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Letter Section

Holocene development of three isolated carbonate platforms, Belize, Central America

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Abstract

Locally operating factors such as topography of the reef basement and exposure to waves and currents rather than regionally effective factors such as the post-glacial sea level rise in the western Atlantic explain the different Holocene developments of the three isolated carbonate platforms Glovers Reef, Lighthouse Reef, and Turneffe Islands offshore Belize. A series of NNE-striking tilted fault-blocks at the passive continental margin forms the deep basement of the Belize reefs. Glovers and Lighthouse Reefs are located on the same fault-block, while Tumeffe Islands is situated west of Lighthouse Reef on an adjacent fault-block. The three platforms are surrounded by deep water and have surface-breaking reef rims. Significant differences exist between platform interiors. Glovers Reef has only 0.2% of land and an 18 m deep, well-circulated lagoon with over 800 patch reefs. Lighthouse Reef has 3% of land and a well-circulated lagoon area. Patch reefs are aligned along a NNE-striking trend that separates a shallow western (3 m) and a deeper eastern (8 m) lagoon. Turneffe Islands has 22% of land that is mainly red mangrove. Interior lagoons are up to 8 m deep and most have restricted circulation and no patch reefs. Surface sediments are rich in organic matter. In contrast, the northernmost part of Turneffe Islands has no extensive mangrove development and the well-circulated lagoon area has abundant patch reefs. Holocene reef development was investigated by means of 9 rotary core holes that all reached Pleistocene reef limestones, and by radiometric dating of corals. Maximal Holocene reef thickness reaches 11.7 m on Glovers Reef, 7.9 m on Lighthouse Reef, and 3.8 m on Turneffe Islands. Factors that controlled Holocene reef development include the following. (1) Holocene sea level. The margin of Glovers Reef was flooded by the rising Holocene sea ca. 7500 YBP, that of Lighthouse Reef ca. 6500 YBP, and that of Turneffe Islands between 5400 and 4750 YBP. All investigated Holocene reefs belong to the keep-up type, even though the three platforms were flooded successively and, hence, the reefs had to keep pace with different rates of sea level rise. (2) Pre-Holocene topography. Pleistocene elevation and relief are different on the three platforms. This is the consequence of both tectonics and karst. Different elevations caused successive reef initiation and they also resulted in differences in lagoon depths. Variations in Pleistocene topography also explain the different facies distribution patterns on the windward platforms that are located on the same fault-block. On Lighthouse Reef tectonic structures are clearly visible such as the linear patch reef trend that is aligned along a Pleistocene fault. On Glovers Reef only short linear trends of patch reefs can be detected because the Pleistocene tectonic structures are presumably masked by the higher Holocene thickness. The lower Pleistocene elevation on Glovers Reef is probably a consequence of both a southward tectonic tilt, and stronger karstification towards the south related to higher rainfall. (3) Exposure to waves and currents. Glovers Reef,

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Lighthouse Reef, and the northernmost part of Turneffe Islands receive the maximum wave force as they are open to the Caribbean Sea. Adjacent lagoons are well-circulated and have luxuriant patch reef growth and no extensive mangrove development. By contrast, most of Turneffe Islands is protected from the open Caribbean Sea by Lighthouse Reef to the east and is only exposed to reduced wave forces, allowing extensive mangrove growth in these protected areas.

Keywords: Belize; reef; carbonate platform; C-14

1. Introduction

There is no unifying model of Holocene reef development, however, three decisive factors are discussed repeatedly in the literature, namely antecedent topography, Holocene sea level, and exposure to waves and currents. The model of antecedent topography was revived by Purdy (1974a,b) based in part on his work in Belize (see below). Later studies, e.g., in Florida have confirmed the model (Shinn et al., 1977), other investigations, e.g., in Panama (Macintyre and Glynn, 1976), in the Great Barrier Reef (Walbran, 1994), or in the Abrolhos (Collins et al., 1996) have shown that Holocene reef development has occurred largely independent of pre-Holocene topography. Different rates of Holocene sea level rise may produce different reef anatomies such as keep-up, catch-up, and give-up reefs as brilliantly discussed by Neumann and Macintyre (1985). However, their model is based solely on examples from the Atlantic/Caribbean where the course of Holocene sea level differs from that in the Indo-Pacific region. Adey (1978) discussed the relations between characteristics of reef margins and wave energy. High-energy reefs are dominated by coralline algae and milleporids with slow and compact growth while lower-energy reefs are characterized by a rather porous framework of fast-growing acroporids. Macintyre (1988) used that model to explain the differences between eastern and western Caribbean reefs. Davies and Marshall (1980) demonstrated that there are differences in reef growth between windward and leeward reefs of One Tree Atoll in the Great Barrier Reef. Windward reefs are composed of massive corals and accumulation-rates are lower than on leeward reefs that are dominated by branched corals. Similar observations were made by Collins et al. (1996) in the Abrolhos. However, there are no studies that compare windward and leeward reef anatomies in the Atlantic/Caribbean region.

Purdy (1974b) was the first to investigate Holocene reef development in Belize. He found that Holocene reef thickness on the Belize shelf increases towards the south and that Holocene reefs are situated on Pleistocene highs. Pleistocene topography was interpreted to be a karst morphology that has been directed in its expression by underlying structure. Increased rainfall towards the south caused higher karstification of the southern Belize shelf (Purdy, 1974b). Halley et al. (1977) and Shinn et al. (1979) interpreted reefs on the central Belize shelf to be located on Pleistocene patch reefs. Choi and Ginsburg (1982) and Choi and Holmes (1982) concluded that reefs on the southern Belize shelf are situated on fluvial deposits of Pleistocene rivers. Based on seismic data Lara (1993) argued that Tertiary and Quaternary fault-tectonics produced a morphology of ridges and valleys that controls distribution of modern reefs on the southern Belize shelf. Lomando et al. (1995) demonstrated on the basis of high-resolution satellite imagery that facies distribution on the isolated platforms is a consequence of Quaternary fault tectonics. Studies on the anatomy of Belize reefs showed that there are keep-up reefs on the northern (Mazzullo et al., 1992), more or less uncemented keep-up and catch-up reefs on the central (Shinn et al., 1979; Westphall and Ginsburg, 1985), and presumably give-up reefs on the southern Belize shelf (Precht, 1994). Macintyre et al. (1981) and Shinn et al. (1982) found that the central barrier reef near Carrie Bow Cay is composed of well-cemented massive and branched coral facies in the fore reef and uncemented reef sand and some massive corals directly behind the reef crest. To date, there are no studies on reef growth and anatomy of the isolated carbonate platforms offshore Belize. Glovers Reef, Lighthouse Reef, and Turneffe Islands are well-suited for a study of Holocene reef development as they exhibit a variety of reef types including windward, leeward, and lagoon reefs. Furthermore there are significant differences in platform interiors even though the platforms are located in a similar geologic setting which urges the question for the factors that led to the diverging development.

2. Study area

2.1. Geological background

Belize can be separated into two geological and morphological areas (Fig. 1a). The flat north is characterized by Tertiary limestone, the mountainous south by a core of Paleozoic metasediments and metavolcanics fringed by Cretaceous limestone. The passive continental margin of Belize is structured by a series of NNE-striking fault-blocks that form the deep basement of the Belize reefs (Dillon and Vedder, 1973). Exploration wells on Glovers Reef and Turneffe Islands penetrated 560 m and 1030 m of shallow water carbonates before reaching clastics of the Late Cretaceous–Early Tertiary and Paleozoic metasediments and metavolcanics (Dillon and Vedder, 1973). Neotectonics along the fault-blocks is due to the close proximity of the North American–Caribbean plate boundary that is located in the Gulf of Honduras.

Surface sediments on the Belize shelf are pure carbonate in the north and mixed siliciclastic–carbonate in the south (Purdy, 1974b; Purdy et al., 1975). Four major surface sedimentary facies may be distinguished on the isolated platforms (Gischler, 1994; Lomando and Gischler, 1996; Gischler and Lomando, 1997). Reef and fore reef sediments are composed of fragments of coral, red algae, and *Halimeda*. Shallow lagoon sediments are dominated by non-skeletal grains, namely fecal pellets. In deeper lagoon environments sediments are composed of mollusc and foram fragments. Lagoon sediments of Turneffe Islands are rich in organic matter with up to 15% TOC.

2.2. Geomorphology and environments

All three platforms are surrounded by deep water (Stoddart, 1962) (Fig. 1b). The platforms have surface-breaking reef rims with a windward spur-and-groove system of *Acropora palmata* and *Agaricia agaricites* dominating, and leeward reefs with *Montastraea annularis* (Stoddart, 1962; James et al., 1976; Gischler, 1994). Reef and fore reef morphologies of Glovers Reef were described in detail by James et al. (1976) and James and Ginsburg (1979). From the reef crest seaward water depth increases along slopes of 20–30°. In water depths usually between 20–40 m there are breaks in the slopes (drop-offs) where almost vertical walls extend to depths of several hundreds of meters. Significant environmental differences may be observed within platform interiors.

2.2.1. Glovers Reef

This oval platform covers 260 km^2 with only 0.2% of land which is sand–shingle cays. Three windward tidal passes through the reef rim connect the open ocean with the well-circulated lagoon that gets up to 18 m deep and has 864 patch reefs. Wallace and Schafersman (1977) interpreted the east-to-west zonation of *Montastraea*-, *Acropora*-, and algae-dominated patch reefs as a succession following a former destructive event. A number of patch reefs in the western lagoon form NNE-striking lines.

2.2.2. Lighthouse Reef

The smallest of the Belize isolated platforms covers 200 km^2 with 2.9% of land that is both sand–shingle cays and mangrove–sand cays. The well-circulated lagoon has hundreds of patch reefs most of which are aligned along a NNE-striking ridge. This ridge separates an up to 3 m deep western lagoon and an up to 8 m deep eastern lagoon. Patch reefs in the eastern lagoon are dominated by *A. palmata*, those in the western lagoon by *M. annularis*. The famous Blue Hole in the eastern lagoon is a 125 m deep Pleistocene cave with collapsed roof (Dill, 1977).

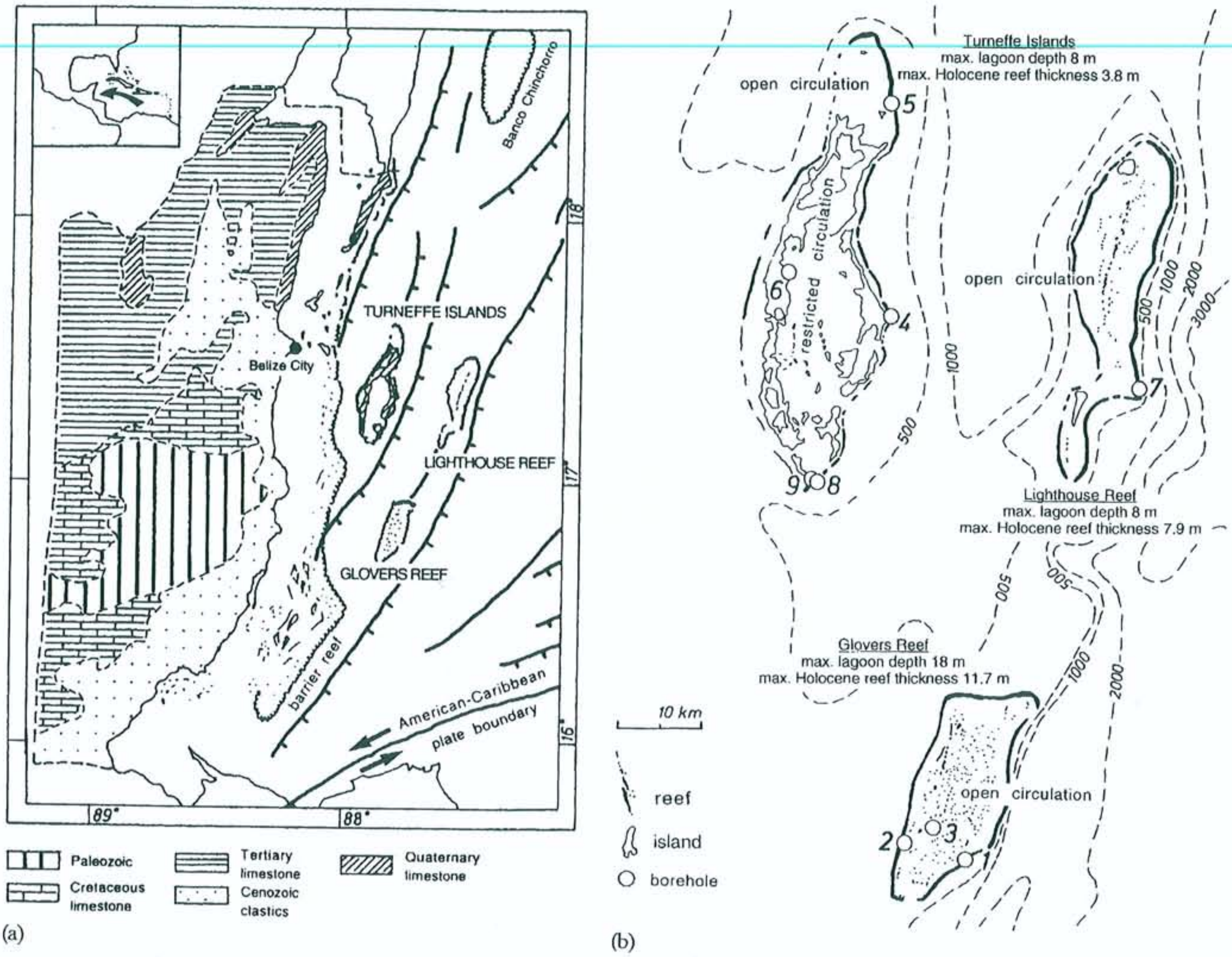

Fig. 1. (a) Map of the study area including simplified geology and most important offshore tectonic structures (after Dillon and Vedder, 1973; Purdy, 1974b, Purdy et al., 1975; James and Ginsburg, 1979). (b) Map of the isolated platforms showing the locations of the nine boreholes and data on bathymetry and Holocene reef thickness. Depth contours are in meters. Water depths between the platforms and the barrier reef (not shown) reach about 400 m east of Glovers Reef and about 250 m east of Turneffe Islands.

2.2.3. Turneffe Islands

The largest of the platforms has an area of 525 km^2 with 22% of land that is mainly covered by red mangrove. Windward and leeward mangrove rims encircle up to 8 m deep lagoons with restricted circulation. Walton Smith (1941) observed extreme fluctuations in water temperature and salinity in the southern lagoon with maximum values of 31°C and 70‰, respectively. Patch reefs are very rare and only occur close to tidal passes within the mangrove rims. They are dominated by the tolerant coral *Siderastrea siderea* and have low diversity. The lagoon floor is entirely covered with the seagrass *Thalassia* and the alga *Halimeda*. Surface sediments are dark-colored and rich in organic matter (Lomando and Gischler, 1996). In contrast, the northernmost part of Turneffe Islands has no extensive mangrove development and the lagoon is well-circulated and has abundant patch reefs of coral.

2.3. Climate and oceanography

Belize has a sub-tropical climate with average air temperatures of 27°C in the summer and 24°C in winter. Water temperatures range between 29°C in the summer and 27°C in winter. There is no long-term data on precipitation on the platforms. However, annual rainfall on the more or less flat mainland west of the northern platforms ranges between 150–200 cm and around 300 cm on the mountainous mainland west of Glovers Reef (Purdy et al., 1975). The tidal range is 30 cm (Stoddart, 1962). Winds are blowing from the east for most of the year with velocities between 7–13 knots, however, during the winter months 'northers' bring cold air from the American continent. Hurricanes may seriously damage the offshore reefs and islands such as, e.g., Hurricane Hattie in 1961 (Stoddart, 1963). The mean wave approach is from ENE, i.e., approximately from 75° (Burke, 1982). Current velocities usually range from 50–100 cm/s. Counter-currents produce north-to-south waterflows in the open lagoon of Glovers Reef (Wallace and Schafersman, 1977). Southward current directions are also observed between the barrier reef and Glovers Reef and Turneffe Islands and between Turneffe Islands and Lighthouse Reef (Purdy et al., 1975).

3. Methods

The cores were taken between late September and early October 1995 and in August 1996 (Fig. 1b). We used an underwater rotary drill on a tripod as described by Macintyre (1975) and Shinn et al. (1982) with a wireline core-barrel. Twenty feet long PVC-pipes with slotted base were inserted into holes 1–3 to make later reef-hydrological studies possible. The core material was cut in half with a rock saw and described. From 29 samples, thin-sections (5 × 7.5 cm) were prepared and investigated with a petrographic microscope. Staining fluids used were Feigl's solution (aragonite) and titan yellow (high-Mg-calcite) according to Friedman (1971). Thirty-one samples were X-rayed with a diffractometer and contents of aragonite, high-Mg-calcite, and low-Mg-calcite determined after the method of Milliman (1974). Selected samples were investigated with SEM. Sixteen Holocene coral samples were used for standard radiometric dating (^{14}C) and one Holocene peat sample for AMS-dating (Beta Analytic, Miami). The dates were neither corrected for reservoir and DeVries effects nor for natural isotopic fractionation.

4. Subsurface data

4.1. Holocene facies

Four Holocene facies could be recognized in our cores, a coral boundstone facies, a grain-rudstone facies, an unconsolidated facies of reef sand and rubble, and peat.

(1) The coral boundstone facies is the most abundant and is dominated by decimeter-sized fragments of *Acropora palmata*, *Montastraea annularis*, *Diploria strigosa*, or *Acropora cervicornis* (Figs. 2 and 3). Minor amounts of early submarine aragonite and high-Mg-calcite cements only occur within coral skeletons (Table 1). Crustose coralline algae are moderately common on the surfaces of coral fragments. *A. palmata* is most common on windward reefs where it may be intercalated with massive corals (*M. annularis*, *D. strigosa*) or cemented grain-rudstone. *M. annularis* is most abundant on the leeward reef side of Glovers Reef. *A. cervicornis* is most common in the upper part of the lagoon reef in Glovers Reef.

(2) The grain-rudstone facies consists of several millimetre- to centimetre-sized fragments of coral, coralline algae, and *Halimeda* in a well-cemented matrix of wackestone to packstone (Fig. 3). In places the encrusting foraminifers *Homotrema rubrum* and *Carpenteria* sp. are abundant in this facies. The most abundant cement is microcrystalline high-Mg-calcite cement. The well-cemented grain-rudstone facies is most common on windward reef sides, indicating that early submarine cementation in Belize reefs may be correlated with water agitation. James et al. (1976) and Gischler and Lomando (1997) came to similar conclusions. However, detailed results of investigations in diagenesis of the core material and reef pore water geochemistry and hydrology will be presented elsewhere.

(3) Unconsolidated reef sand and rubble consists of fragments of coral, coralline algae, and

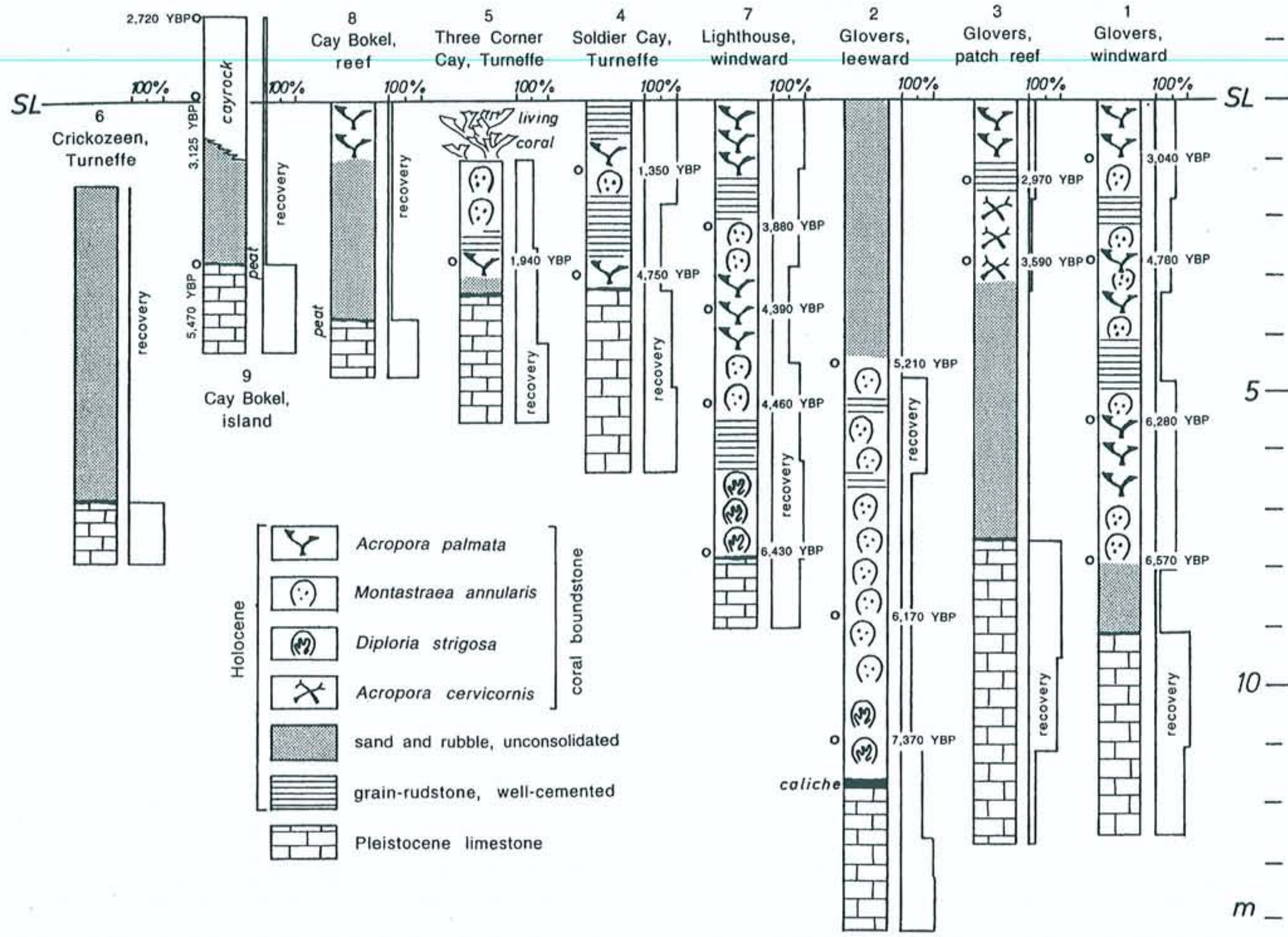

Fig. 2. Core data of the nine boreholes on isolated carbonate platforms offshore Belize. There was no core recovery in unconsolidated sand and rubble, however, loose material was flushed to the surface by the drill fluid, collected, and identified. For locations of coreholes see Fig. 1b.

Halimeda and is most common on leeward reef sides and in the lagoon patch reef section.

(4) Only at the base of the two Holocene sections at Cay Bokel, Turneffe Islands, was a Holocene peat recovered.

Holocene thickness is highest on Glovers Reef with marginal reef thickness ranging from 9.1–11.7 m. Patch reef thickness is 7.5 m. Second highest Holocene reef thickness is reached on Lighthouse Reef with 7.9 m. It is lowest on Turneffe Islands where it ranges from 3.1–3.8 m. The fact that *A. palmata* overlies unconsolidated sand and rubble at the reef near Cay Bokel indicates that the reef grew back over its own rubble, a phenomenon also described by Shinn et al. (1977) from the Florida Reef Tract. The boreholes in the back reef and in the lagoon of Turneffe Islands as well as numerous probings with a 4-m long aluminium rod in lagoon areas of all platforms showed that Holocene sediment thickness ranges between 2 and 5 m in platform interiors. That range is in good accordance with data from lagoon areas on the Belize shelf (Table 2).

4.2. Pleistocene facies

The downward transition from Holocene to Pleistocene sections is characterized by a distinct change from mostly weak cemented sections to well-cemented limestones and a mineralogical change from aragonite/high-Mg-calcite to low-Mg-calcite predominance. High-Mg-calcite cement is

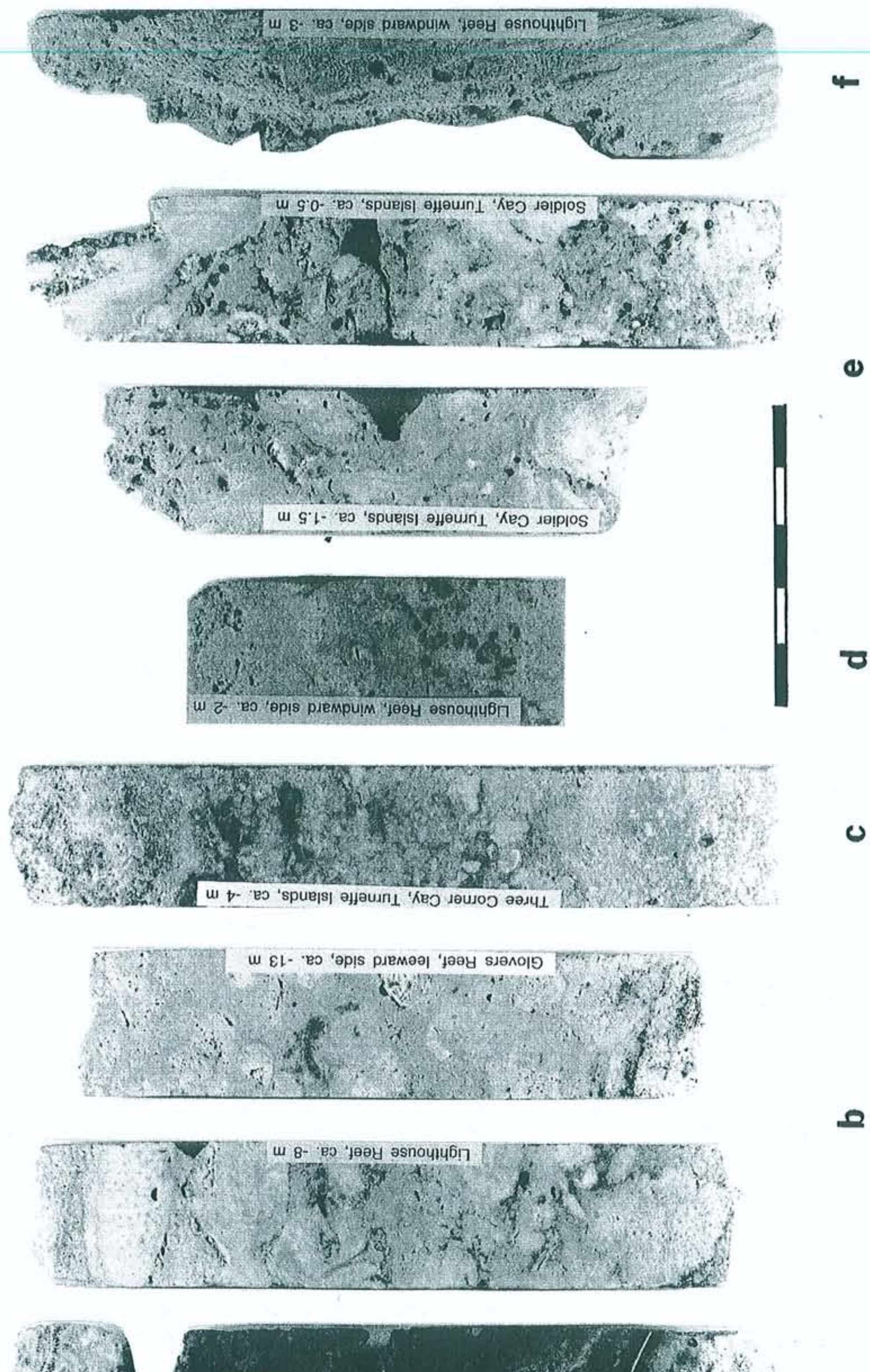

Fig. 3. (a) Holocene–Pleistocene contact in core from the leeward side of Glovers Reef is marked by a 0.2 m thick Pleistocene soil. Pleistocene coral below soil, Holocene coral above soil. (b) Pleistocene coral boundstones facies from Lighthouse and Glovers Reefs are dominated by branched corals. (c) Pleistocene grain-rudstone facies from Three Corner Cay, Turneffe Islands with abundant mollusc and coral fragments. (d) Holocene grain-rudstone facies from Lighthouse Reef consists of fragments of coralline algae, mollusc, and *Homotrema rubrum* in a matrix of wackestone to packstone. (e) Holocene grain-rudstone facies from Soldier Cay, Turneffe Islands, with abundant fragments of coral and coralline algae. Internal sediment contains fragments of *Halimeda*, *Homotrema* and mollusc. (f) Holocene coral (*Diploria* sp.) boundstone facies from Lighthouse Reef. Note overgrowth by layers of crustose coralline algae and *Homotrema*. Scale bar is 10 cm.

Table 1
Diagenetic features in the cores

Feature	Dimensions	Occurrence	Abundance
(1) Acicular aragonite cement	≤150 μm	Holocene	moderate
(2) Botryoidal aragonite cement	≤150 μm	Holocene	low
(3) Aragonite silt	≤20 μm	Holocene	moderate
(4) Microcrystalline high-Mg-calcite cement	≤5 μm	Pleistocene	high
		Holocene	low
(5) Peloidal high-Mg-calcite cement	30–60 μm	Holocene	moderate
		Pleistocene	low
(6) Blocky low-Mg-calcite cement	≤1 mm	Pleistocene	high
(7) Small blocky low-Mg-calcite cement	10–30 μm	Pleistocene	moderate
(8) Scalenohedral low-Mg-calcite cement	≤300 μm	Pleistocene	low
(9) Microcrystalline low-Mg-calcite cement	≤5 μm	Pleistocene	low
(10) Calcite whiskers cement	≤150 μm	Pleistocene	low
(11) Rhizocretions	≤500 μm	Pleistocene	low
(12) Grain dissolution		Pleistocene	low

Abundance of features given as 'high', 'moderate', and 'low'.

Table 2
Data on Holocene accumulation on the Belize shelf

Author	Setting	Max. Holocene thickness in m	Accumulation rate in m/1000 years
Purdy, 1974b	barrier reef	16.4	0.7–1.5 (mean: 1.1)
	shelf cay	25.9	–
	shelf lagoon	2.1	0.1–0.3 (mean: 0.2)
Halley et al., 1977	patch reef	13.4	1.6 (average)
	off-reef	5.9	0.4–0.5 (average)
Macintyre et al., 1981	fore reef	>11.6	massive facies 1.4–8.3
			branched facies 1.1–2.1
Shinn et al., 1982	barrier reef	15.7	1.0–6.0
	shelf	5.0	0.1–1.4
Westphall and Ginsburg, 1985	shelf reef	>13.0	>1.4
Mazzullo et al., 1992	patch reef	2.5	3.0–5.0
	off–reef	0.25	–
Macintyre et al., 1995	mangrove cay	10.0	0.4–4.3

still present in small quantities, but blocky and other low-Mg-calcite cements are most common in the Pleistocene sections (Table 1). Coral skeletons are often neomorphosed.

There are three well-cemented Pleistocene facies namely coral boundstone, grain-rudstone, and caliche.

(1) Coral boundstone is most abundant and is composed of centimetre- to decimetre-sized fragments of coral in a packstone to grainstone matrix. Common corals are *A. palmata*, *A. cervicornis*, branched *Porites* sp., *Agaricia* sp., and *M. annularis*. Smaller fragments of coral, mollusc, coralline algae, and *Halimeda* are common in the matrix.

(2) Grain-rudstone contains millimetre- to centimetre-sized fragments of coral, mollusc, coralline algae, and *Halimeda* in a wackestone to packstone matrix. From the abundance of coral and the comparison with data of Tebbutt (1975) of Pleistocene limestone on Ambergris Cay, northern Belize, Pleistocene boundstone and grain-rudstone facies are interpreted to be deposited in reefal environments.

(3) At the tops of all Pleistocene sections several

millimetres thick laminated crusts of low-Mg-calcite occur, which is indicative of subaerial exposure. Rhizocretions are common. In the borehole on the leeward side of Glovers Reef a 0.2 m thick brown caliche marks the boundary between Pleistocene and Holocene (Fig. 3). It consists of low-Mg-calcite, chlorite, smectite, montmorillonite, and quartz. It has a typically mottled and clotted texture including rhizocretions and shrinkage cracks. Borehole data shows that Pleistocene relief is higher on Glovers Reef than on the two northern platforms.

4.3. Ages

The radiometric dates from corals indicate that the margins of the three platforms were flooded by the rising Holocene sea successively. Glovers Reef was flooded not later than 7370 YBP, Lighthouse Reef not later than 6430 YBP, and Turneffe Islands between 5400 and 4750 YBP (Fig. 2). Most of the radiometric dates plot on or slightly above the Holocene sea level curve of Belize (Macintyre et al., 1995) that is in good accordance with the Lighty et al. (1982)-curve for the western Atlantic (Fig. 4). All reefs investigated belong to the keep-up type. Average Holocene reef accumulation rates are highest on the leeward side of Glovers Reef, followed by the windward sides of Glovers and Lighthouse Reefs. They are lowest on Turneffe Islands and on the patch reef in Glovers Reef (Table 3). However, calculated rates between single radiometric dates fluctuate highly and may reach 20 m/1000 years.

5. Discussion and conclusions

Factors that controlled Holocene reef development include Holocene sea level, antecedent topography, and exposure to waves and currents. Antecedent topography and exposure may also be used to explain the different developments of platform interiors.

5.1. Sea level

Even though the margins of the three platforms were flooded successively by the rising Holocene

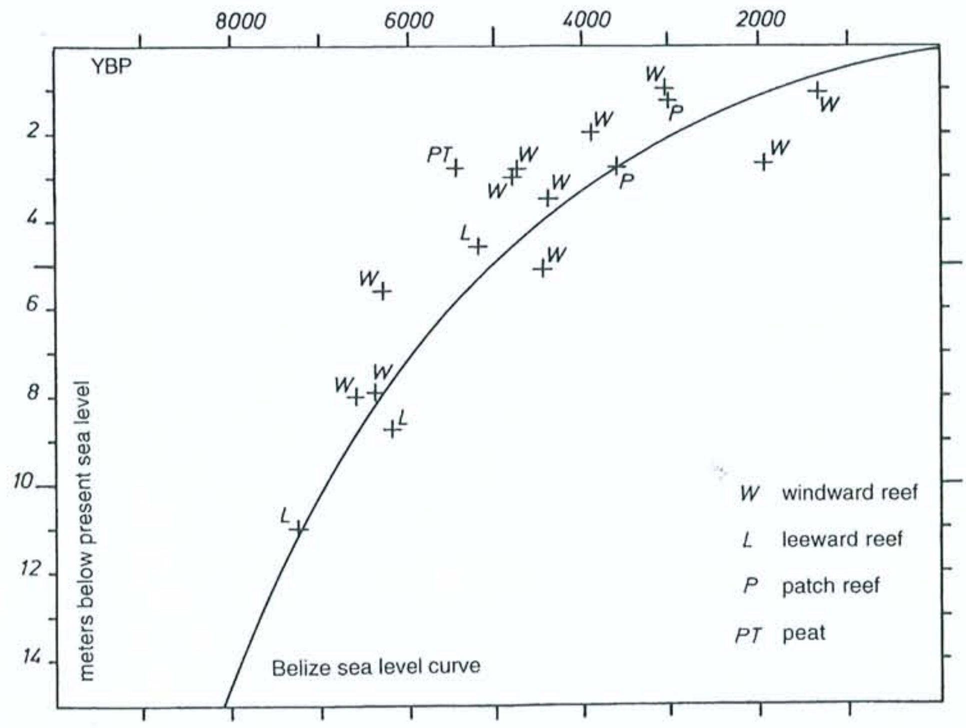

Fig. 4. Sea level curve of western Atlantic (Lighty et al., 1982) and similar Belize sea level curve (Macintyre et al., 1995). Note that most of the radiometric dates fall on or slightly above the curves indicating that reefs belong to the keep-up type.

Table 3
Conventional radiometric dates (not corrected) from corals of the Holocene sections of the cores and calculated accumulation rates

Depth rel. to SL (m)	Distance of dates	Radiometric datum (yr B.P. ± SD)	δt (yr)	Accum.-rate (m/1000 yr)	Average accum.-rate (m/1000 yr)
Glovers Reef, leeward side					
−11.0		7370 ± 70			1.49
	2.25		1200	1.88	
−8.75		6170 ± 90			
	4.15		960	4.32	
−4.6		5210 ± 90			
	4.6		5210	0.88	
0		0			
Glovers Reef, windward side					
−8.0		6570 ± 80			1.22
	2.4		290	8.28	
−5.6		6280 ± 80			
	2.8		1500	1.87	
−2.8		4780 ± 70			
	1.8		1740	1.03	
−1.0		3040 ± 70			
	1.0		3040	0.33	
0		0			
Glovers Reef, patch reef					
−2.8		3590 ± 80			0.78
	1.55		620	2.5	
−1.25		2970 ± 80			
	1.25		2970	0.42	
0		0			
Lighthouse Reef, windward side					
−7.9		6430 ± 60			1.28
	2.8		1970	1.42	
−5.1		4460 ± 60			
	1.6		70	22.86	
−3.5		4390 ± 70			
	1.5		510	2.94	
−2.0		3880 ± 50			
	2.0		3880	0.52	
0		0			
Turneffe Islands, near Soldier Cay, windward side					
−3.0		4750 ± 80			0.63
	1.9		3400	0.56	
−1.1		1350 ± 40			
	1.1		1350	0.81	
0		0			
Turneffe Islands, Cay Bokel, island, windward side					
−2.8		5470 ± 50 [a]			1.67
	3.0		2305	1.3	
0		3125 ± 55 [b]			
	1.5		405	3.7	
+1.5		2720 ± 50 [b]			
Turneffe Islands, near Three Corner Cay, windward side					
−2.7		1940 ± 60			1.39
	2.7		1940	1.39	
0		0			

[a] AMS-date of peat.
[b] Standard dates of shells of *Strombus gigas* (from Gischler and Lomando, 1997).

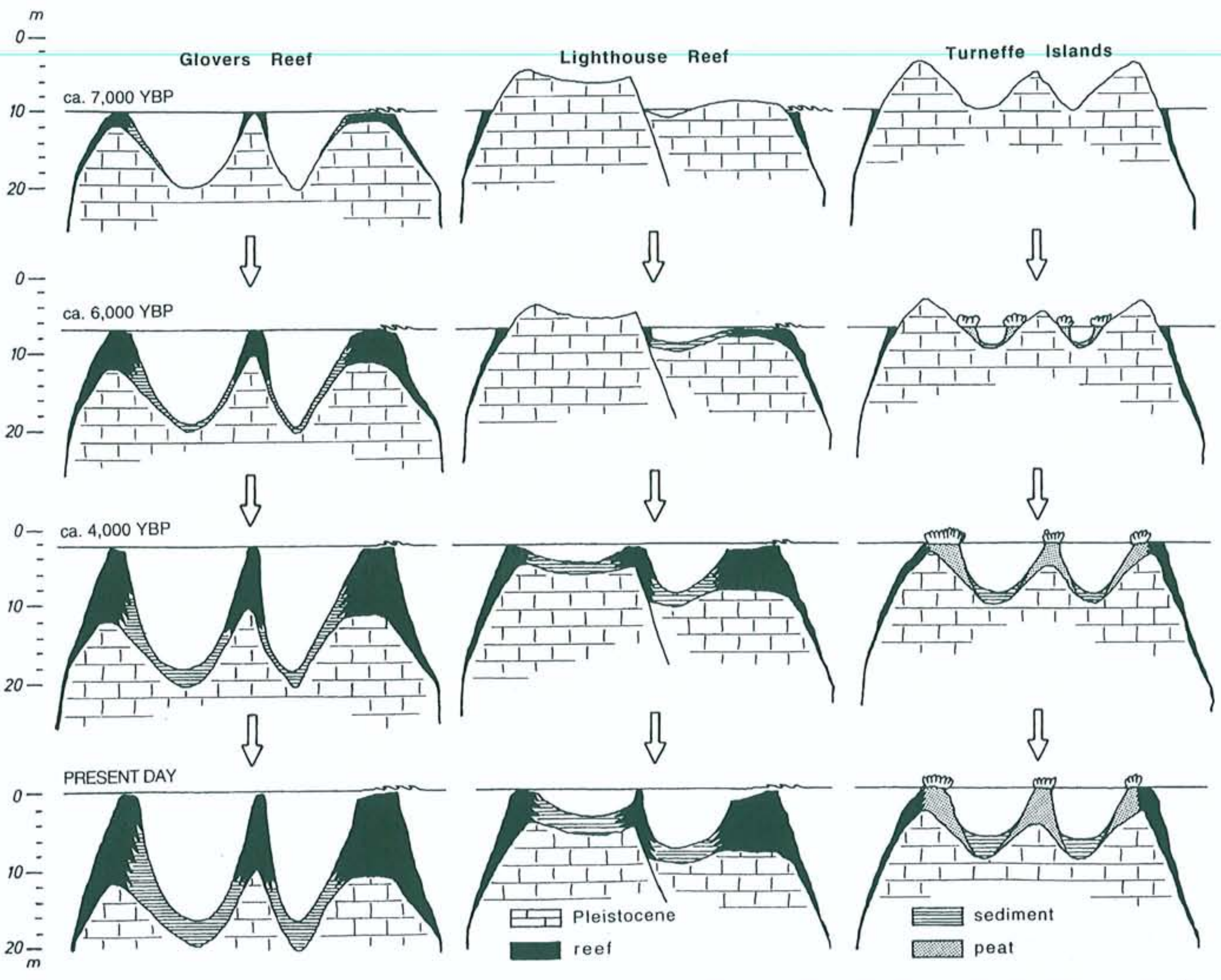

Fig. 5. Tentative model of Holocene development of the three isolated carbonate platforms offshore Belize based on core data, numerous shallow probings, submarine topography, and radiometric dating. During initial Holocene flooding of the interiors of the windward platforms, mangrove growth presumably also started in these protected and restricted areas. As soon as the platform margins were flooded, however, platform interiors had good circulation and were colonized by abundant coral.

sea (Fig. 5), all investigated reefs belong to the keep-up type. This is remarkable as the different platforms had to keep pace with different rates of sea level rise.

Stoddart (1962) speculated correctly that Pleistocene elevation on the three platforms increases from Glovers Reef to Lighthouse Reef to Turneffe Islands. The slower the rate of sea level rise, the higher the possibility of extensive mangrove growth and island development on a platform. This would explain the increasing mangrove and island areas from Glovers Reef to Lighthouse Reef to Turneffe Islands. The fact that there is no difference in Pleistocene elevation between the main part of Turneffe Islands that has extensive mangrove growth and the northernmost part of the same platform where abundant mangrove growth is missing, however, speaks against this model.

5.2. Topography of the reef base

Pleistocene elevation and relief are different on the three platforms which is a consequence of both tectonics and karst topography (Figs. 2 and 5). Different elevation caused successive flooding and

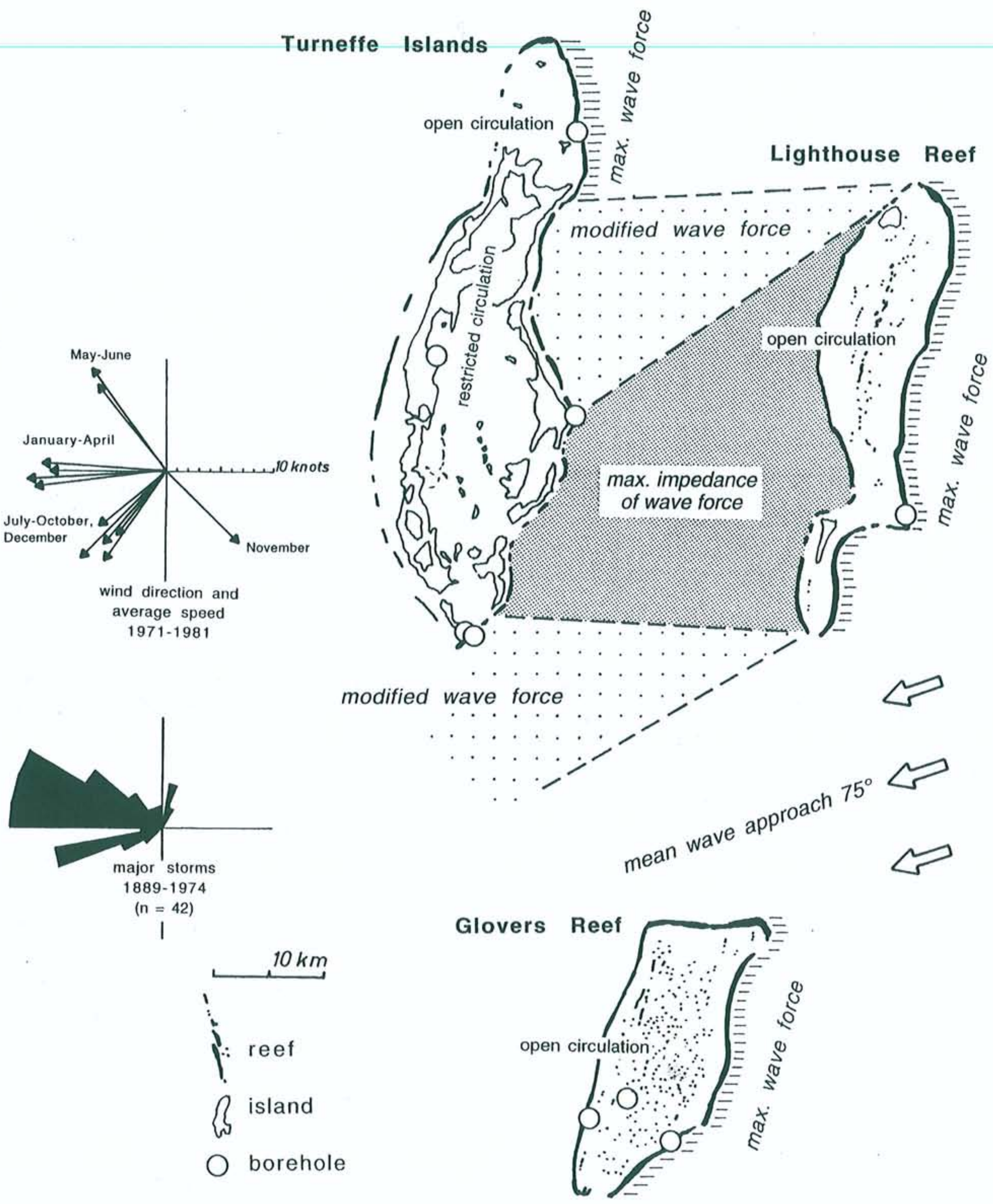

Fig. 6. Map of the Belize isolated platforms including data on exposure to waves and currents (Burke, 1982), wind data (Belize Weather Bureau), and storm data (NOAA). Mean wind direction, and thus mean wave approach equals 75° as determined by vector addition of directional frequencies of the wind (Burke, 1982). Eighty-seven percent of the easterly waves come from between 52° and 97°, with 75° being the mean. Outlines and locations of the isolated platforms and areas of modified and impeded wave force are corrected for inaccurate geography in Burke (1982, fig. 224). According to island distribution Stoddart (1965) distinguished several wave energy zones: Maximum and sub-maximum energy zones (windward reefs of Glovers and Lighthouse Reefs and northernmost reef of Turneffe Islands, northern and southern barrier reef), high energy zone (main windward reef of Turneffe Islands), medium energy zone (central barrier reef), low energy zone (Belize shelf), and moderate energy zone (southwestern Belize shelf).

successive Holocene reef initiation on the platforms. It also led to differences in lagoon depths and, more importantly, it explains the different facies distribution patterns between Glovers and Lighthouse Reefs. On Lighthouse Reef, pre-Holocene tectonic structures are visible, such as the inferred NNE-striking fault in the Pleistocene that underlies the lagoon and forms the basement of the linear patch reef trend. On Glovers Reef similar structures can be detected by linear patch reef accumulations in the western part of the lagoon, however, they are much shorter and less clearly defined. This is because the higher Holocene reef thickness presumably masks existing pre-Holocene tectonic structures.

The Turneffe Islands and Lighthouse–Glovers Reefs are situated on different fault-blocks that have probably had different subsidence histories (Lomando and Ginsburg, 1995). Glovers and Lighthouse Reefs are located on the same fault-block, however, the top of the Pleistocene is deeper on the southern platform. This might be due to a southward tectonic tilt during the Pleistocene which is indicated by northward tilted Pleistocene stalactites in the Blue Hole on Lighthouse Reef (Dill, 1977). Another possible explanation for the lower Pleistocene elevation on the southern platform is more intensive limestone dissolution caused by higher precipitation rates. Rainfall in the mountainous south of Belize is significantly higher than rainfall in the flat north. The same effect has been used to explain the southward decreasing Pleistocene elevation on the Belize shelf (Purdy, 1974b). It is problematic though that there exist no long-term data on precipitation rates on the isolated platforms in Belize. However, the higher Pleistocene relief on Glovers Reef as opposed to the two northern platforms lends evidence to the assumption of more intensive karstification towards the south.

5.3. Exposure to waves and currents

Glovers and Lighthouse Reefs and the northernmost part of Turneffe Islands receive the maximum wave force as they are open to the Caribbean Sea (Fig. 6). Most of Turneffe Islands, however, only receives modified and significantly reduced wave force. Stoddart (1965) was able to show that the large-scale distribution of reef island types on the isolated platforms and the Belize shelf may be explained with a wind and wave energy model. Burke (1982) explained the difference in reef development on the northern and southern as opposed to the central barrier reef with the protecting effect of the isolated platforms.

It is striking that the northernmost and unprotected part of Turneffe Islands has a wide windward reef and a lagoon with open circulation that is similar to that of the two windward platforms. The southern protected part, however, has wide mangrove rims encircling lagoons with restricted circulation. The lower exposure to waves and currents presumably favored extensive growth of red mangrove on most of Turneffe Islands as opposed to the windward platforms that are exposed to much higher wave energy and lack extensive mangrove growth.

During initial Holocene flooding of the interiors of the windward platforms, mangrove growth presumably also started in these protected and restricted areas. As soon as the platforms margins were flooded, however, platform interiors had good circulation and were colonized by abundant coral.

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