-cemented coral grainstones-rudstones. Holocene reef accumulation rates average 3.25 m/ky. The degree of reef consolidation is negatively correlated with Holocene thicknesses, indicating that slowly growing reefs are better cemented than fast growing ones. We present a Holocene sea-level curve for Belize based on 36 dates from this study and 33 dates from our previous studies in the area.

Keywords: Belize; Reef; Holocene; Pleistocene; C-14; TIMS

1. Introduction

The modern reef complex offshore Belize, Central America, is the largest in the Atlantic Ocean. It consists of a 250-km-long barrier reef, which becomes a fringing reef in northern Belize and adjoining Yucatán, and includes three of the rare Caribbean occurrences of atolls or isolated carbonate platforms named Glovers Reef, Lighthouse Reef, and Turneffe Islands (Fig. 1). The distribution of modern facies including the reefs are strongly controlled by underlying structure (Purdy, 1974, 1998; Lara, 1993; Purdy and Gischler, 2003; Purdy et al., 2003). Major structural elements include the Ambergris Cay-shoreline trend, the Turneffe-Chinchorro trend, and the Glovers-Lighthouse trend, all formed by NNE-trending faults that created topographic highs along this passive continental margin (Dillon and Vedder, 1973) (Fig. 1). The elevation of the Pleistocene limestone beneath the majority of Belize Holocene reefs is quite variable

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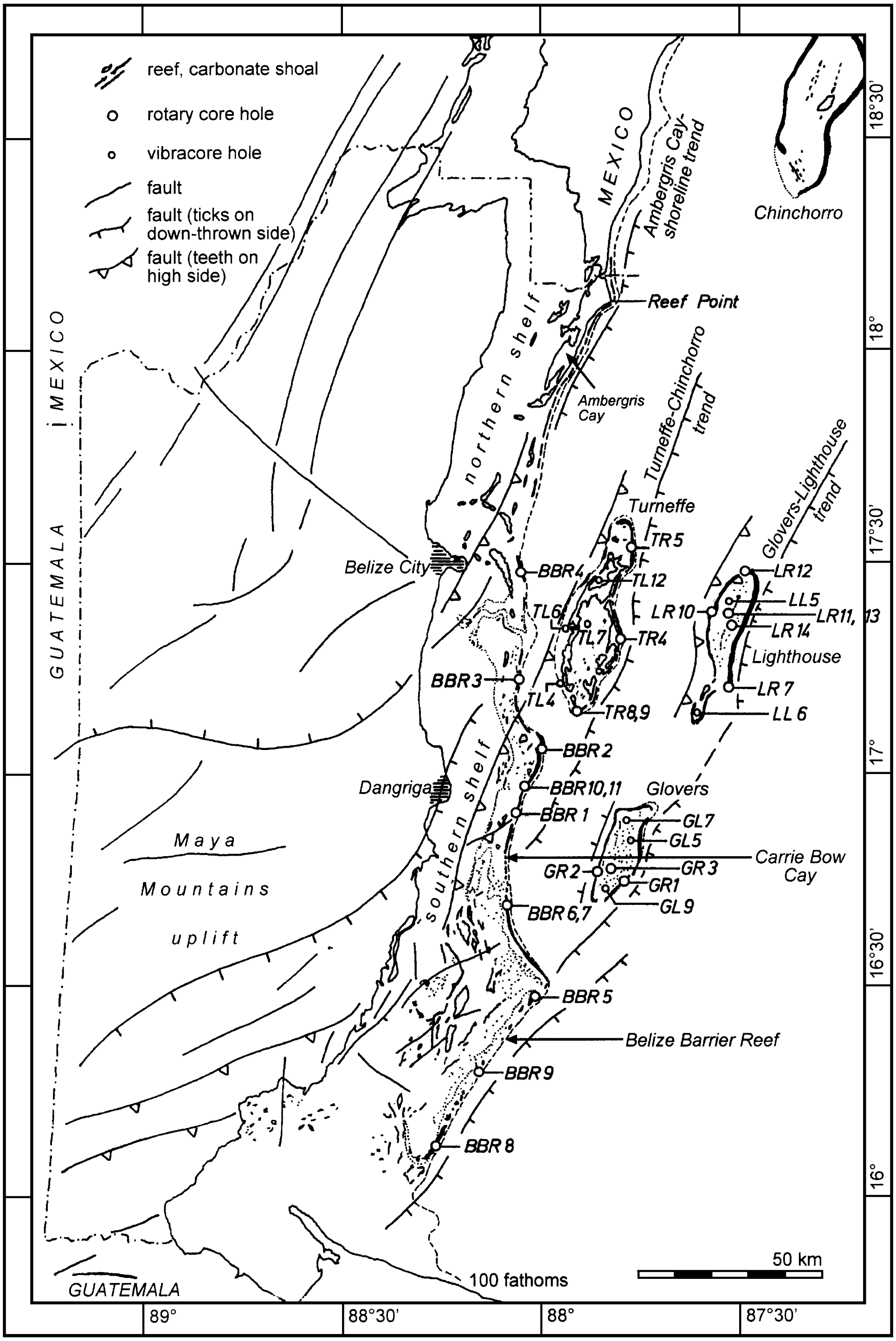
reef, carbonate shoal
rotary core hole
vibracore hole
fault
fault (ticks on down-thrown side)
fault (teeth on high side)
MEXICO
Ambergris Cay-shoreline trend
Chinchorro
Reef Point
Ambergris Cay
northern shelf
Turneffe-Chinchorro trend
Glovers-Lighthouse trend
Turneffe
TR5
TL12
LR12
LL5
LR10
LR11, 13
LR14
Lighthouse
LR7
LL6
BBR4
Belize City
TL6
TL7
TR4
BBR3
TL4
TR8,9
BBR2
Dangriga
BBR10,11
Glovers
BBR1
GL7
GL5
Carrie Bow Cay
GR2
GR3
GR1
GL9
BBR6,7
southern shelf
MEXICO
GUATEMALA
Maya Mountains uplift
BBR5
Belize Barrier Reef
BBR9
BBR8
100 fathoms
50 km
GUATEMALA
18°30'
18°
17°30'
17°
16°30'
16°
89°
88°30'
88°
87°30'

(see, e.g., Gischler et al., 2000). Nonetheless, outcrop and shallow seismic data have indicated an overall deepening trend from 1 m above present sea level at Reef Point on Ambergris Cay in the north to >25 m at the southern end of the barrier reef (Purdy, 1974).

1.1. Previous drilling results

A core hole on Tobacco Cay (close to our location Belize Barrier Reef (BBR) 1, Fig. 1) reached the top of Pleistocene limestone 14–16.4 m below sea level (bsl) (Purdy, 1974). On Carrie Bow Cay, Shinn et al. (1982) drilled a borehole that penetrated Pleistocene limestone at 15.7 m bsl (Fig. 1). A coral from the base of the Holocene was dated at 6.96 ky BP. Farther south at the Queen Cays, about 1.5 km west of the barrier reef (near our location BBR 5, Fig. 1), Ginsburg et al. (1995) found Pleistocene limestone at 14.4–17.4 m bsl. All three of the abovementioned cores had almost no Holocene recovery. In northern Belize, Mazzullo et al. (1992) encountered the Pleistocene 2.5 m bsl in a patch reef situated 200 m west of the barrier reef proper and about 20 km south of the Ambergris Cay Pleistocene reef outcrop at Reef Point. Under the mangrove islands of Tobacco Range, 3–4 km west of BBR 1, Macintyre et al. (1995) found the Pleistocene limestone bedrock as deep as 10 m bsl. Basal Holocene peats were dated at 7 ky BP.

On the basis of 14 cores from reefs on the Belize isolated platforms Gischler and Hudson (1998) and Gischler and Lomando (2000) demonstrated an N-to-S decrease in Pleistocene limestone elevation along the Glovers-Lighthouse trend. This observation was interpreted as a consequence of differential subsidence along the abovementioned major structural trends coupled with an increase in karstification towards the south where higher rainfall precipitation-rates occur (Gischler et al., 2000). Five U-series dates from corals in the Pleistocene limestones of the isolated platforms and one date from the Pleistocene reef limestone that crops out at Reef Point in northern Belize suggest that the antecedent Pleistocene reef limestone formed during the sea level highstand of isotope stage 5e, around 125 ky BP (Gischler et al., 2000).

Core data allowing the reconstruction of the Holocene development of the barrier reef itself is limited to two studies near Carrie Bow Cay (Fig. 1). Macintyre et al. (1981) drilled three core holes in the fore reef at water depths of 12–16 m. They found Holocene successions of massive corals, which grade upward into a predominance of branched corals. Accumulation rates ranged from 1.1 to 8.3 m/ky. Shinn et al. (1982) drilled two cores in the shallow fore reef spur-and-groove system and reported the occurrence of foliose corals (*Agaricia* sp.). Two cores drilled in the back reef and on Carrie Bow Cay had almost no recovery, indicating the presence of unconsolidated sand and rubble. Accumulation rates ranged from 1 to 6.5 m/ky. Investigations on marginal reefs of the offshore isolated platforms showed that the Holocene windward reefs are dominated by the branched *Acropora palmata*. Massive corals of the *Montastraea annularis* group and consolidated grainstone-rudstone are less common. In contrast, leeward Holocene reefs were clearly dominated by massive corals of the *M. annularis* group and unconsolidated sand and rubble (Gischler and Hudson, 1998; Gischler and Lomando, 2000). Accumulation rates were highly variable and ranged from 0.5 to >20 m/ky.

1.2. Present study

It becomes clear from the foregoing that the knowledge of the late Quaternary development of the BBR proper is very limited. With this in mind, this study was designed (1) to detail the Holocene development of the BBR including the identification of controlling factors such as sea level, antecedent topography, and

Fig. 1. Location map of the study area. Only major tectonic elements are shown (from Purdy et al., 2003). Open circles on the Belize Barrier Reef (BBR 1-BBR 11) show the core stations of this study. Please note that BBR 6, 7 and BBR 10, 11 were taken at the same latitude on reef crest, ca. 20 m apart. The other open circles on the isolated platforms east of the barrier reef are from previous studies (Gischler and Hudson, 1998; Gischler and Lomando, 2000; Gischler, 2003) with Holocene dates used for the sea-level curve shown in Fig. 5 as well as Pleistocene dates (Gischler et al., 2000).

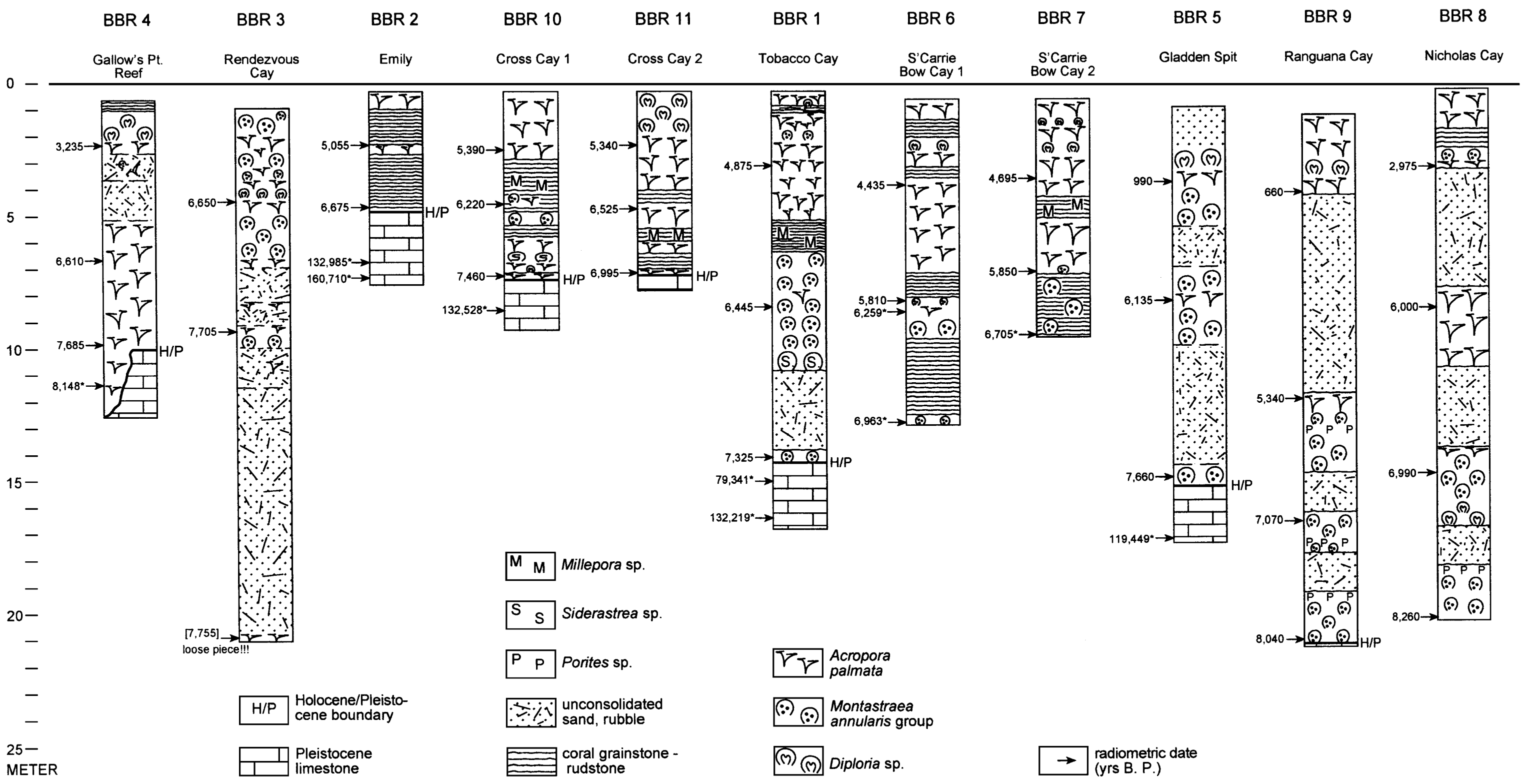

Fig. 2. Logs of rotary cores obtained in this study from north to south along the BBR. Calibrated ^{14}C-dates are shown. TIMS-dates are marked by asterisks. Core recovery averages 33.2%. Please note that BBR 6, 7 and BBR 10, 11 were taken at the same latitude on reef crest, ca. 20 m apart. For core hole locations see Fig. 1.

environmental parameters including exposure to waves, currents and clastic input, and (2) to further investigate the nature and age of the Pleistocene surface beneath the BBR.

2. Methods

Eleven rotary drill cores totalling 150 m of rock penetration were taken in July 2002 on the 20–30 m

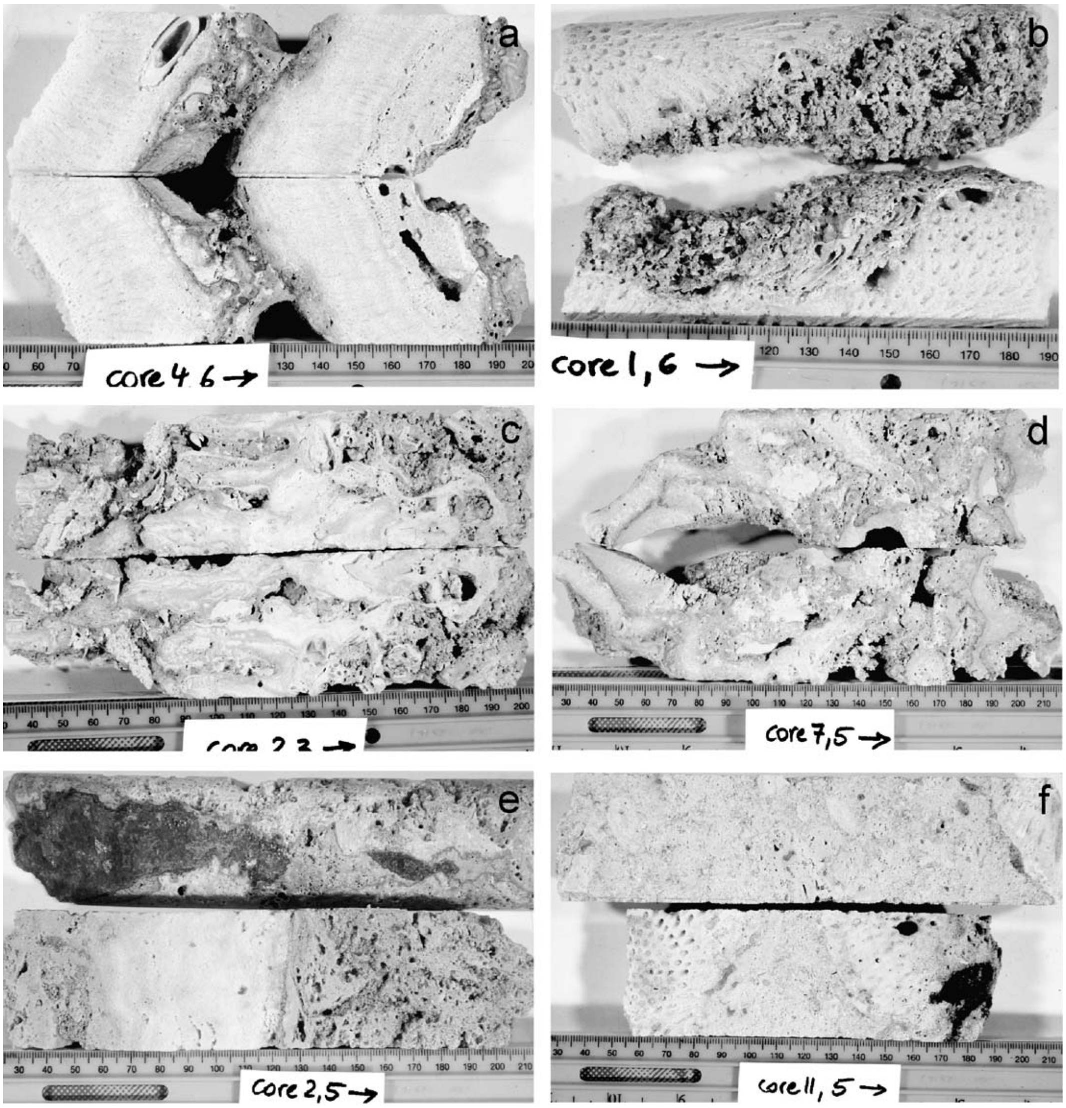

Fig. 3. Slabs of Holocene and Pleistocene core from the Belize Barrier Reef. Scale is in centimeters. (a) Coral facies, Holocene. Slabs of *A. palmata* cemented together by microcrystalline high Mg–calcite and crustose coralline algae. Core 4; 6.5 m bsl. (b) Coral facies, Holocene. Microbialite on piece of *Montastraea* sp. Core 1; 6.5 m bsl. (c) Well-cemented grainstone-rudstone facies, Holocene. Pieces of foliaceous *Millepora* sp. are encrusted by crustose coralline algae. Cemented sediment with coral, coralline algae, and *Halimeda* sp. Core 2; 3.5 m bsl. (d) Well-cemented grainstone-rudstone facies, Holocene. Pieces of *Millepora* sp. and well-cemented sediment. Note that *Millepora* is encrusted by microbialite. Core 7; 4.5 m bsl. (e) Two pieces of Pleistocene limestone from core 2; 5 m bsl. Lower sample with fragment of *A. palmata*. Upper sample exhibits karst dissolution; cavity filled with dark caliche. (f) Two pieces of Pleistocene limestone from core 11; 7.5 m bsl. Lower sample with fragments of massive corals *Montastraea* sp. and *Siderastrea* sp. Upper sample with branched *Porites* sp. fragments in a coarse-grained matrix.

wide reef crest (sensu James et al., 1976) of the BBR (Fig. 1). Nine roughly equally spaced locations between the latitude of Belize City and the southern end of the barrier reef were selected. At two locations, two cores each were taken on the eastern and western edges of the reef crest ca. 20 m apart (BBR 6, 7; BBR 10, 11; Fig. 1). We used the portable rotary drill described by Shinn et al. (1982) with a wire line core barrel. In the laboratory, cores were cut with a rock saw and described. Selected core sections were either polished or thin-sectioned for more detailed inspection. Beta Analytic, Miami dated 32 Holocene corals using the C-14 standard method. A. Eisenhauer, Kiel dated 10 possible

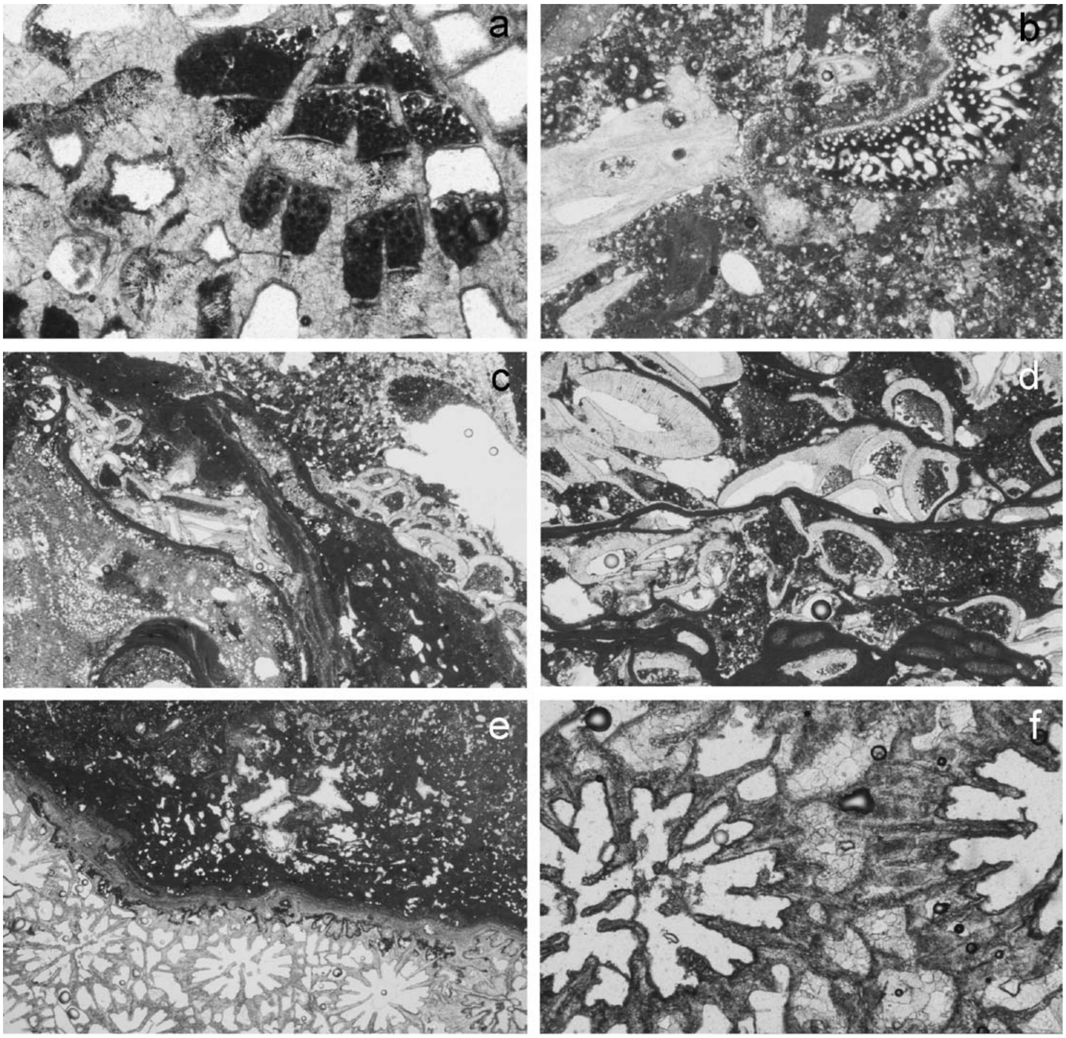

Fig. 4. Thin-section photographs from Holocene and Pleistocene core from the Belize Barrier Reef. (a–d) Holocene; (e–f) Pleistocene. (a) Intracorallite voids of *Montastraea* sp. filled with peloidal high Mg–calcite and aragonite needle cements. Core 7; 8 m bsl. Width of picture 3.5 mm. (b) Fragments of coral, coralline algae, and *Halimeda* sp. cemented together by high Mg–calcite. Core 1; 6 m bsl. Width of picture 3.5 mm. (c) Coral (lower left corner) encrusted by foraminifera (*H. rubrum*, *Carpenteria* sp.) and crustose coralline algae. Core 11; 6 m bsl. Width of picture 10 mm. (d) Encrusting foraminifera (*Carpenteria* sp.) intergrown with thin crustose coralline algae. Note peloidal high Mg–calcite cement. Core 7; 4 m bsl. Width of picture 5 mm. (e) Top of Pleistocene section with *Montastraea* coral overlain by laminated crust and caliche, both low Mg–calcite. Caliche with mottled texture and voids that are lined by blocky low Mg–calcite cement. Core 2; 5 m bsl Width of picture 17 mm. (f) Pore spaces in Pleistocene *Montastraea* sp. filled with blocky low Mg–calcite cement. Core 2; 5.5 m bsl. Width of picture 5 mm.

Pleistocene corals with the thermal ionization mass spectrometry (TIMS) method (Chen et al., 1986; Edwards et al., 1986; Hamelin et al., 1991). Aragonite contents of these 10 corals were determined using X-ray diffraction.

3. Results

3.1. Holocene

Seven cores penetrated the entire Holocene section and reached the underlying Pleistocene bedrock. Cores BBR 3, 6, 7, and 8 did not reach the Pleistocene (Fig. 2). Holocene thicknesses range from 4.8 m (BBR 2) to >21 m (BBR 3). Recovery ranged from 12.8% to 65.6% and averaged 33.2%. There is a statistically significant negative correlation between Holocene reef thickness and recovery ($r = -0.848$, $p < 0.001$).

Three Holocene facies are distinguished (Fig. 3). (1) The coral facies consists of cm- to dm-sized pieces of coral and makes up 54.2% of the Holocene section with *A. palmata* (31.9%), *Montastraea* sp. (16.2%), *Diploria* sp., *Siderastrea* sp., and *Porites* sp. (6.1%). It was not possible to distinguish between autochthonous and allochthonous corals in the core material. (2) A well-cemented coral grainstone-rudstone facies forms

Table 1
Standard radiocarbon ages of corals from drill cores on Belize Barrier Reef

Sample	Coral/material	Depth below SL in m	Measured age (year BP)	$^{13}C/^{12}C$	Conventional age (year BP)	Calibrated age in years, 2-σ range	BETA, no.
BBR 1-2.8	*A. palmata*	3.1	4230 ± 70	0.0	4640 ± 70	BP 5040–4710	171,847
BBR 1-8.1	*M. annularis*	8.4	5610 ± 60	0.0	6020 ± 60	BP 6590–6300	171,848
BBR 1-13.9	*M. annularis*	14.2	6390 ± 60	0.0	6800 ± 60	BP 7420–7230	171,849
BBR 2-2.0	*A. palmata*	2.3	4350 ± 70	0.0	4770 ± 70	BP 5270–4840	171,850
BBR 2-4.4	*A. palmata*	4.7	5810 ± 70	0.0	6230 ± 80	BP 6860–6490	171,851
BBR 3-3.5	*A. palmata*	4.4	5780 ± 80	0.0	6200 ± 80	BP 6840–6460	171,852
BBR 3-8.4	*A. palmata*	9.3	6810 ± 80	0.0	7220 ± 90	BP 7860–7550	171,853
BBR 3-20.0	*A. palmata*	20.9	6880 ± 60	0.0	7290 ± 60	BP 7870–7640	171,854
BBR 4-1.7	*A. palmata*	2.3	2970 ± 70	0.0	3380 ± 70	BP 3400–3070	171,855
BBR 4-6.0	*A. palmata*	6.6	5760 ± 70	0.0	6170 ± 80	BP 6790–6430	171,856
BBR 4-9.3	*A. palmata*	9.9	6810 ± 60	0.0	7220 ± 60	BP 7790–7580	171,857
BBR 5-2.8	*A. palmata*	3.7	1010 ± 60	0.0	1420 ± 60	BP 1100–880	171,858
BBR 5-7.3	*P. astreoides*	8.2	5330 ± 70	0.0	5740 ± 70	BP 6290–5980	171,859
BBR 5-14.0	*M. annularis*	14.9	6770 ± 90	0.0	7180 ± 90	BP 7820–7500	171,860
BBR 6-3.2	*A. palmata*	3.8	3900 ± 70	0.0	4310 ± 70	BP 4620–4250	171,861
BBR 6-7.6	*M. annularis*	8.2	5030 ± 80	0.0	5450 ± 90	BP 6000–5620	171,862
BBR 7-3.0	*A. palmata*	3.6	4120 ± 70	0.0	4530 ± 70	BP 4860–4530	171,863
BBR 7-6.4	*M. annularis*	7.0	5070 ± 70	0.0	5480 ± 80	BP 6020–5680	171,864
BBR 8-2.9	*A. palmata*	3.2	2760 ± 70	0.0	3170 ± 70	BP 3170–2780	171,865
BBR 8-8.3	*A. palmata*	8.6	5170 ± 80	0.0	5580 ± 80	BP 6170–5830	171,866
BBR 8-14.5	*M. annularis*	14.8	6090 ± 60	0.0	6500 ± 70	BP 7180–6800	180,399
BBR 8-20.0	*M annularis*	20.3	7380 ± 60	0.0	7790 ± 60	BP 8370–8150	171,867
BBR 9-2.9	*A. palmata*	4.1	680 ± 60	0.0	1100 ± 60	BP 760–560	171,868
BBR 9-10.7	*A. palmata*	11.9	4570 ± 70	0.0	4990 ± 80	BP 5550–5130	171,869
BBR 9-15.5	*M. annularis*	16.7	6160 ± 70	0.0	6570 ± 70	BP 7240–6900	180,400
BBR 9-19.8	*M. annularis*	21.0	7160 ± 60	0.0	7570 ± 60	BP 8160–7920	171,870
BBR 10-2.2	*A. palmata*	2.5	4590 ± 70	0.0	5010 ± 80	BP 5570–5210	171,871
BBR 10-4.2	*A. palmata*	4.5	5400 ± 80	0.0	5810 ± 80	BP 6390–6050	171,872
BBR 10-7.0	*A. palmata*	7.3	6530 ± 60	0.0	6940 ± 60	BP 7560–7360	171,873
BBR 11-2.0	*A. palmata*	2.3	4580 ± 70	0.0	4990 ± 80	BP 5550–5130	171,874
BBR 11-4.4	*A. palmata*	4.7	5680 ± 60	0.0	6090 ± 60	BP 6660–6390	171,875
BBR 11-6.8	*A. palmata*	7.1	6070 ± 60	0.0	6480 ± 60	BP 7150–6840	171,876

Dating by Beta Analytic, Miami, USA.
Conventional ages are corrected for $\delta^{13}C/^{12}C$. Reservoir correction applied; 2-sigma range has 95% probability.

14.5% of the Holocene sections. In addition to mm- to cm-sized pieces of corals from the abovementioned taxa *Millepora* sp., *Agaricia* sp., the codiacean alga *Halimeda*, coralline algae, and mollusk fragments are common in this facies. Encrusting foraminifera such as *Homotrema rubrum* and *Carpenteria* sp., as well as rare small (< 1 cm) coralline sponges are found in cavities between blades of foliaceous corals. The most common cement is microcrystalline high Mg–calcite; aragonite needle cement is less abundant and occurs preferentially in coral skeletons (Fig. 4). Both in the coral facies and in the well-cemented grainstone-rudstone facies, microbialites are observed occasionally (Fig. 3). They consist of laminated, microcrystalline high Mg–calcite and apparently formed in cavities of the reef framework (Fig. 3). (3) Unconsolidated sand and rubble make up the remaining 31.3% of the Holocene section. Recovery in this facies was usually very low. There is a statistically highly significant positive correlation between Holocene reef thickness and unconsolidated sand and rubble in the core ($r = 0.881$, $p < 0.0001$).

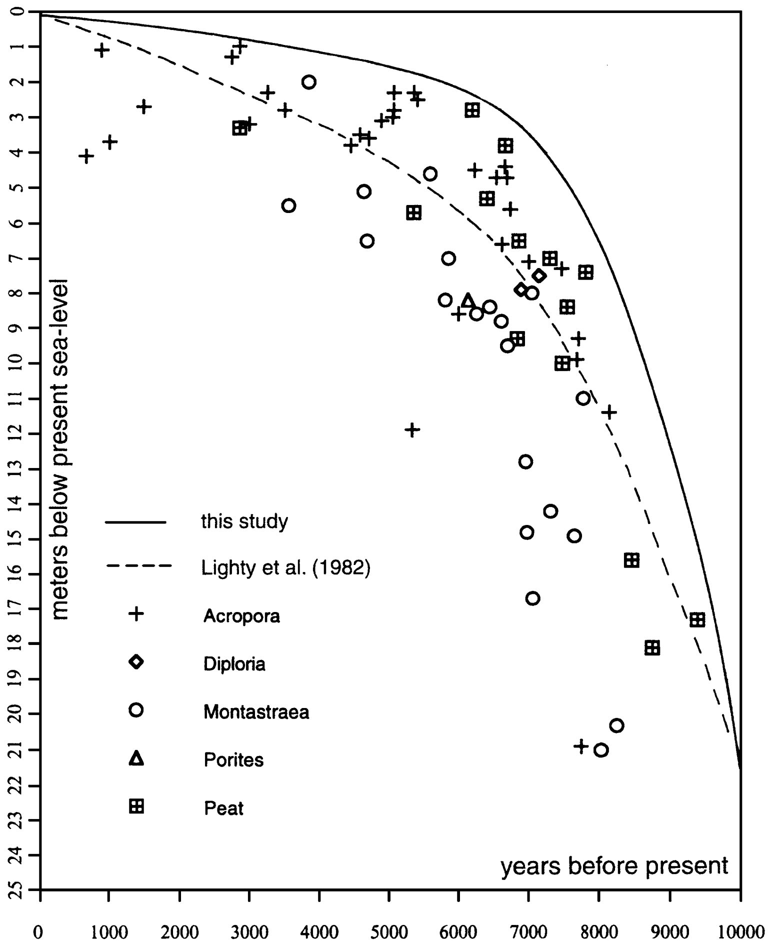

Fig. 5. Sea-level curve for Belize (solid line) based on 69 calibrated ages (36 coral dates from this study; 33 coral and peat dates from previous work on isolated platforms: Gischler, 2003; Gischler and Hudson, 1998; Gischler and Lomando, 2000). Western Atlantic sea-level curve of Lighty et al. (1982) (stippled line) for comparison. These authors had used 42 uncorrected age dates from the coral *A. palmata* to construct a western Atlantic/Caribbean minimum sea-level curve. For this figure, the Lighty et al. (1982) dates were calibrated by applying the INTCAL 98 software from Stuiver et al. (1998) and using a $^{13/12}C$ ratio of 0.0‰. Both curves are constructed by positioning lines a short distance above *A. palmata* and peat dates, respectively.

Table 2
Results of radiometric dates using thermal ionization mass spectrometry (TIMS)

Sample	Depth below sea level (m)	Coral	Aragonite (%)	^{238}U (ppm)	$^{234/238}$U initial activity	Age (ky)	Isotope stage[a]
BBR 1-16.1	16.4	*S. siderea*	5	1.9182	1.615 ± 0.002	132,219 ± 1184	5 (?)
BBR 2-6.4	6.7	*M. annularis*	5	1.6370	1.622 ± 0.003	132,985 ± 1159	5 (?)
BBR 2-7.0	7.3	*A. palmata*	4	1.1755	1.754 ± 0.002	160,710 ± 1844	5 (?)
BBR 5-16.3	17.2	*M. annularis*	3	1.0951	1.562 ± 0.004	119,449 ± 1012	5 (?)
BBR 10-8.2	8.5	*A. palmata*	10	1.8763	1.620 ± 0.005	132,528 ± 1964	5 (?)
BBR 1-14.7	15.0	*M. annularis*	3	1.7594	1.399 ± 0.002	79,341 ± 900	5 (?)
BBR 4-10.8	11.4	*A. palmata*	100	2.8616	1.172 ± 0.001	8148 ± 52	Holocene
BBR 6-12.2	12.8	*M. annularis*	100	2.8164	1.177 ± 0.004	6963 ± 66	Holocene
BBR 6-8.0	8.6	*M. annularis*	100	2.5080	1.173 ± 0.003	6259 ± 48	Holocene
BBR 7-8.9	9.5	*M. annularis*	100	2.6680	1.175 ± 0.003	6705 ± 89	Holocene

Dating by laboratory A. Eisenhauer, GEOMAR, Kiel, Germany.

[a] Pleistocene dates are considered not reliable as initial uranium activity clearly exceeds the value for modern seawater of 1.145 (Chen et al., 1986). Initial uranium activity in Holocene dates is slightly elevated as compared to values of modern seawater as well; however, dates are taken as being reliable.

Thirty-six Holocene radiometric dates (Tables 1 and 2) were obtained and indicate that the BBR began to grow between >8.26 ky (BBR 8) and 6.68 ky (BBR 2). Thirty-two ages obtained are calibrated ^{14}C-dates and four ages were measured using TIMS. Accumulation rates were calculated between calibrated age dates and range from 0.87 to 6.59 m/ky and average 3.25 m/ky. There is a statistically significant positive correlation between calculated growth rates and Holocene reef thickness ($r = 0.609$, $p < 0.047$). Together with 33 other calibrated ^{14}C-dates from corals and basal peats from the Belize isolated platforms (Gischler, 2003; Gischler and Hudson, 1998; Gischler and Lomando, 2000), a sea-level curve is presented in Fig. 5, which is drawn based on the assumption that all coral and peat dates have to plot slightly below sea level. Two *A. palmata* dates fall 10 and 15 m below the sea-level curve, respectively; however, even though these numbers are beyond the optimum depth of this coral (< 5 m), they are still within the bathymetric limit reported for this species (Lighty et al., 1982). Our curve differs from the *A. palmata*-based western Atlantic curve of Lighty et al. (1982) in that it is steeper from 10 to 7 ky BP and higher from 7 to 1 ky BP (Fig. 5).

3.2. Pleistocene

The Pleistocene–Holocene boundary is easily recognized. In the upper part of the Pleistocene sections, indications for subaerial exposure such as brown laminated crusts, roundish karst solution holes, and root holes occur (Figs. 3 and 4). The Holocene–Pleistocene contact is also characterized by a change from aragonite and high Mg–calcite to low Mg–calcite mineralogies. The Pleistocene deposits are well-cemented coral rudstones with cm- to dm-sized fragments of *A. palmata*, *Montastraea* sp., *Siderastrea* sp., and *Porites* sp. The predominant cement is blocky low Mg–calcite (Fig. 4). No Pleistocene siliciclastics were encountered.

U-series ages of six Pleistocene corals range from 79 to 160 ky, but none of the six Pleistocene ages are reliable as the initial $^{234/238}$U activity ratios clearly exceed the average value of 1.145 of modern seawater (Chen et al., 1986). Diagenetic alteration occurred as seen in the relatively low aragonite contents of the Pleistocene coral samples, and U-concentrations below 2 ppm indicate loss of uranium during the same process (Table 2).

4. Discussion and conclusions

4.1. Holocene reef facies

According to existing descriptions of modern zonation and cementation (James et al., 1976; Shinn et al., 1982), Holocene facies found in the core are interpreted to belong to the reef margin proper. The coral facies and the well-cemented coral grainstone-rudstone facies probably represent the reef crest. Among these, *Acropora*-rich core sections belong to the windward edge of the reef crest, whereas *Montastraea*-rich sections might be indicative of a more leeward position of this facies. It is possible that some *Millepora*-rich sections even belong to the upper spurs, which are located seaward of the modern reef crest and which are very rich in this hydrocoral. However, rubble of *Millepora* is also found within the reef crest (James et al., 1976). The unconsolidated sand and rubble facies might represent the adjacent back reef area, which is to a large part uncemented (Shinn et al., 1982). Even so, this interpretation might not generally be valid as well, as even in the modern reef crest and pavement, cementation only extends from the seabed to about 1 m depth (James et al., 1976). Following these facies interpretations, changes in reef anatomy along the cores (Fig. 2) may be interpreted as retrogradation and progradation, being the consequence of variations in rate of sea-level rise. During rapid rises of sea level in the earlier Holocene one would expect retrogradation or back-stepping, i.e., in examples where coral-rich facies of the reef crest overlie unconsolidated back reef sands in the cores. Progradation would have prevailed in the later Holocene when the rate of sea-level rise decreased thereby diminishing available accommodation space. Core examples would include unconsolidated sand and rubble of the back reef area overlying coral-rich facies of the reef crest. Both examples may be seen in the core; however, we do not attempt to interpret these facies changes with regard to retrogradation and progradation. First, in the majority of locations there is only one core (except at BBR 6, 7 and BBR 10, 11) and no geometries are available. Second, as discussed above, facies interpretations might be problematic due to sediment redeposition, due to variation in cementation, and due to the fact that autochthonous components cannot be distinguished with certainty from allochthonous material in cores. For example, Hubbard et al. (1998) interpreted large parts of Holocene Caribbean reefs as lacking in-place and interlocking framework and being comprised of mixtures of corals (“primary framework”), loose sediment, and coralgal fragments bound together by cementation and biological encrustation (“secondary framework”).

4.2. Pleistocene reef substrate

Pleistocene carbonate facies with abundant *A. palmata* clearly speaks for a marginal reef depositional environment, comparable to the present conditions at the BBR. Likewise, Tebbutt (1975) interpreted the Pleistocene *A. palmata*-bearing reef limestones at Reef Point in northern Belize as high-energy deposits.

As first reported by Purdy (1974) based on core data, and later interpreted by Choi and Holmes (1982) and Choi and Ginsburg (1982) based on seismic data, some late Quaternary reefs and carbonate shoals of the southern shelf lagoon were established on Pleistocene siliciclastics. Based on seismic studies, Ferro et al. (1999) proposed that prograding wedges of siliciclastic sediment were deposited below and seaward of the exposed BBR during Pleistocene sea-level lowstands and that a new barrier reef was established over siliciclastics during the following transgression. Based on our core data, this possibility has to be rejected, at least for the previous late Pleistocene sea-level highstand phase.

Even though Pleistocene radiometric ages obtained during this study are not reliable, their range from 79 to 160 ky indicates that Pleistocene reef limestone underlying the Holocene reefs in the central and southern BBR was deposited during the sea-level highstands of oxygen isotope stage 5. Due to the diagenetic loss of uranium our dates have to be interpreted as maximum ages (personal communication with Prof. A. Eisenhauer, Kiel). Thus, deposition during isotope stages 5 or 3 is taken into consideration. As the sea-level highstand of isotope stage 3 was between 30 and >50 m below present level (Shackleton, 1987; Bard et al., 1990) and as major uplift of tens of meters during the late Pleistocene can be ruled out for the study area, we interpret the Pleistocene deposits dated in the course of this study as being deposited during the sea-level highstands of isotope substages 5e, 5c, or 5a. Sea level in the Caribbean was at least 3.5 m above present level during isotope substage 5e (Fruijtier et al., 2000) and around 10 m below present level during the highstands of substages 5c and 5a (Toscano and Lundberg, 1999) as shown in south Florida. Pleistocene elevation in the area investigated here of >20 m below present level may be explained by late Quaternary subsidence along the Belize offshore fault-blocks underlying the reefs in combination with karst dissolution (Gischler et al., 2000), and by the possibility that some of the dated Pleistocene corals did not live close to sea level. The assumption of deposition of Pleistocene deposits investigated during this study during isotope stage 5 is further corroborated by the existence of reliable and moderately reliable age dates from Pleistocene reef limestone in the northern BBR at Reef Point and on the offshore isolated platforms that range from 125 to 145 ky (Gischler et al., 2000).

4.3. Controlling factors of Holocene reef initiation and growth

As outlined by Macintyre (1988), Caribbean reef development was controlled by the interaction of antecedent topography, the Holocene sea-level rise, and patterns of wave energy conditions. The data obtained during this study suggest that elevation of antecedent topography is the most important factor controlling Holocene development of the BBR. The elevation of the Pleistocene antecedent topography does not simply decrease along the BBR from north to south, but along the NNE-trending underlying structures that cut the barrier reef at a high angle. When the core data of the present study is combined with that of the marginal reefs of the isolated platforms (Gischler and Hudson, 1998; Gischler and Lomando, 2000), it becomes evident that the antecedent topography decreases in elevation from NNE to SSW along the major structural trends (Fig. 6). Under the Turneffe–Chinchorro-trend Pleistocene elevation decreases from 3 to 4 m in Turneffe, to 4.8 m at BBR 2, and to 14.3 m at BBR 1. Along the Glovers Lighthouse-trend it decreases from 7 m in Lighthouse to 10 m in Glovers and to 15.2, 21.6, and >21 m along the southern barrier reef. It decreases in a similar way along the Ambergris Cay-shoreline trend as seen in the 10 m difference in elevation between Reef Point and BBR 4, and the further drop towards BBR 3, which lies within a regional tectonic low as mapped by Purdy et al. (2003). These findings support the earlier interpretation of differential subsidence along the major offshore structural trends in combination with an increase in karstification towards the south where higher rainfall precipitation rates prevail (Gischler et al., 2000).

The initiation of reef growth was dependent upon the elevation of the Pleistocene antecedent surface with respect to sea-level inundation of that surface. Consequently, basal Holocene ages do not simply reflect increasing depth of that surface from north to south. For example, barrier reef growth started before 8 ky BP (BBR 8) not only in the very south but also at topographic lows farther to the north such as localities BBR 3 or BBR 4. On topographic highs, reef growth was initiated as late as 6.68 ky BP (BBR 2).

The shelf lagoon behind the BBR was first inundated between 10 and 8 ky BP based on peat data from the shelf south of Dangriga (Halley et al., 1977; Shinn et al., 1982; Westphall, 1986; Esker et al., 1998). The northern shelf lagoon was flooded between 5.6 and 6.1 ky BP by the rising Holocene sea based on peat data from Purdy (1974) from the area west of Ambergris Cay. There are no peat age data from the 100 km of shelf between Dangriga and the south end of Ambergris Cay.

Another factor that could have influenced Holocene BBR growth includes variation in exposure to waves and currents. This is a consequence of the position of the offshore isolated platforms that modify wave forces along the BBR, west of these platforms (Burke, 1982; Gischler and Lomando, 2000, their Fig. 8). There are some differences in Holocene reef anatomy between the southern unprotected locations (BBR 5, 8, 9) and the more protected locations to the north in that the former have more unconsolidated sand and rubble, but this is most probably a function of antecedent topography elevation. In location BBR 3, e.g., which is characterized by low Pleistocene elevation, there are long sections of unconsolidated facies as well even though this location is strongly protected by Turneffe to the east. The largely unprotected location of BBR 2 on the other hand, with high bedrock elevation, shows the highest degree of reef consolidation among all the boreholes. The observation that there is a highly significant negative statistical correlation between reef consolidation and Holocene reef thickness indicates that slow growing reefs are more consolidated than fast growing ones, and that,

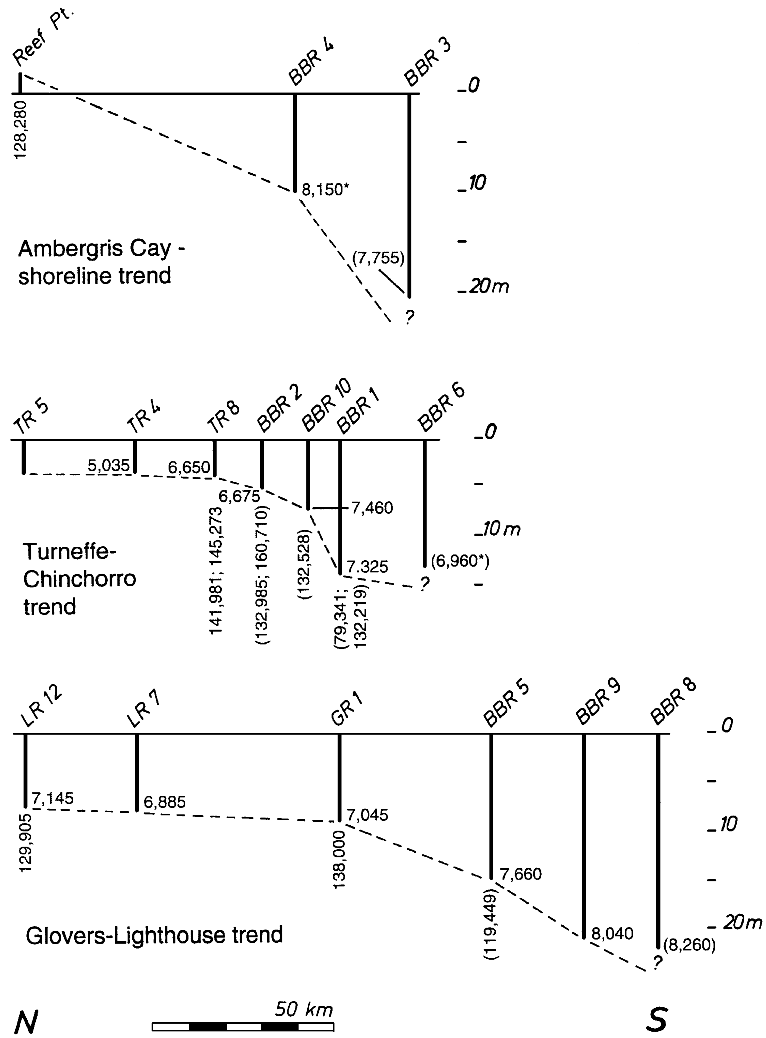

Fig. 6. Schematic sections along the three major tectonic trends offshore Belize showing the depths from present sea level to the Pleistocene surface as seen in rotary cores through the BBR and marginal reefs of the offshore isolated platforms. Basal Holocene ages in cores in ky before present (horizontal numbers). GR = Glovers Reef; LR = Lighthouse Reef; TR = Turneffe Reef. For core hole locations refer to Fig. 1. Data are from this study and from studies on the Belize isolated carbonate platforms (Gischler and Hudson, 1998; Gischler and Lomando, 2000). Holocene dates are calibrated ^{14}C-ages; Holocene TIMS-dates are marked by asterisks. Pleistocene TIMS-dates in ky (vertical numbers) from this study and from Gischler et al. (2000). Ages in parentheses are either not from Holocene bases or not reliable (Pleistocene). Reversed ages among BBR 1 and BBR 10 in Turneffe-Chinchorro trend might result from the fact that different coral taxa were dated, which presumably lived in markedly different depths (BBR 1: *M. annularis*; BBR 10: *A. palmata*).

not surprisingly, the degree of submarine cementation is a function of time available for cementation.

Another factor that varies from north to south along the Belize shelf is the increasing clastic input south of Belize City due to the hinterland provenance of southern Belize (Maya Mountains) that includes siliciclastic sedimentary rocks and granites and differs from the northern Belize sedimentary provenance of Tertiary and Cretaceous limestones. As we found no siliciclastics during our study, however, we regard their influence on the Holocene development of the BBR proper as negligible.

Note added in proof: Recently, Toscano and Macintyre (2003) published a corrected western Atlantic sea-level curve based on 145 calibrated *A. palmata* and basal peat dates from south Florida, Belize, and the wider Caribbean. This new curve is quite similar to the modified Lighty et al. (1982)-curve, which we redrew for this publication by calibrating the 42 uncorrected dates from Lighty et al. (1982) (see Fig. 5).

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