Last interglacial reef growth beneath Belize barrier and isolated platform reefs

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ABSTRACT

We report the first radiometric dates (thermal-ionization mass spectrometry) from late Pleistocene reef deposits from offshore Belize, the location of the largest modern reef complex in the Atlantic Ocean. The results presented here can be used to explain significant differences in bathymetry, sedimentary facies, and reef development of this major reef area, and the results are significant because they contribute to the knowledge of the regional geology of the eastern Yucatán. The previously held concept of a neotectonically stable eastern Yucatán is challenged. The dates indicate that Pleistocene reefs and shallow-water limestones, which form the basement of modern reefs in the area, accumulated ca. 125–130 ka. Significant differences in elevation of the samples relative to present sea level (>10 m) have several possible causes. Differential subsidence along a series of continental margin fault blocks in combination with variation in karstification are probably the prime causes. Differential subsidence is presumably related to initial extension and later left-lateral movements along the adjacent active boundary between the North American and Caribbean plates. Increasing dissolution toward the south during Pleistocene sea-level lowstands is probably a consequence of higher precipitation rates in mountainous southern Belize.

Keywords: Belize, Pleistocene, reef, U-series dating.

INTRODUCTION

The modern reefs of Belize occur in the form of a 250-km-long barrier reef and three isolated carbonate platforms or atolls (Fig. 1). They represent the largest reef system in the Atlantic Ocean. The depth of the lagoon area behind the barrier reef north of Belize City does not exceed 5 m, whereas water depths of the lagoon south of Belize City increase to >40 m at the southern end of the barrier reef. A similar deepening trend from north to south may be seen on the offshore isolated platforms. The deepest parts of the lagoons within Turneffe Islands and Lighthouse Reef are ≤8 m deep. In contrast, to the south, the platform interior of Glovers Reef has a maximum water depth of 18 m.

The deep basement of this major reef system is a series of three, more or less parallel, north-northeast–trending fault blocks along the passive continental margin (Dillon and Vedder, 1973; James and Ginsburg, 1979). These are, from west to east, the Ambergris Cay shoreline trend, the Turneffe-Chinchorro trend, and the Glovers-Lighthouse trend (Fig. 2). The Belize mainland can be divided into two morphologic and geologic regions. Flat-lying Cenozoic limestones underlie the low-relief north. Southward, the Maya Mountains have a Paleozoic core that is fringed by Cretaceous limestones and dolomites. The active boundary between the North American and Caribbean plates is located less than 50 km south of the southern end of the Belize barrier reef (Fig. 1).

Exposures of Pleistocene rocks only occur in northernmost Belize in the form of rare outcrops of shallow-water limestones that are usually recrystallized. Tebbutt (1975) described a zoned Pleistocene barrier reef to shelf section on Ambergris Cay. Shallow drilling has shown that Pleistocene reef and shallow-water limestones also make up most of the pre-Holocene rocks underlying the barrier-reef platform, patch reefs and shoals on the shelf, the northern barrier-reef lagoon (Purdy, 1974), and reefs and lagoons of the offshore atolls (Gischler and Hudson, 1998; Gischler and Lomando, 1999). Pre-Holocene rocks of the southern shelf lagoon are Pleistocene terrigenous clastic strata (Purdy, 1974). The closest radiometrically dated Pleistocene deposits so far reported are about 300–400 km to the north of Belize. Szabo et al. (1978) dated corals from Pleistocene limestones south of Cancun and on the island of Cozumel at 2–4 m above present sea level as ca. 125 000 yr B.P. and concluded that the eastern Yucatán has been tectonically stable since the last interglacial highstand of sea level.

Drilling and seismic studies have shown that the position of the Pleistocene top beneath Holocene deposits is highly variable on the Belize shelf and barrier reef (Purdy, 1974; Halley et al., 1977; Shinn et al., 1982; Westphall and Ginsburg, 1985; Mazzullo et al., 1992; Macintyre et al., 1995) and on the isolated platforms offshore (Gischler and Hudson, 1998; Gischler and Lomando, 1999) (Fig. 2). The elevation of the Pleistocene top beneath and adjacent to Holocene reefs, shoals, and islands ranges from 1 m above present sea level in northern Belize to >25 m below present sea level in southern Belize. Beneath lagoonal areas, the depth of the Pleistocene top increases from 3–4 m below sea level in northern Belize to more than 50 m below sea level in southern Belize. Consequently, there are significant differences with regard to bathymetry, sedimentary facies, and Holocene reef development from north to south on the shelf (Purdy, 1974) and among the isolated platforms (Gischler and Lomando, 1999).

This study was designed (1) to produce the first radiometric dates of Pleistocene limestones in Belize and (2) to clarify whether the variation in Pleistocene elevation is related to differences in karstification, i.e., increasing precipitation rates toward the south, or to tectonics, i.e., increasing subsidence toward the south and/or variation in subsidence from fault block to fault block.

MATERIALS AND METHODS

Seven Pleistocene coral samples were selected from within the top 5 m of Pleistocene sections in cores from the Belize isolated carbonate platforms

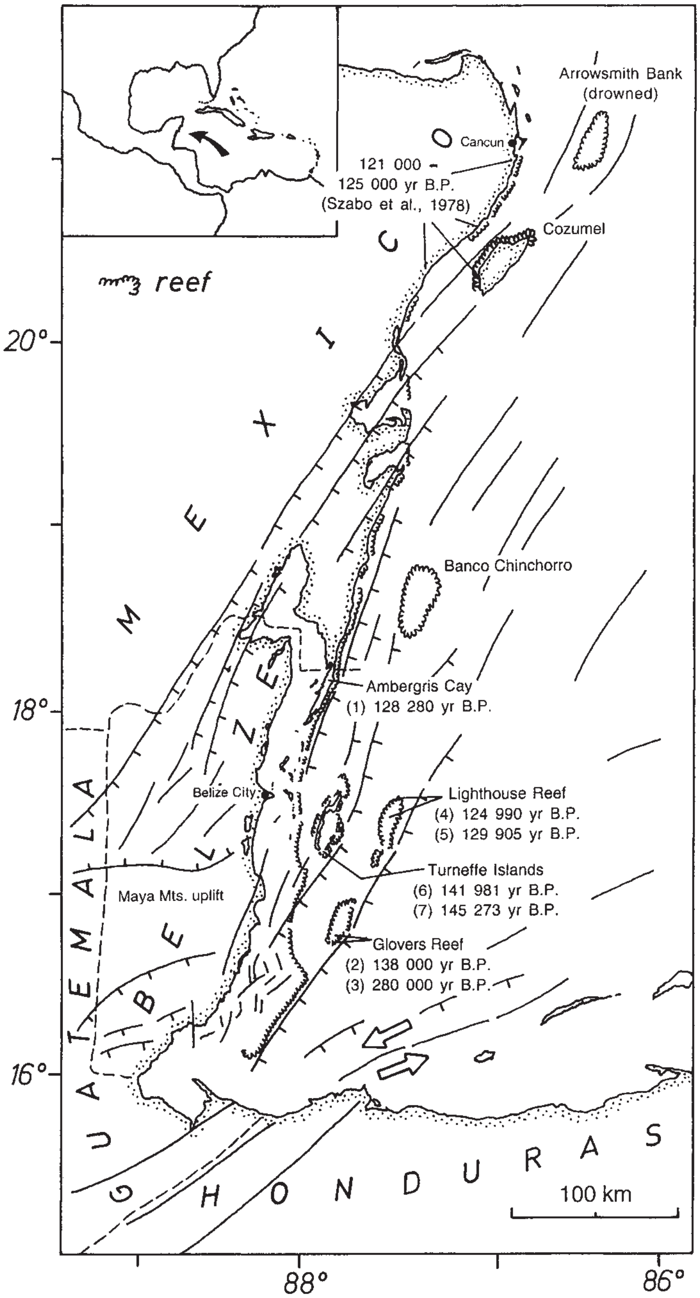

Figure 1. Radiometric dates (thermal-ionization mass spectrometry) from Pleistocene corals on simplified tectonic map of eastern Yucatán peninsula and offshore areas (after Dillon and Vedder, 1973; Case and Holcombe, 1980). Arrows indicate active plate boundary. Radiometric dates from upper Pleistocene deposits closest to those presented here are from area around Cancun and from island of Cozumel (Szabo et al., 1978). See Table 1 for full data set of samples 1–7.

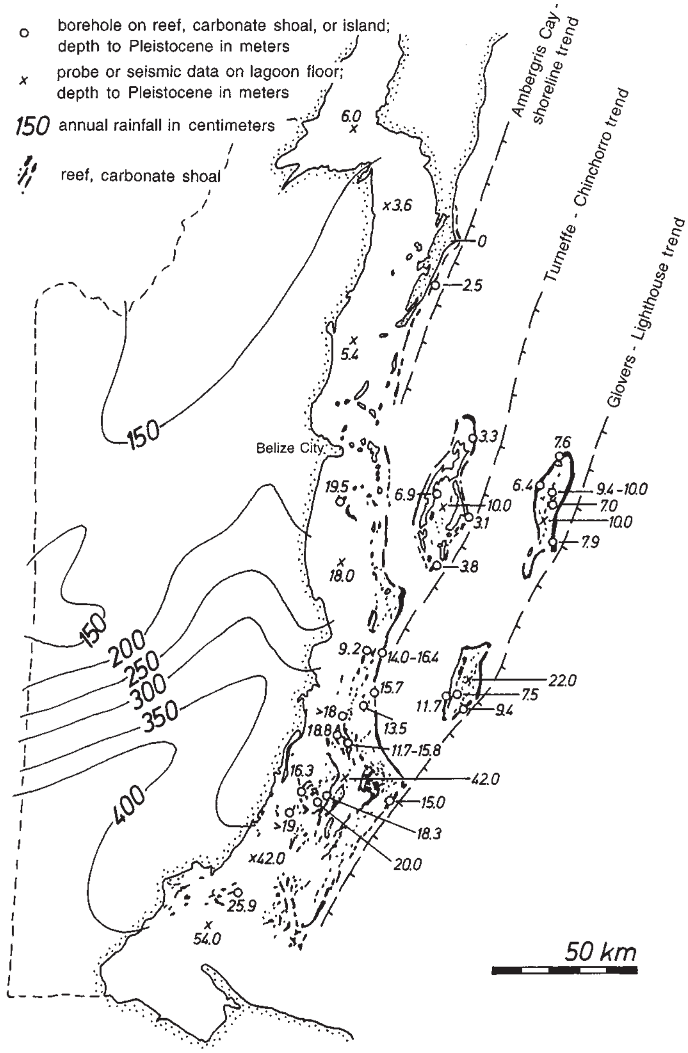

Figure 2. Belize offshore area showing elevation of Pleistocene top under reefs, carbonate shoals, and islands as well as under lagoonal areas (simplified). Map is based on data from Purdy (1974), Halley et al. (1977), Shinn et al. (1982), Westphall and Ginsburg (1985), Mazzullo et al. (1992), Macintyre et al. (1995), Gischler and Hudson (1998), and Gischler and Lomando (1999).

and from an outcrop in northern Belize (Figs. 1 and 2). Samples were analyzed for aragonite content by using X-ray diffractometry (Milliman, 1974, p. 21–29) and dated by thermal-ionization mass spectrometry (Edwards et al., 1986; Chen et al., 1986; Hamelin et al., 1991).

RESULTS

Ages obtained from late Pleistocene corals of Belize range from 125 to 145 ka, except for sample 3, which yielded an age of 280 ka (Table 1; Fig. 1). Uranium concentrations are between 2.3 and 2.7 ppm. For comparison, Szabo et al. (1994) measured uranium contents between 2.3 and 3.4 ppm in more than 30 pristine Pleistocene corals of Hawaii. The calculated initial uranium activity ratio, which is taken as an important parameter of reliability in U-series dating, ranges from 1.15‰ to 1.17‰. Values for modern seawater range from 1.14‰ to 1.15‰; the mean is 1.148‰ (Chen et al., 1986). The measured variation in uranium activity of our samples is in a range typical of that found in other U-series analyses of Pleistocene corals. This variation is a general problem in mass spectrometric dating because subtle diagenetic alteration can occur, even in largely aragonitic coral skeletons, and identifying pristine coral skeletons for dating is a problem still to be resolved (Ku et al., 1990; Bar-Matthews et al., 1993; Henderson et al., 1993). We consider the dates obtained from samples 1 and 3 to be reliable. The dates obtained from samples 2, 4, 5, and 7 are moderately reliable, because the uranium activity ratios exceed 1.160, which is >1% above the value of modern seawater. The uranium activity ratio of sample 6 is 1.157‰; however, because the aragonite content is only 86%, we consider this date to be moderately reliable. In addition to the mineralogy and the uranium activity ratio being significant indicators of reliability in age dates, the context of local geologic history is also important, including neotectonics, karst processes, and fluctuations in sea level, discussed in the following.

TABLE 1. U-TH DATES (THERMAL-IONIZATION MASS SPECTROMETRY) OF PLEISTOCENE CORALS FROM BELIZE

Sample	Aragonite content (%)	Location	Elevation (m)	^{238}U (ppm)	^{234}U/^{238}U initial (%)	Age (yr B.P.)	Lab	Reliability
(1) *A. palmata*	98%	Ambergris Cay	+ 1 m	---	1.157	128 280 ± 1330	UNM*	R
(2) *M. annularis*	5%	Glovers, hole 1	–9 m	---	1.168	138 000 ± 810	USGS†	M
(3) *M. annularis*	97%	Glovers, hole 3	–8 m	---	1.160	280 300 ± 3000	USGS†	R
(4) *A. cervicornis*	93%	Lighthouse, hole 11	–9.5 m	2.54	1.168	124 990 ± 355	USGS†	M
(5) *A. palmata*	97%	Lighthouse, hole 12	–8 m	2.67	1.165	129 905 ± 484	USGS†	M
(6) *A. palmata*	86%	Turneffe, hole 8	–4 m	2.53	1.157	141 981 ± 542	USGS†	M
(7) *M. annularis*	89%	Turneffe, hole 8	–4 m	2.29	1.171	145 273 ± 498	USGS†	M

Note: For location, see also Figure 1. Uranium contents of samples 1–3 were lost during data transfer and could not be retrieved. R—reliable; M—moderately reliable. Descriptions of core holes are published in Gischler and Hudson (1998) and Gischler and Lomando (1999). Outcrop on Ambergris Cay is described in Tebbutt (1975).

* Analyzed by the University of New Mexico, Albuquerque, New Mexico, Y. Asmerom.

† Analyzed by the U.S. Geological Survey, Denver, Colorado, C. W. Holmes.

DISCUSSION

Neotectonics

The active boundary between the North American and Caribbean plates is a major tectonic element in the study area (e.g., Mann et al., 1990; McCann and Pennington, 1990) (Fig. 1). This boundary is the left-lateral Motagua-Polochic fault zone in Guatemala that continues offshore into the Cayman Trough spreading center, located about 750 km to the east. With continued spreading at the Cayman Trough since the early Tertiary, the series of north-northeast–trending fault blocks along the Belize continental margin have been subsiding. Reefal deposits have been accumulating on fault-block highs, with more than 500 m thickness on Glovers Reef and >1000 m on Turneffe Islands and the barrier reef (Dillon and Vedder, 1973). Lara (1993) presented seismic evidence for Pliocene and younger tectonic structures such as northeast-trending wrench faults in the southern Belize barrier reef and lagoon. The existence of younger wrench faulting as well as older, fault-block–parallel structures on the offshore carbonate platforms was discussed by Lomando et al. (1995) and Lomando and Ginsburg (1995). Further evidence of neotectonic movements includes repeated earthquakes and surface-breaking faults in seismic lines (e.g., Dillon and Vedder, 1973). Dill (1977) suggested a Pleistocene southward tilt of Lighthouse Reef on the basis of tilted Pleistocene stalactites in the famous "blue hole" in the lagoon of that same offshore carbonate platform. However, on the basis of borehole data, Gischler and Lomando (1999) found no indication of a southward inclination of the Pleistocene top of the same platform.

Considering the differences in Pleistocene elevation among fault blocks as purely the result of differential subsidence would produce subsidence rates of 39 mm/k.y. for the Ambergris Cay shoreline trend (calculation based on sample 1), 69–70 mm/k.y. for the Turneffe-Chinchorro trend (calculation based on samples 6 and 7), and 112–119 mm/k.y. for the Glovers-Lighthouse trend (calculation based on samples 4 and 5) since interglacial oxygen isotope stage 5e. This calculation is based on a sea-level datum 6 m higher than today during that sea-level highstand. The calculated values are within the typical rates of long-term subsidence of carbonate platforms (Schlager, 1981).

Karst Processes

Purdy (1974) gave evidence that the pre-Holocene surface of the Belize shelf and barrier reef has a Pleistocene karst morphology, the expression of which was controlled by the underlying structural grain. The trend of a southward decrease in Pleistocene elevation can be related to the increase in precipitation in the same direction (Fig. 2). In the low-relief area of north Belize, rainfall is about 150 cm/yr, whereas in the mountainous south, annual precipitation exceeds 400 cm (Purdy, 1974). Even though absolute rainfall rates in the Pleistocene were different from those of today, relative differences between the areas were probably much the same. Gischler and Hudson (1998) and Gischler and Lomando (1999) favored the same interpretation to explain the increase in Holocene reef thickness and Pleistocene relief from Turneffe Islands (3–4 m and 4–5 m, respectively) to Lighthouse Reef (6.5–8 m and 4–5 m, respectively) to Glovers Reef (9.5–12 and 10–12 m, respectively) in the south. That reef limestones of oxygen isotope stage 9 are found together with those of stage 5 near the Pleistocene top only on Glovers Reef (sample 3) corroborates the assumption of stronger Pleistocene dissolution in the south of Belize. According to Purdy (1974) and to estimates by Purdy and Winterer (1999), dissolution since the last sea-level highstand about 125 ka was not sufficient to produce the observed relief of the Pleistocene top in the Belize atolls. Rather, this relief is a temporal composite of both subaerial dissolution during glacial lowstands and carbonate accretion during interglacial highstands of sea level throughout the Pleistocene.

Coral Bathymetry, Changes in Sea Level

When using radiometric dates from corals as indicators of former sea level, it is crucial to know whether they lived close to sea level. Maximum depth ranges of the corals used here are reported as 0–5 m for *Acropora palmata* framework (Lighty et al., 1982), 0–25 m for *Acropora cervicornis* thickets, and 0–80 m for *Montastraea annularis* (James and Ginsburg, 1979; Cairns, 1982). The occurrence of *A. palmata* in outcrops on Ambergris Cay and in Pleistocene core sections from Glovers Reef, Lighthouse Reef, and Turneffe Islands suggests deposition in shallow water. Redeposition is unlikely, because all the samples come from topographic highs.

The majority of dates suggest that the pre-Holocene deposits accumulated during the sea-level highstand of oxygen isotope stage 5. According to the oxygen isotope curves of deep-sea cores (Imbrie et al., 1984; Shackleton, 1987), the maximum level of the sea was reached at 125 ka. However, curves based on data from coral reefs show that the last interglacial already had begun ca. 140 ka, and lasted about 20 k.y. (e.g., Edwards et al., 1986, 1987; Bard et al., 1990; Chen et al., 1991; Zhu et al., 1993; Szabo et al., 1994). A sea-level stand of about 2 m above the present level was reached between 131 and 133 ka. In the light of these data, the ages of samples 2, 6, and 7 appear to be too old. Dates of ca. 140–145 ka are in the lowstand of oxygen isotope stage 6, during which sea level was ~120 m below present level, and would require significant uplift of several hundreds of millimeters per thousand years, which is inconsistent with the geologic history of the area. Sample 3 was apparently deposited during the highstand of oxygen isotope stage 9. An age of 280 ka would put the sample at about 50 m below present sea level on the curve, which would require significant uplift, inconsistent with regional geology. Therefore, the obtained age of sample 3 remains enigmatic.

The accuracy of the dates creates another problem. Errors of reliable data amount to >1000 yr (Table 1); therefore, the exact positions of samples relative to sea level are difficult to determine. Toward oxygen isotope stage 5, for example, sea level rose at rates of as much as 10 000 mm/k.y., i.e., 10 m in only 1000 yr.

CONCLUSIONS

Pleistocene reef and shallow-water limestones from offshore Belize form major parts of the basement of the largest modern reef system in the Atlantic Ocean, and have been dated for the first time. These limestones accumulated during the last interglacial sea-level highstand (oxygen isotope stage 5). The reasons for significant variation of Pleistocene elevation offshore Belize cannot be identified with certainty; however, differential subsidence from complex extension and transtension and variation in intensity of karst processes are probably responsible. The assumption of a neotectonically stable eastern Yucatán (Szabo et al., 1978) should be modified.

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