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Andre Droxler
Rice University

Stéphan J. Jorry
Institut Français de Recherche pour l…

Deglacial Origin of Barrier Reefs Along Low-Latitude Mixed Siliciclastic and Carbonate Continental Shelf Edges

André W. Droxler[1] and Stéphan J. Jorry[1,2]

[1]Department of Earth Science, Rice University, Houston, Texas 77005; email: andre@rice.edu

[2]Department of Marine Geosciences, IFREMER, Brest 29280, France; email: stephan.jorry@ifremer.fr

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Keywords

low-latitude carbonates, mixed continental shelf edges, sea level, Plio-Pleistocene, deglaciation

Abstract

Because the initial phase of barrier reef evolution is often buried under more recent phases of coralgal growth, the origins of modern barrier reefs have remained elusive. Direct observations on the nature of the substrate on top of which barrier reefs have developed are lacking, and simple questions about whether the substrate contributes to their overall linear morphology have remained unanswered. We present here a review dedicated to late-Quaternary shelf-edge deposition in tropical mixed siliciclastic-carbonate systems. These modern analogs are used to develop a quantitative understanding of shelf-edge barrier reef formation during different segments of relatively well-established sea-level cycles. The onset of rapid sea-level rise during early deglaciations, when siliciclastics were deposited along newly formed coasts at up-dip positions, provided opportune time windows for coralgal communities to establish themselves on top of maximum lowstand siliciclastic coastal deposits, such as beach ridges and lowstand shelf-edge deltas.

1. INTRODUCTION

Modern coral barrier reefs extend along the edges of some low-latitude siliciclastic shelves as continuous or discontinuous, elongated, and distinct morphological features over distances ranging from tens to hundreds of kilometers, or even—in the case of the Great Barrier Reef (GBR) in northeastern Australia—up to several thousand kilometers. Specific conditions of temperature, salinity, and water qualities (in terms of light, nutrients, and turbidity) within the upper part of the water column; fluctuations in sea level; and the occurrence of adequate substrata have favored their establishment, influenced their evolution through time, and in some cases contributed to their demise.

Comparing the general and detailed shapes of most modern barrier reefs with the adjacent siliciclastic coastlines and barrier islands reveals surprisingly similar morphologies. These similarities provide a first clue that modern barrier reefs used older lowstand siliciclastic coastal deposits as the main substratum on which to establish themselves during intervals of deglaciation and the consequent lowstand fluvial plain reflooding. Corroborating this initial observation and interpretation, some of these early-deglacial phases of carbonate growth, mimicking old delta fronts and siliciclastic beach ridges, have been discovered along modern continental shelves as drowned carbonate banks that line up at approximately the water depths at which the Last Glacial Maximum (LGM) coastal zones are thought to have been located. These drowned carbonate reefs would therefore represent the initial establishment of early-deglacial reefal limestone on top of flooded coastal siliciclastic accumulations. Because these initial reefs drowned rapidly, they remain frozen in time, unburied by younger carbonate growth phases keeping up with sea-level rise. In other words, these drowned carbonate reefs would represent the roots of modern barrier reef growth.

Moreover, contrary to the intuitive idea that modern barrier reefs are long lived and have existed for several million years, the results of several research programs in the past two decades have demonstrated that barrier reefs such as the Australian GBR (Int. Consort. Great Barrier Reef Drill. 2001, Peerdeman & Davies 1993, Webster & Davies 2003), Florida Keys barrier reef (Cunningham 1998, Multer et al. 2002), and New Caledonian barrier reef (Cabioch et al. 2008, Montaggioni et al. 2011) correspond in reality only to relatively thin late-Quaternary carbonate deposits—namely, four or five stacked coralgal units, dating from the mid-to-late-Brunhes period, separated by exposure horizons, which are then covering mostly siliciclastic sediments dating from the early Brunhes or earlier.

This pattern of typically 100–120-m-thick, mid-to-late-Brunhes, stacked coralgal units covering early-Brunhes, nonreefal, often siliciclastic deposits can be interpreted in the following simple conceptual depositional model. High-amplitude (>100-m) sea-level fluctuations are characteristic of the past five 100,000-year glacial-interglacial cycles (Lisiecki & Raymo 2005, Miller et al. 2005). During this time, barrier reefs thrived only during short interglacial stages (such as the current period) when the sea level had reflooded the exposed and karstified tops of older barrier reefs, initially established during marine isotope stage (MIS) 12–MIS 11 deglaciation and the unusually long sea-level highstand of the interglacial MIS 11 period (Raynaud et al. 2003). These successive long exposures and short refloodings related to the series of late-Brunhes high-amplitude sea-level fluctuations enhanced the initial short-lived mid-Brunhes barrier reefs. In summary, during transgressions and highstands, coralgal carbonates thrived while siliciclastics remained confined along the coastlines and the fluvial plain because of commonly well-developed longshore currents.

This review focuses on the central Belize Barrier Reef (BBR) and the northern extremities of the Australian GBR and Papua New Guinea (PNG) barrier reef in the Gulf of Papua (GoP), all of which thrive on the edge of mixed siliciclastic-carbonate continental margins. We describe the striking similarities between the shape of the modern BBR and the morphologies observed along the Belize coastal system itself, and discuss other typical siliciclastic coastal and fluvial deposits. We then describe a series of drowned bank/barrier reefs in the GoP on the northern extremities of the GBR and the PNG barrier reef, in the central Belize margin, at the mouth of English Caye Channel, and in the small atoll-like reefs (the Rhomboid Reefs) within the southern shelf lagoon, in addition to a series of drowned carbonate banks lined up along the modern south Texas shelf in the Gulf of Mexico (GoM). The establishment, growth, and demise of these drowned reefs are placed in the well-constrained sea-level framework of the early uppermost-Pleistocene deglaciation. The model explaining the mid-Brunhes origin of the modern barrier reefs is tested along the central BBR. Finally, we demonstrate that at the northern extremity of the GBR, phases of coralgal growth on the mixed siliciclastic-carbonate shelf edge—such as the phase initiated in the mid-Brunhes—occurred earlier, during well-defined sea-level transgression intervals in the early and middle Pleistocene approximately 2.0, 1.5, and 1.0 Mya as well as during the mid-Pliocene warmth optimum centered at 3.0 Mya.

2. THE MIXED SILICICLASTIC-CARBONATE BELIZE MARGIN

2.1. Overall Physiography

The 250-km-long BBR extends from the Yucatan Peninsula to the Gulf of Honduras. The modern BBR can be morphologically subdivided into northern, central, and southern segments (Burke 1982) (**Figure 1**). Along the northern portion of the Belize margin, at approximately the latitude of Ambergris Caye, the BBR is a fringing reef attached to the Yucatan coast (**Figure 1**); along the central and southern portions it becomes a continuous and discontinuous (respectively) but truly detached barrier. The northern BBR segment stretches north of Belize City and contains a 15–20-km-wide, 6–8-m-deep lagoon with fairly restricted marine conditions (e.g., Purdy & Gischler 2003, Purdy et al. 1975). Stretching south from the Belize River delta, the central and southern segments contain a barrier and back barrier reef carbonate system (**Figure 1**). The barrier reef protects a 3–10-km-wide back barrier carbonate province that is rarely deeper than 3 m and is characterized by a myriad of carbonate shoals as well as patch reefs and small atolls such as the Rhomboid Reefs (e.g., James & Ginsburg 1979, Purdy & Gischler 2003, Purdy et al. 1975). The back barrier reef is isolated from the purely siliciclastic coast by a mixed siliciclastic-carbonate shelf lagoon. This portion of the shelf lagoon, which has generally open marine conditions, reaches widths of 30 km and deepens from 10 m just south of the Belize River delta to more than 80 m in the Gulf of Honduras.

2.2. Similarities Between the Morphologies of the Belize Barrier Reef and Belize Coastline

The close resemblance between the morphologies of the BBR and the present-day siliciclastic Belize shoreline suggests a possible link between the two. The BBR's longest and continuous segments are on the edge of the central Belize margin (**Figure 2**). On satellite images, these well-defined, separated, and gently curved barrier segments north of Gladden Entrance clearly converge to the north into a single barrier slightly north of South Water Caye (**Figure 2**).

A series of widely separated beach barrier ridges, clearly apparent on satellite images, converge to one area to the south of the Belize River delta at the level of Colson Point (**Figure 2**). One could therefore speculate that in the early Brunhes, analogous siliciclastic systems could have formed paleoshorelines associated with beach ridges that would have converged to the north owing to longshore currents along the eastern flank of Camels Hump when the Belize margin was

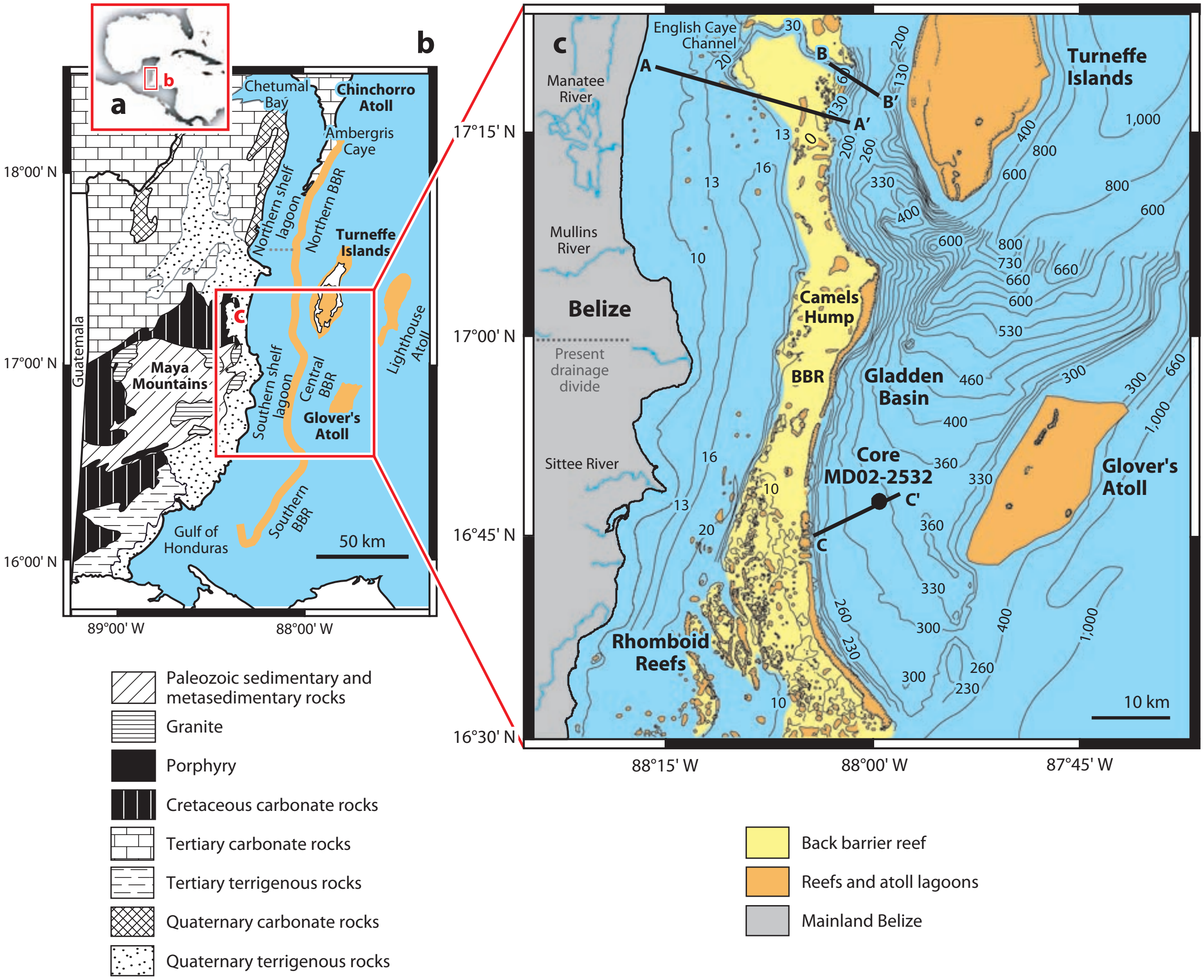


Figure 1

Map of the Belize continental margin, showing the Belize Barrier Reef (BBR); Gladden Basin; the locations of the seismic profiles presented in **Figures 3**, **4**, and **11**; and the location of core MD02-2532. (*a*) Location of Belize. (*b*) Belize geological map (Ferro et al. 1999, Purdy 1974, Wantland & Pusey 1971). (*c*) Central BBR with present-day bathymetry in meters (Ferro et al. 1999, James & Ginsburg 1979) along with the locations of seismic lines A–A′, B–B′, and C–C′ (see **Figures 3**, **4**, and **11**, respectively).

mostly exposed. Subsequently, these beach ridges, flooded during the unusually high-amplitude transgressions of the mid-Brunhes, may have served as initial substrata for carbonate growth, explaining the observed convergent alignments of the modern barrier reef morphologies.

The foundation of the Rhomboid Reefs in the back barrier reef area of the southern shelf lagoon (Victoria Channel) has been recently proven to be siliciclastic in nature and to date from the early Brunhes (Gischler et al. 2010). These findings further support the earlier model that siliciclastic fluvio-deltaic and coastal deposits served as substrata for mid-Brunhes barrier reef development along the central Belize margin (Choi & Ginsburg 1982, Choi & Holmes 1982, Ferro et al. 1999). The rhomboid shapes of those modern back barrier small-atoll reefs strongly mimic the typical and unique morphology of river channel bars and associated levees visible on

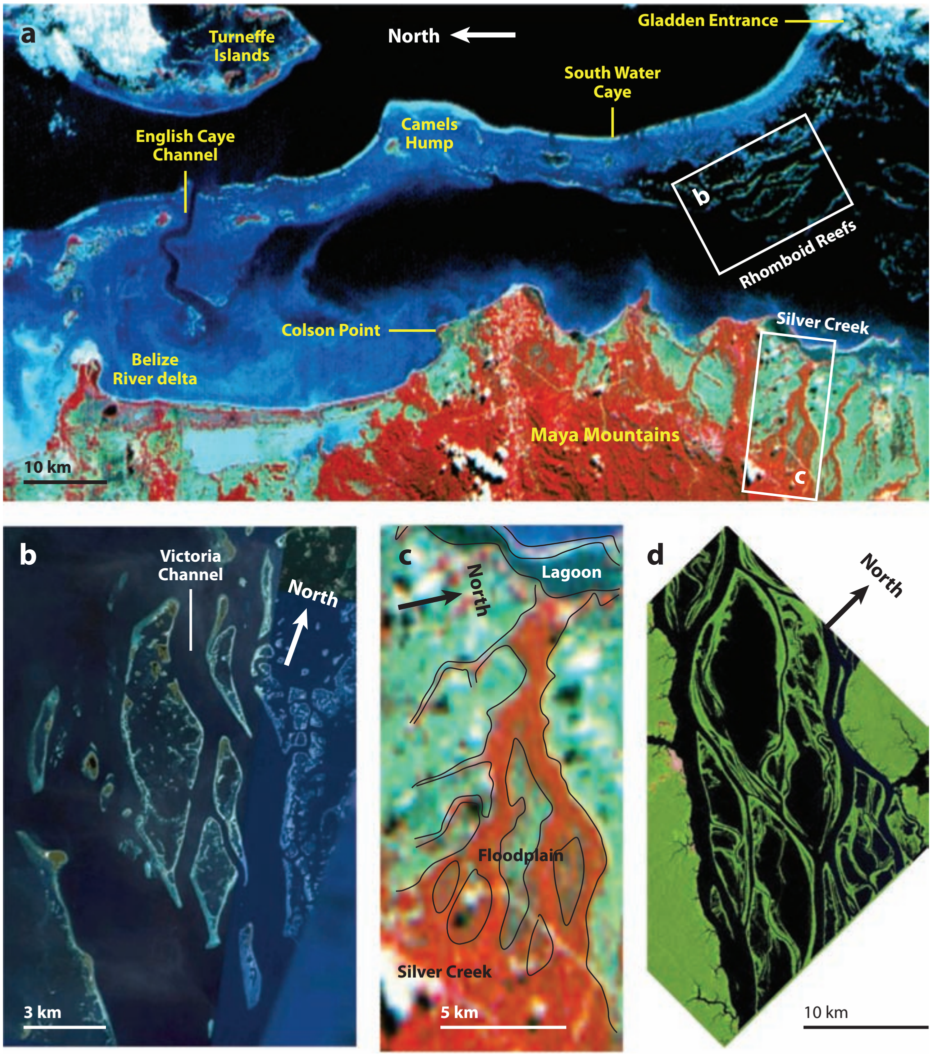


Figure 2

(*a*) The morphologies of the Belize Barrier Reef and Belize coastline, illustrating the clear similarities between the two (adapted from Rankey & Harris 2008). (*b*) Satellite view of the Rhomboid Reefs in the Belize Lagoon (taken from Google Earth; imagery date March 12, 2006; data SIO, NOAA, US Navy, NGA, GEBCO; image US Geological Survey, copyright © 2012 CNES/Spot Image). (*c*) Schematic interpretation of the Silver Creek deltaic plain. (*d*) Satellite image of the Rio Negro point bars in Brazil (taken from Mongabay.org; **http://mongabay.org/images/satellite_rio_negro.gif**). The Rio Negro is a good analog for previous lowstands, e.g., during the early-Brunhes fluvial system (Gischler et al. 2010). The Rhomboid Reefs initially became established in the mid-Brunhes on top of these levee systems and then were stacked on top of one another during subsequent deglaciations and sea-level transgressions.

satellite images along the modern Rio Negro braided river bed in Brazil (**Figure 2**). Moreover, the configuration of the modern Belize fluvial drainage of Silver Creek, which is quite analogous to that of the Rio Negro, would add some strength to the model that the modern Belize Rhomboid Reefs initially grew in the mid-Brunhes on a series of channel bars and levees and therefore reflect the intimate relationship between and interdependence of carbonates and siliciclastics (**Figure 2**).

As an illustration of these observations, a seismic line crossing the buried incised drainage system in the Belize southern shelf lagoon just north of the Rhomboid Reefs, which then merges into the channels separating the rhomboid micro-atolls, clearly shows a series of narrow, elongated reefs on the edges/levees of the incised channels (Ferro et al. 1999, figure 5C). Unable to keep up with sea-level rise during the late part of the last transgression, these reefs drowned. They are therefore a good example of the initial phase of carbonate establishment on levees during the last deglaciation (Ferro et al. 1999).

Moreover, it has been well established that the English Caye Channel (**Figure 2**) is a modern expression of an incompletely filled incised fluvial valley that was most likely carved during early-mid-Brunhes glacial-interval sea-level lowstands and then reoccupied several times during the late Brunhes and (most recently) the LGM (Ferro et al. 1999). The occurrence of carbonate patch reefs and cayes that preferentially thrive north of the Belize River delta points to a similar sedimentary depositional setting that probably existed at the mouth of the English Caye Channel during the LGM (**Figure 2**). Carbonate deposits are concentrated on the northern side of the Belize River mouth and are only sparsely present on its southern side. Southerly marine longshore currents are thought to have caused this preferential production and accumulation of carbonate deposits north of the river mouths, whereby freshwater and fine suspended siliciclastic sediment, preferentially deflected to the south along the coast after exiting the river mouths, are impeding carbonate growth in that particular area. Similar southerly longshore currents during the LGM would explain the observed preferential occurrence of reefal buildups on top of a well-developed lowstand shelf-edge delta to the north of the mouth of the English Caye Channel (**Figure 2**).

2.3. The Origin of the Modern Belize Barrier Reef

These relationships, added to the others mentioned above, strengthen the intuitive model that the Belize barrier and back barrier reef system was originally established in the mid-Brunhes on top of essentially siliciclastic fluvial and coastal lowstand systems from the early Brunhes. All of the observations along the Belize mixed continental shelf system clearly indicate that modern reefs were able to take advantage of the unique window during the mid-Brunhes transgression(s) to use lowstand siliciclastic coastal deposits as a substratum for initial growth. Within the overall shape of the Belize barrier and back barrier system, the obvious preservation of the initial morphologies of this siliciclastic substratum (as a linear coastline, tidal channels, point bars and levees, and coastal dunes) provides valuable support for the idea that carbonate production might start rapidly, immediately after a major flooding event. It is also obvious that lowstand siliciclastic depositional topographic reliefs—particularly when indurated or cemented prior to the onset of the early transgression—become an excellent substratum on top of which carbonates can grow. The neritic carbonates would therefore be covering siliciclastic deposits in the manner of "icing on the cake" (R.N. Ginsburg, personal communication).

At this point, one can suggest the following model to explain the late-Quaternary evolution of the Belize barrier and back barrier reef system. The Belize shelf was subaerially exposed for most of the early Brunhes, and was dominated by siliciclastic sedimentation—possibly during the MIS 24–MIS 12 period—when sea-level highstands were relatively weak in comparison with those prior to the Brunhes (Ferro et al. 1999, Gischler et al. 2010, Miller et al. 2005) (**Figure 3**).

In the mid-Brunhes, beginning with two high-amplitude sea-level transgressions during the MIS 16–MIS 15 and MIS 12–MIS 11 deglaciations, and in particular during the unusually long duration of the MIS 11 interglacial highstand (Raynaud et al. 2003), the Belize central margin was entirely flooded and the reefs preferentially developed on top of siliciclastic fluvial and coastal deposits (Droxler et al. 2003, Ferro et al. 1999, Gischler et al. 2010). The initial mid-Brunhes

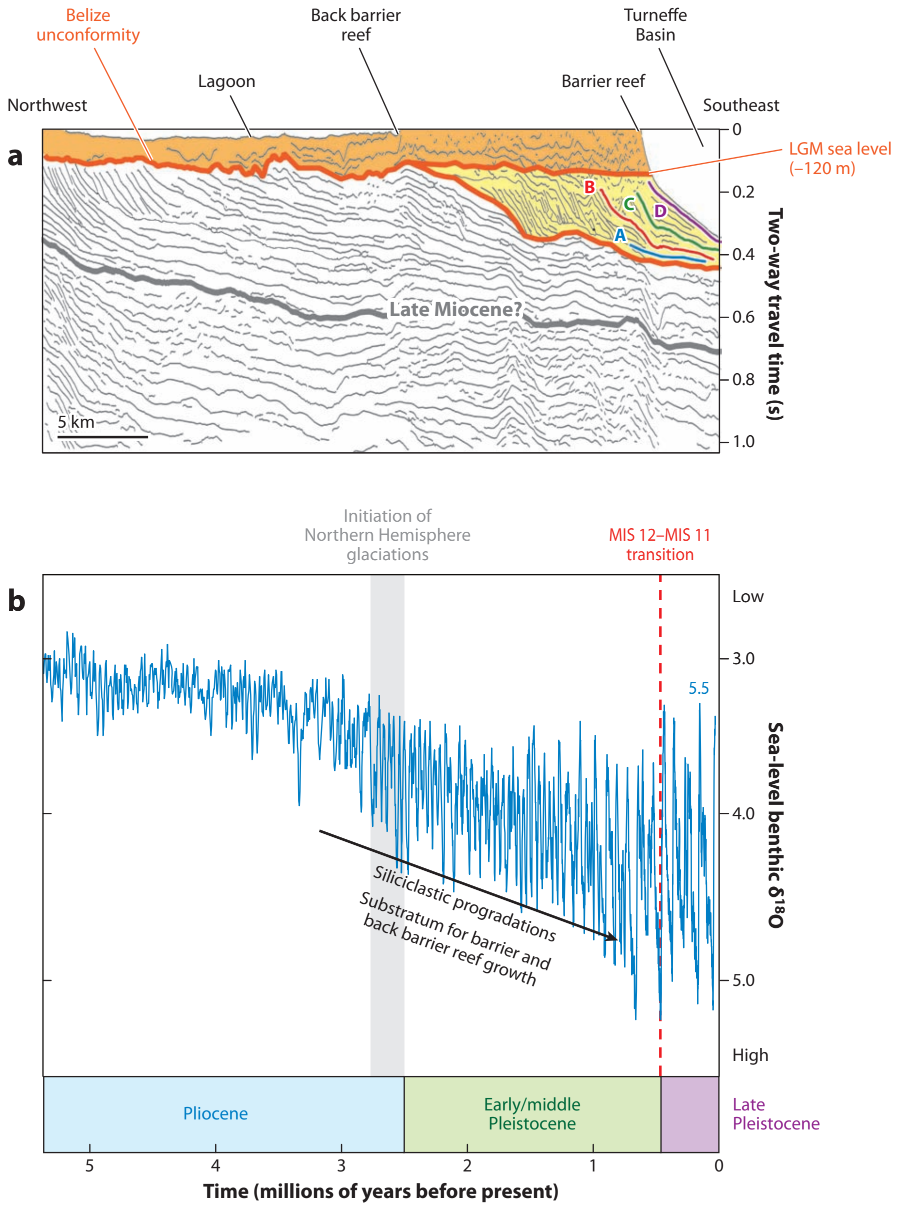


Figure 3

(*a*) Sedimentary geometries observed in the seismic line across the central Belize Barrier Reef (A–A′ in **Figure 1**). These can be interpreted to be linked to climate/sea-level records shown in panel *b*. Four seismic horizons (A–D) have been identified in the prograding lowstand shelf-edge delta and can be correlated throughout the overall Turneffe Basin (Ferro et al. 1999). These deposits, observed at the mouth of the English Caye Channel (see **Figure 4**), consist of the latest phase of a series of late-Pliocene–Pleistocene prograding lowstand siliciclastic wedges, which served as a substratum for reef establishment during successive late-Pleistocene transgressions and highstands. (*b*) Climatic development during the past 5 million years as seen in marine benthic $\delta^{18}O$ (Lisiecki & Raymo 2005). Note the extreme excursion at the transition between marine isotope stage (MIS) 12 and MIS 11. Abbreviation: LGM, Last Glacial Maximum. Adapted from Ferro et al. (1999).

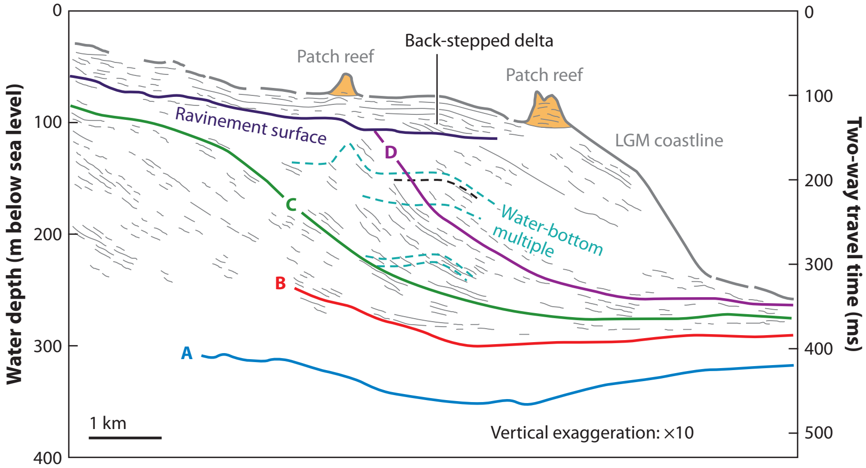


Figure 4

Seismic line crossing the English Caye Channel on the northern Belize Barrier Reef (B–B′ in **Figure 1**). As in **Figure 3**, four seismic horizons (A–D) have been identified in the prograding lowstand shelf-edge delta and can be correlated throughout the overall Turneffe Basin (Ferro et al. 1999); these deposits consist of the latest phase of a series of late-Pliocene–Pleistocene prograding lowstand siliciclastic wedges, which served as a substratum for reef establishment during successive late-Pleistocene transgressions and highstands. Coral patch reefs grew on top of the Last Glacial Maximum (LGM) lowstand siliciclastic coast. Adapted from Ferro et al. (1999).

carbonate accumulation along the Belize barrier and back barrier reef system enhanced the inherited topographies of its siliciclastic fluvial and coastal deposit substratum.

During the four successive high-amplitude (≥100-m), 100,000-year late-Brunhes glacial-interglacial sea-level fluctuations, the overall carbonate-positive morphologies of the mid-Brunhes, although partially karstified and weakened during lowstands, were preferentially reoccupied during the successive deglaciations (transgressions) and highstands for carbonate growth, mimicking the original morphology of the early-Brunhes siliciclastic substratum. Vertically stacked series of four or five coralgal reef packages, separated by exposure horizons and usually overlying a nonreefal and often siliciclastic substratum, correspond to recovered sedimentary sequences drilled through the Belize Rhomboid Reefs (Gischler et al. 2010), Australian GBR (Webster & Davies 2003), Florida Keys barrier reef (Multer et al. 2002), and New Caledonian barrier reef (Cabioch et al. 2008). Through burial and successive karstification, the vertically stacked multiphases of the coralgal units have partially erased the original morphology of the initial siliciclastic substratum on top of which the first mid-Brunhes transgressive coralgal sequence grew.

In these instances, understanding the initial growth of coralgal reefs during a sea-level transgression on top of siliciclastic deposits in a flooded lowstand coastal and fluvial plain remains difficult. However, it is easier to study the initial carbonate growth phase on top of the LGM lowstand siliciclastic coastline—currently often located on the modern shelf edge (**Figure 4**)—during the last deglaciation, which is the period for which the global sea-level curve is best known and understood.

3. DROWNED REEFS ON MODERN SHELF EDGES

Early sea-level transgressions can be considered windows of opportunity for barrier reef establishment on top of lowstand siliciclastic coastal deposits such as elongated barrier islands and linear beach ridges. In this section, we describe some examples of drowned reefal edifices that grew

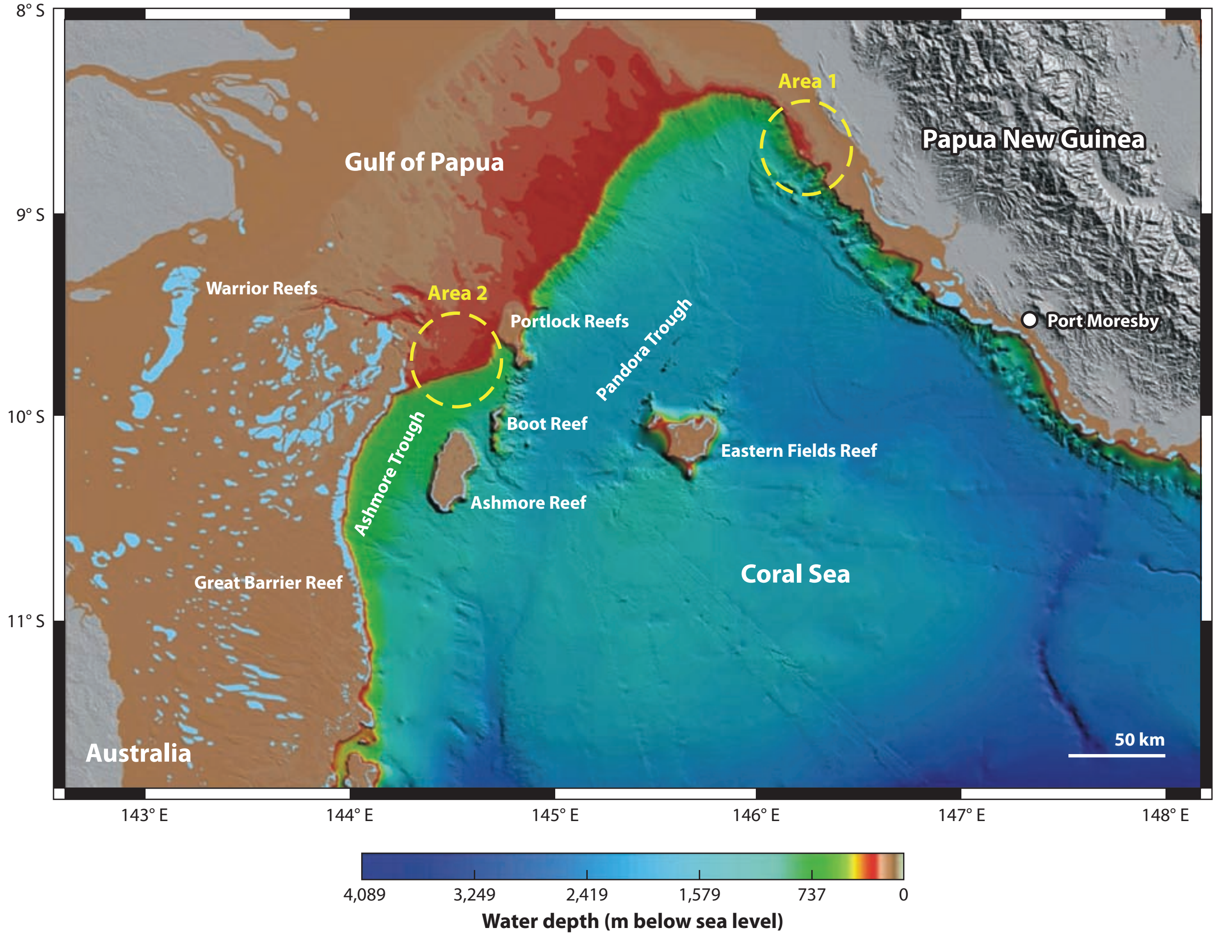


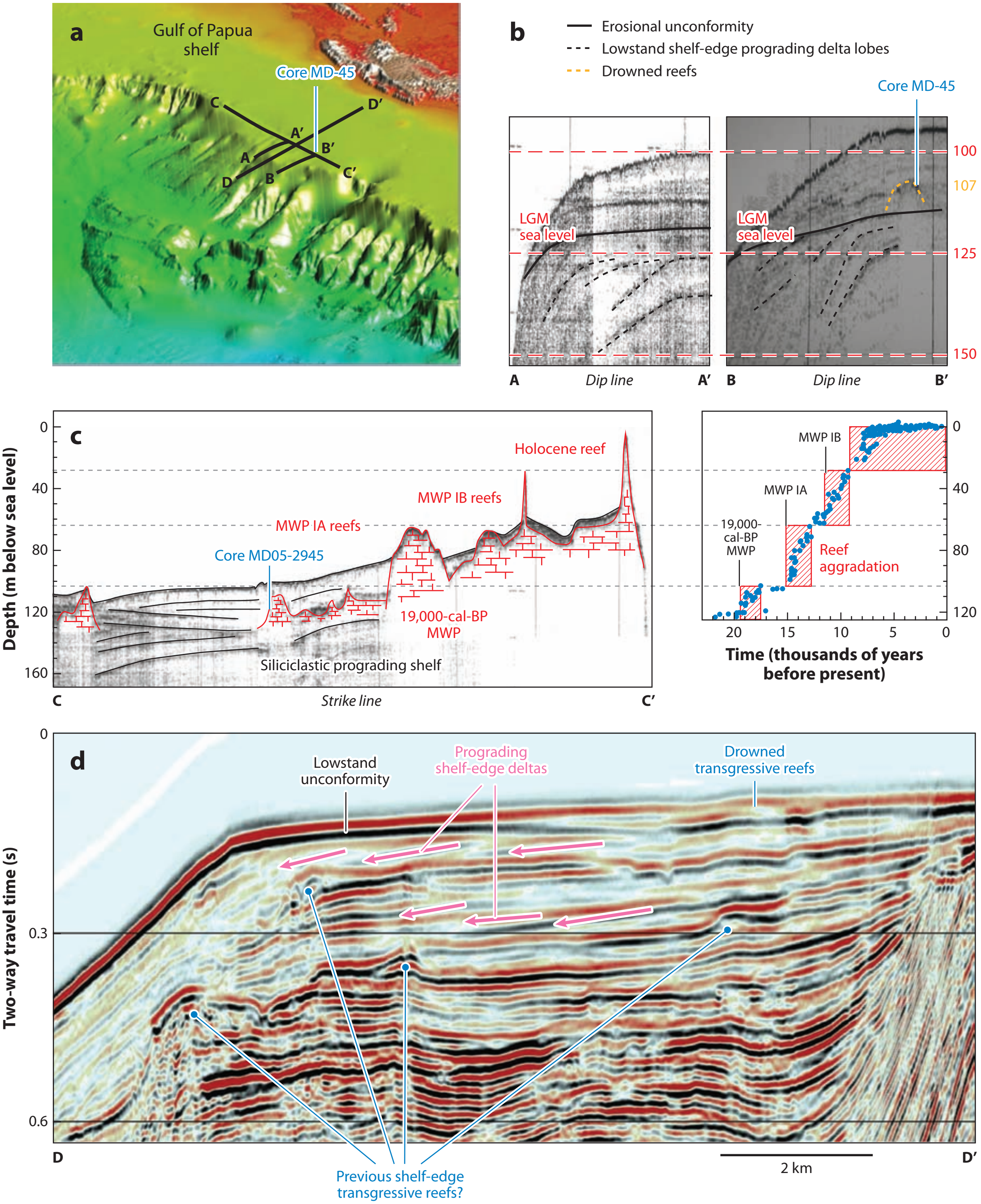
Figure 5

Modern physiography of the Gulf of Papua. The Ashmore and Pandora Troughs represent two main oceanic basins directly adjacent to the modern shelf edge. Living coral reefs are shown in light blue. The yellow dashed circles correspond to the locations of drowned reefs along the modern shelf edge; area 1 is detailed in **Figure 6**, and area 2 is detailed in **Figures 7** and **8**. Adapted from Francis (2007).

on the LGM lowstand coastlines along the modern shelf edge at the northeastern extremity of the GBR and the northwestern extremity of the PNG barrier reef in the GoP. Along the south Texas shelf edge in the GoM, a series of drowned coralgal reefs, partially buried by the Texas mud blanket (Belopolsky & Droxler 1999, Rezak & Bright 1976, Weight et al. 2011) and lined along the shelf edge between the Rio Grande and the Brazos/Colorado River lowstand deltas, provide excellent illustrations of the initial coralgal growth phase during the early part of the last deglaciation, which used preserved positive reliefs of the LGM lowstand siliciclastic coastline as the substratum. Similar drowned early-deglacial reefs are observed on the lowstand shelf-edge delta at the mouth of English Caye Channel in Belize (Ferro et al. 1999) (**Figure 4**).

3.1. The Gulf of Papua

The GoP represents a large modern siliciclastic and mixed siliciclastic-carbonate continental shelf ranging in water depth from 0 to 130 m (Daniell 2008, Francis et al. 2008) (**Figure 5**). Siliciclastic


a
Gulf of Papua shelf
Core MD-45
C
D′
A′
B′
A
B
C′
D
b
Erosional unconformity
Lowstand shelf-edge prograding delta lobes
Drowned reefs
Core MD-45
LGM sea level
LGM sea level
100
107
125
150
Depth (m)
A
Dip line
A′
B
Dip line
B′
c
Depth (m below sea level)
0
40
80
120
160
Holocene reef
MWP IB reefs
MWP IA reefs
Core MD05-2945
19,000-cal-BP MWP
Siliciclastic prograding shelf
C
Strike line
C′
MWP IB
MWP IA
19,000-cal-BP MWP
Reef aggradation
20
15
10
5
0
Time (thousands of years before present)
Depth (m below sea level)
d
Two-way travel time (s)
0
0.3
0.6
Lowstand unconformity
Prograding shelf-edge deltas
Drowned transgressive reefs
D
2 km
D′
Previous shelf-edge transgressive reefs?

sediments—the erosion products of relatively young mountains more than 4 km in elevation on the PNG island—have been supplied to the GoP in large volumes, predominantly from the north and northwest by numerous relatively short rivers that annually discharge ∼200–300 megatons of siliciclastic sediments (Harris et al. 1996, Milliman 1995, Milliman & Syvitski 1992, Pickup & Chewings 1983, Salomons & Eagle 1990). At present, most of this sediment discharge accumulates along the coast, particularly on the GoP inner shelf, in a series of muddy prograding clinoforms at water depths of less than 40–50 m (Harris et al. 1993, 1996; Slingerland et al. 2008a,b; Walsh & Nittrouer 2003). Hyperpycnal currents may also cross the entire GoP shelf and feed the Pandora Trough with the deposition of muddy and sandy turbidites (Carson et al. 2008; Febo et al. 2008; Jorry et al. 2008, 2010; Muhammad et al. 2008; Walsh & Nittrouer 2003) (**Figure 5**). Moreover, a large portion of the southwestern GoP shelf holds the northern extremity of the GBR, a major shelf-edge barrier reef system with a broad lagoon and numerous reefs on the shelf. A less well-known barrier reef flanks the narrower southern shelf of the PNG southeastern peninsula (area 1 in **Figure 5**). During the R/V *Melville* (2004) and R/V *Marion Dufresne* (2005) surveys, two extensive drowned early-deglacial coralgal barrier reefs were discovered at the modern PNG barrier reef northwestern extremity and GBR northeastern extremity (areas 1 and 2 in **Figure 5**, respectively). Those 30–50-m-high elongated carbonate edifices, presently drowned, briefly grew on the front of lowstand prograding siliciclastic shelf-edge deltas when the GoP continental shelf—at that time a fluvial plain—began to be reflooded (Francis et al. 2008, Tcherepanov et al. 2010) (**Figure 6**).

Along the PNG shelf edge (area 1 in **Figure 5**), a coralgal edifice complex as thick as 80 m was discovered. Based on the interpretation of strike and dip 3.5-kHz profiles across this edifice (**Figure 6**), one can conclude that the coralgal complex was apparently established just after the LGM on top of partially eroded prograding shelf-edge delta lobes located at approximately 115–125 m below modern sea level (**Figure 6**). A *Galaxea* coral colony, which would typically live at water depths of less than 5 m, was recovered in growth position in the MD-45 core catcher at ∼107 m below modern sea level; radiocarbon dating of the colony yielded an age of 19,000 calibrated years before present (cal BP). The early-deglacial coralgal reef complex, forced to back-step toward the southeast, had grown vertically during at least three different phases (**Figure 6*c***), which have been interpreted to be linked to the three meltwater pulses (MWPs) in the last deglaciation: the initial MWP at 19,000 cal BP and the following MWP IA and MWP IB[1] (Alley et al. 2005, Clark et al. 2004, Fairbanks 1989, Weaver et al. 2003, Yokoyama et al. 2000) (**Figure 6*c***). Only a small portion of the southeastern coralgal reef complex, still alive along this part of the northeastern Pandora

Figure 6

Drowned reefs along the northern Gulf of Papua shelf edge (area 1 in **Figure 5**). (*a*) Bathymetric map showing the locations of three 3.5-kHz seismic lines (A–A′, B–B′, and C–C′) and one additional seismic line (D–D′). (*b*,*c*) Dip lines for A–A′ and B–B′ (panel *b*) and strike line for C–C′ (panel *c*). Coralgal reefs grew on top of the Last Glacial Maximum (LGM) prograding shelf edge, the aggradation being favored by the last three rapid rises in sea level—i.e., meltwater pulses (MWPs)—during the last deglaciation. The successive MWPs are represented on the relative sea-level curve in panel *c* (adapted from Alley et al. 2005). (*d*) A prestack time-migrated seismic line (D–D′) crossing the northern Gulf of Papua shelf edge (data courtesy of Fugro Multi Client Services). On this dip line, it appears that older reefs have grown on older lowstand shelf-edge deltas. Abbreviation: cal BP, calibrated years before present.

[1]The Barbados record suggests that the last deglaciation was punctuated by two brief intervals of extremely rapid sea-level rise, i.e., MWP IA and MWP IB (Bard et al. 1990, Fairbanks 1989, Peltier & Fairbanks 2006). The new Tahiti sea-level record shows that the sea-level rise slowed during the Younger Dryas and then accelerated again during the Holocene (Bard et al. 2010). The Tahiti reef record does not support the occurrence of an abrupt reef drowning event coinciding with a sea-level pulse of ∼15 m, and implies an apparent rise of 40 mm $year^{-1}$ during the time interval corresponding to MWP IB in Barbados (Bard et al. 2010, Camoin et al. 2012).

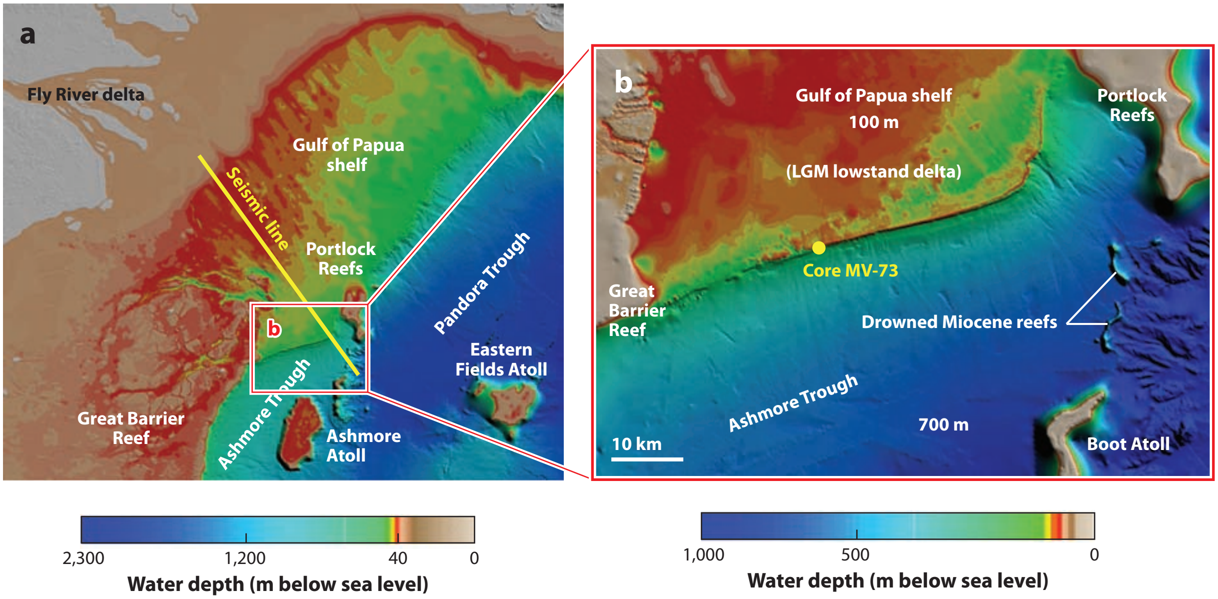


Figure 7

(*a*) Bathymetric map of the western Gulf of Papua, with the location of a regional seismic line crossing the shelf edge (*yellow line*; see **Figure 13**). (*b*) Detail showing the preservation of a Last Glacial Maximum (LGM) lowstand delta and the location of core MV-73, which was collected at the base of the shelf edge. Adapted from Tcherepanov et al. (2008a).

Trough, was capable of keeping up with sea-level rise during MWP IB. Surprisingly, the recent GoP shelf edge has apparently not been influenced by significant subsidence and uplift rates, because the shelf-edge water depths range between 120 and 130 m, and coastal or very shallow environments have been recovered in core MD-45. Bird (2003) has shown that the GoP is currently inactive in terms of tectonic and earthquake occurrence. Seismic lines across different parts of the GoP shelf (Tcherepanov et al. 2010) also show that the GoP shelf is sedimentary, gradually dipping, prograding and aggrading, and devoid of faults or folds displacing the seafloor. Previous, most likely older, short-lived transgressive reefs formed on earlier shelf edges (**Figure 6*d***).

In the northern part of Ashmore Trough (area 2 in **Figure 5**; **Figures 7** and **8**), the R/V *Melville* and R/V *Marion Dufresne* surveys uncovered a 30–70-m-thick, >50-km-long ridge that closely parallels the shelf edge, with linear segments exceeding 10 km in length, and that is established along a large, prograding, mostly siliciclastic lowstand shelf-edge delta (**Figures 7** and **8**). The ridge ranges in water depth from 50 to 130 m. Core MV-73 (the location of which is shown in **Figures 7*b*** and **8**) was retrieved in a small reentrant to the east and at the toe of the ridge, at a water depth of ~126 m. This 8.5-m-long piston core consists of mixed siliciclastic-carbonate sediments. Sedimentological, micropaleontological, and radiocarbon data sets indicate that the lower three-quarters of the core was deposited in upper- to lower-shoreface environments (paleowater depth of ~10 m) dated by radiocarbon at ~17,000–16,000 cal BP. At that time, therefore, the coastline was located at or very close to the present-day shelf edge. In the upper quarter of core MV-73, dated at 15,000–11,000 cal BP, sedimentary depositional water depths increased from lower-shoreface depths (10–15 m) to midshelf depths (~60 m); by inference, the 50–70-m-thick coralgal ridge adjacent to core MV-73 probably grew during Bølling-Allerød MWP IA after establishing itself on top of an LGM/Oldest Dryas siliciclastic beach barrier complex (**Figure 8**). Because the

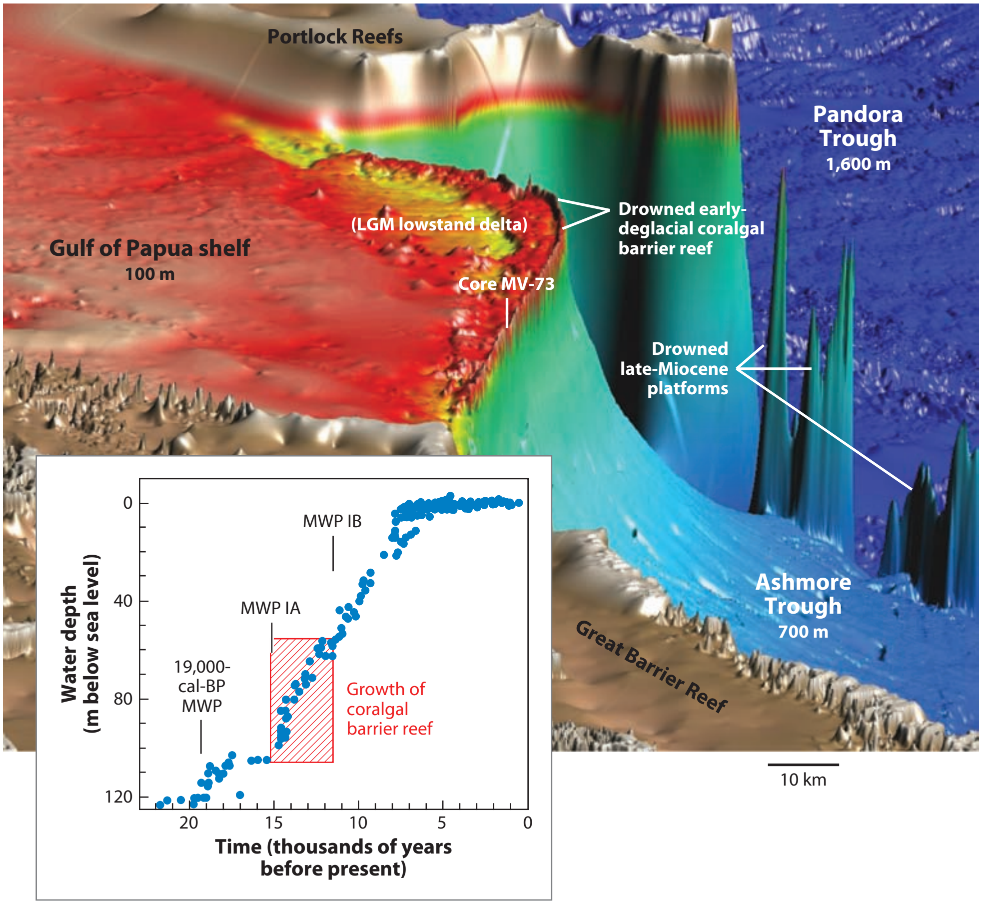


Figure 8

Three-dimensional perspective map showing the atolls located on the Portlock Ridge and drowned late-Miocene carbonate platforms bordering the Ashmore Trough. A drowned transgressive barrier reef is located in the northeastern Ashmore Trough on the shelf edge at a water depth of 60–80 m. Core MV-73, which was collected at the toe of the ridge, indicates that a coralgal barrier reef established on top of a Last Glacial Maximum (LGM) siliciclastic beach barrier complex and grew during Bølling-Allerød meltwater pulse (MWP) IA. This early-deglacial barrier reef most likely drowned during the transition between the Younger Dryas and the Pre-Boreal/MWP 1B. Perspective map adapted from Tcherepanov et al. (2008a); relative sea-level curve adapted from Alley et al. (2005). Abbreviation: cal BP, calibrated years before present.

highest ridge crest segments currently reach water depths of 50–60 m and are covered by younger (~3,000-year-old) red algal deposits, the early-deglacial barrier reef most likely drowned during the transition between the Younger Dryas and the Pre-Boreal/MWP IB (**Figure 8**).

3.2. The Gulf of Mexico

A series of 20 uppermost-Pleistocene drowned coralgal banks and mounds are lined up along the south Texas continental shelf edge between the Rio Grande and the Brazos/Colorado River lowstand deltas (Belopolsky & Droxler 1999, Rezak & Bright 1976) (**Figure 9**). These drowned reefs, partially buried in late-Holocene clay-rich deposits referred to on the Texas shelf as the

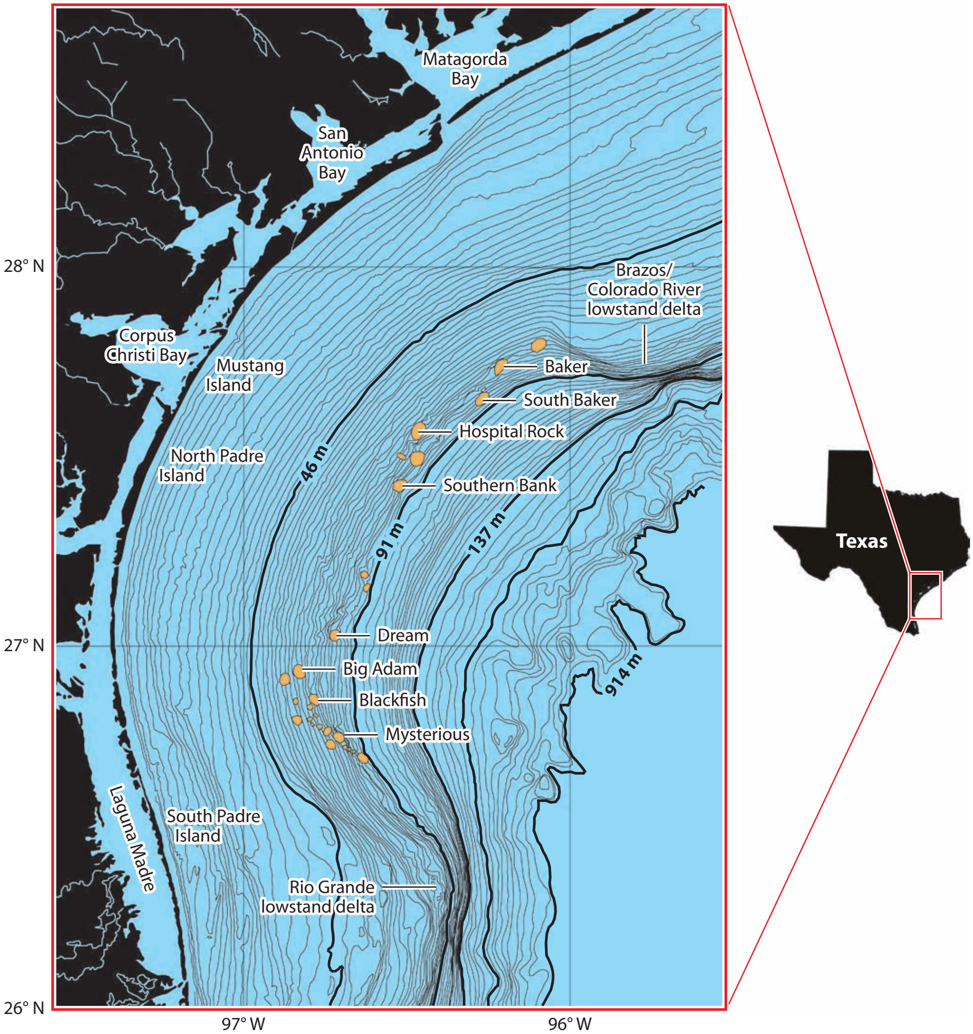


Figure 9

Relict reefal complex along the margin of the south Texas shelf offshore of Corpus Christi. The orange areas are the coralgal reefs; contours show depths in meters (converted from fathoms). Adapted from Belopolsky & Droxler (1999).

mud blanket, are cropping out today on the seafloor at water depths ranging from 58 to 82 m (Belopolsky & Droxler 1999, Weight et al. 2011). Description and interpretation of published single-channel seismic lines crossing several banks and a grid of multichannel, high-resolution seismic profiles acquired across the Southern Bank coralgal reef edifice demonstrate that the edifices are partially buried in clays and are twice as thick as the average 20 m of relief exposed on the seafloor (Belopolsky & Droxler 1999) (**Figure 10**).

The multichannel, high-resolution seismic grid, acquired in the area of Southern Bank, provides a good illustration of the establishment, growth, and demise of the drowned reefs lining the essentially siliciclastic south Texas shelf. The relationship between the Southern Bank coralgal reef edifice and the underlying and surrounding siliciclastic sediments, as well as the morphology

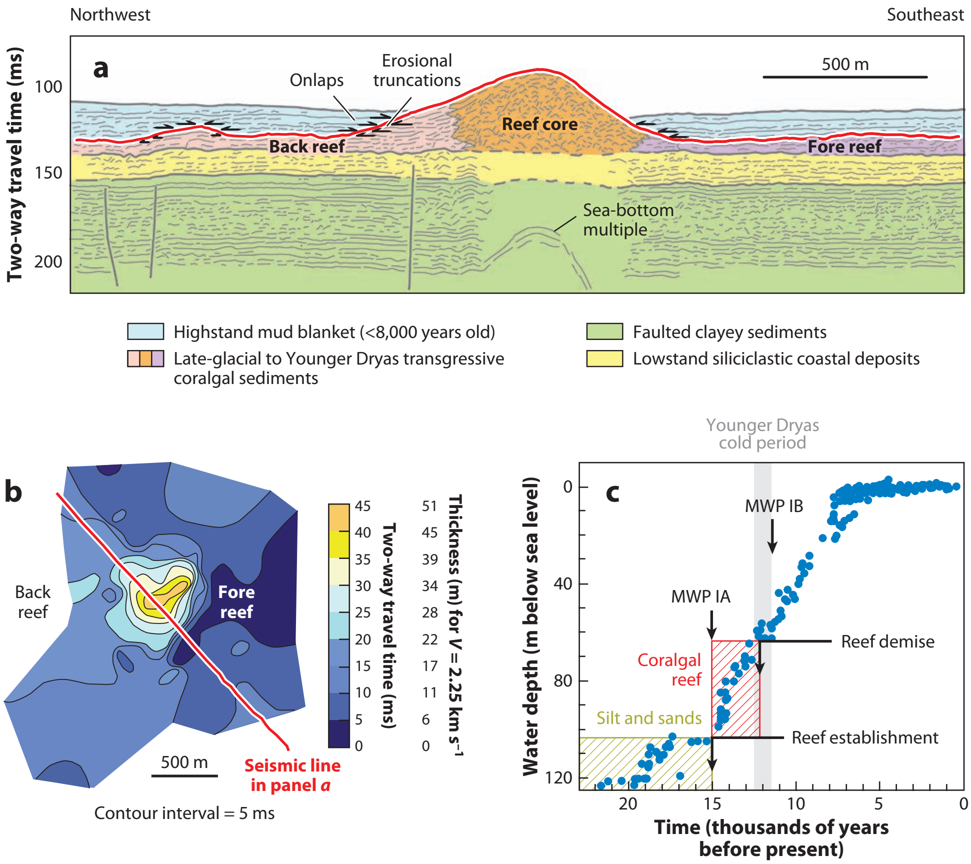


Figure 10

(*a*) Interpreted cross section through Southern Bank. (*b*) Isopach map of the back reef, reef core, and fore reef (late-glacial to Younger Dryas sediments) and location of the multichannel seismic line interpreted in panel *a*. The map shows the estimated thicknesses of the reefal deposits. Panels *a* and *b* adapted from Belopolsky & Droxler (1999). (*c*) Relative sea-level records from far-field sites (after Alley et al. 2005). Reefs were established after 21,500 cal BP and stopped aggrading at approximately 12,300 cal BP. Abbreviation: MWP, meltwater pulse.

and internal structure of the reef package itself, are well imaged. Southern Bank established itself on a north-trending topographic high formed during lowstand siliciclastic deposition. Its asymmetric morphology is typical of a reef edifice with well-defined reef core, back-reef, and fore-reef geometries (**Figure 10**). The reef core is characterized by chaotic reflectors; the back-reef facies by subparallel, gently dipping reflectors; and the fore-reef facies by discontinuous, steeply dipping reflectors. The study of Belopolsky & Droxler (1999) and the radiocarbon dates of coral material collected in previous studies (Rezak & Bright 1976) show that the reefs were established sometime after 21,500 cal BP and stopped accreting at approximately 12,300 cal BP (**Figure 10**). These 30–50-m-thick coralgal edifices were constructed at maximum rates of reef growth during the first 7,000 years of the last glacial-to-interglacial sea-level transgression. The reef demise fell either within or at the end of the Younger Dryas, a ~1,000-year interval when the rates of sea-level rise first slowed considerably (with the sea level possibly dropping by several meters) and then significantly accelerated. Subsequent to the drowning of the reefs, late-Holocene (<8,750 cal BP) clay-rich deposits partially buried the coralgal edifice (Weight et al. 2011) (**Figure 10**). If these early transgressive reefs had kept up with sea-level rise through the entire Holocene, a 160-km-long barrier reef—comparable in size to the BBR—would bound the modern south Texas shelf edge.

In summary, the model that early transgressive coralgal reefs were initially established on top of LGM lowstand siliciclastic coastal deposits and served as the early foundation for modern barrier reefs might appear relatively simple. The drowned barrier reefs along the GoP and western GoM shelf edges and the Belize shelf-edge delta at the mouth of English Caye Channel should be convincing examples. This scenario likely corresponds with a more common phenomenon than expected, and it was undoubtedly multiplied many times at the edges of tropical and subtropical continental shelves across geological periods.

4. MULTIPHASES OF THE FLOURISHING AND EXPOSURE OF BARRIER REEFS IN THE PAST 400,000–500,000 YEARS

Additional evidence for the predicted mid-Brunhes BBR establishment and its subsequent intermittent flourishing is found in the giant piston core MD02-2532 retrieved from Gladden Basin at 330 m of water depth, 3 km east of the BBR (**Figures 1** and **11**). A robust chronology was established based on a high-resolution planktic oxygen isotope stratigraphy anchored by radiocarbon dates and several nannofossil and tephrochronologic markers (**Figure 12**). The chronology demonstrates that the core represents a little more than the full Brunhes, or approximately 850,000 years (Carson 2007) (**Figure 12**).

The upper three-quarters of MD02-2532 penetrated the five or six subunits of the distal portion of a sedimentary wedge, which had accumulated at the BBR toe of the slope (**Figure 11**). These five

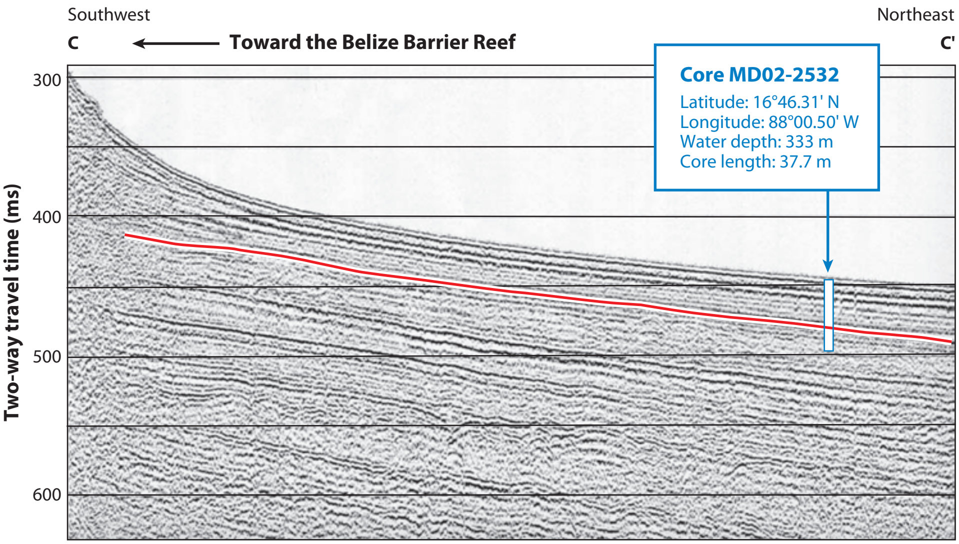


Figure 11

Segment of a single-channel, high-resolution seismic dip line from the slope of the central Belize Barrier Reef margin (C–C′; location shown in **Figure 1**), showing the location of core MD02-2532 (after Carson 2007, Droxler et al. 2003). The red line marks the transition from the early-Brunhes exposed Belize Barrier Reef (corresponding to the development of a fluvial plain) to the mid-Brunhes reefal episode, resulting in the increase of the Belize slope wedge accretion.

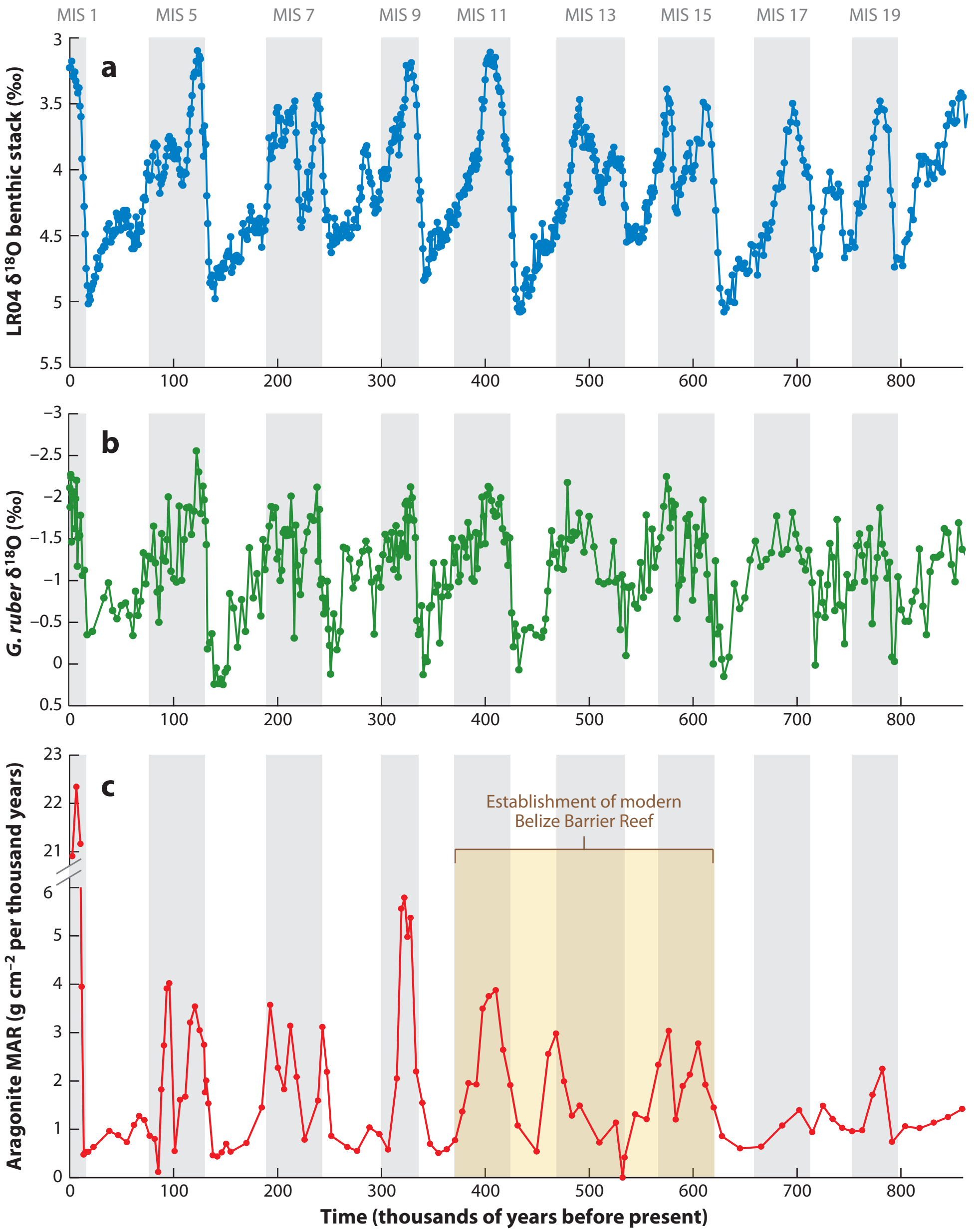


Figure 12

Chronostratigraphy and aragonite trend in core MD02-2532 (after Carson 2007). (*a*) LR04 stacked benthic oxygen isotope record of Lisiecki & Raymo (2005). (*b*) MD02-2532 (Gladden Basin) *Globigerinoides ruber* oxygen isotope record. The MD02-2532 chronology is based on correlation of marine isotope stage (MIS) excursions with the Lisiecki & Raymo (2005) oxygen isotope record, as well as calibrated radiocarbon ages, the relative abundance of the planktic foraminiferal *Globorotalia menardii* complex, nannofossil datums, and ash layers. (*c*) MD02-2532 fine (<63-μm) carbonate aragonite mass accumulation rate (MAR). Interglacial intervals are shaded gray; glacial intervals are white.

or six subunits correspond to the last interglacial intervals from MIS 15 to MIS 1 (the Holocene), when the BBR was intermittently flourishing between long-term exposures. In contrast, the lower quarter of the core recovered an upper portion of an underlying subparallel reflector seismic unit (**Figure 11**) characterized by early-Brunhes low and relatively constant aragonite concentration values corresponding to an interval when the Belize margin was mostly an exposed fluvial plain (Carson 2007, Droxler et al. 2003, Gischler et al. 2010).

Bulk and fine fraction carbonate percentage values vary cyclically down-core; low values of 40%–50% typically occurred during the interglacial-to-glacial transitions (sea-level regressions), whereas high values of 70%–80% typically occurred at the glacial-to-interglacial transitions (Carson 2007). Calculated siliciclastic fluxes to the slope reached their highest values during early sea-level regressions, whereas their lowest values occurred during transgressions and early highstands. In contrast, barrier reef–derived fine-aragonite fluxes, which were low during glacial lowstands (when the BBR was exposed and karstified) increased during transgressions and reached their maximum during early highstands (when the BBR was flourishing) (**Figure 12**).

The aragonite flux variations in Gladden Basin since the mid-Brunhes illustrate a clear case of carbonate highstand shedding (Droxler & Schlager 1985, Schlager et al. 1994). Fine aragonite is observed throughout the Brunhes, and in Gladden Basin at the location of MD02-2532, the first significant increase of aragonite fluxes had already occurred at the MIS 16–MIS 15 boundary, which predicts the first significant increase of reef-derived aragonite flux prior to the MIS 12–MIS 11 transition. It is obvious, however, that aragonite fluxes reached their highest rates during the mid-Brunhes MIS 11 and MIS 9 interglacials (**Figure 12**). The two-step transition in aragonite fluxes to Gladden Basin occurred through the first two high-amplitude MIS 16–MIS 15 and MIS 12–MIS 11 mid-Brunhes transgressions, likely representing first partial flooding and then full reflooding of the central Belize margin, which was essentially exposed and siliciclastic during the early Brunhes. This scenario is well illustrated by Gischler et al. (2010), who demonstrated that the typical mid-to-late-Brunhes morphology of the Rhomboid Reefs can be explained by the diamond-shaped geometries of their early-Brunhes siliciclastic fluvial levee clay deposits in a system of braided rivers, on top of which coralgal reefs first established themselves sometime in the mid-Brunhes (**Figure 2**). Reef growth phases older than the last mid-to-late-Brunhes phase do exist. For instance, Gischler et al. (2010) clearly showed that older (mid-Pleistocene) limestone underlies the early-Brunhes siliciclastic substratum on top of which mid-to-late-Brunhes coral reefs were established. Based on the model for transgressive and early sea-level highstand coralgal reef growth developed in the Brunhes, other reef growth phases can be predicted to have occurred during intervals of unusually high-amplitude sea-level rise. The late-Pliocene–Pleistocene GoP evolution provides a good illustration that coral reefs thrived during intervals of high-amplitude sea-level rise.

5. MULTIPHASES OF REEF DEVELOPMENT IN THE PAST 3-MILLION/0.5-MILLION-YEAR CYCLIC PATTERN

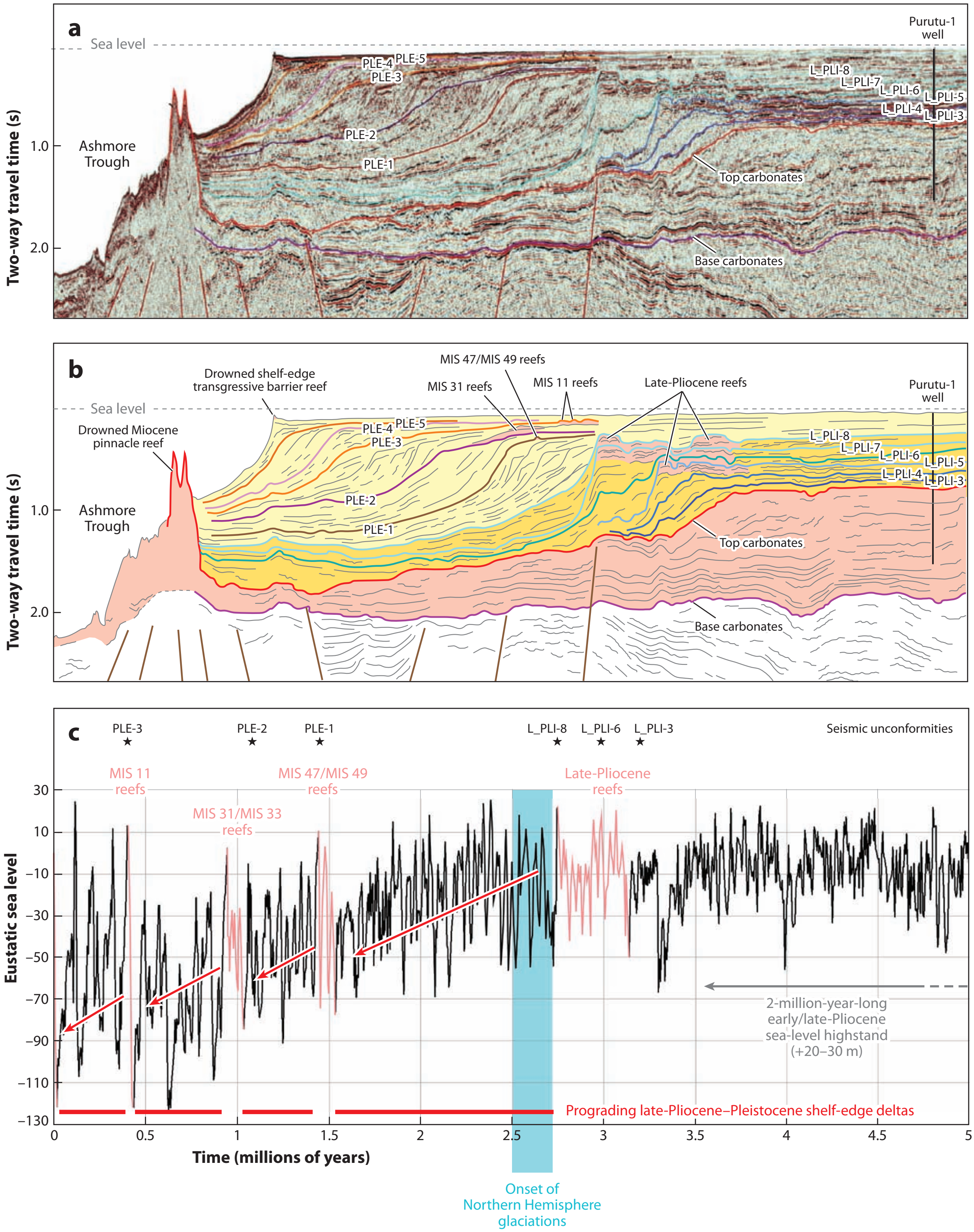
In the Pliocene and Pleistocene, the GoP margin was transformed into a wide and extensive siliciclastic shelf where a huge volume of siliciclastics had to be transported into the GoP to infill several 2–4-km-deep offshore troughs and cover the preexisting carbonate shelf, forming a clastic shelf with a surface area exceeding 20,000 km^2 (Tcherepanov et al. 2010). The transformation of the GoP continental margin from carbonate to siliciclastic had to be linked to one or more regional/global processes, likely including tectonics, eustasy, and climate variations (Tcherepanov et al. 2010). The long-term, systematic late-Pliocene–Pleistocene sea-level fall that followed the long-lasting early-Pliocene sea-level highstand is thought to have enhanced the large flux of siliciclastics into the GoP (Tcherepanov et al. 2008a,b). In spite of the huge siliciclastic influx into the GoP during the late Pliocene and Quaternary, short-lived reefal platforms and barriers were in particular able to grow along the GoP shelf edge during intervals of high-amplitude sea-level transgression (**Figure 13**).

Systematic progradation of siliciclastic sediments during the late Pliocene is observed across the GoP, in particular in the southwestern part (sequences L_PLI-4–L_PLI-8; **Figure 13**) (Tcherepanov et al. 2010). Beginning with the L_PLI-4 deposition, an aggradation component was added to the progradation for each of the last five sequences (L_PLI-4–L_PLI-8), marking an overall relative sea-level transgression during this particular interval of the late Pliocene (~3.3–2.9 Mya). The rollovers or outer-shelf–shelf-edge environments of the L_PLI-4–L_PLI-8 prograding and aggrading sequences (**Figure 13**) are characterized by high-amplitude reflections and mounded seismic facies, especially in the three youngest sequences (L_PLI-6–L_PLI-8), when the mound-like edifices were replaced by several-kilometer-wide positive flattop features of high relief, which were undoubtedly small, short-lived carbonate platforms or barrier reefs.

These high-amplitude, mounded or flattop seismic buildups are interpreted to correspond to times during early sea-level transgressions, when the outer-shelf siliciclastic environments and particularly the shelf edges became enriched in carbonates. Elongated coralgal reef edifices and barriers grew on top of lowstand coastal deposits and delta fronts when the siliciclastics were accumulating further up-dip along the new coast and perhaps on the inner shelf (Tcherepanov et al. 2008b, 2010). The early transgressive reefs often drowned during the late transgression and were buried under prograding siliciclastics during subsequent late sea-level highstands and regressions. These early transgressive reefs growing on the shelf edge or in the outer-shelf environments (**Figure 13**) therefore remained relatively short-lived carbonate systems.

In the southwestern corner of the GoP, close to the northern-current extremity of the modern GBR, five Pleistocene boundaries (PLE-1–PLE-5), observed in the seismic line shown in **Figure 13**, can be easily picked out southeast of the characteristic L_PLI-8 boundary, including the best-developed mid-Pliocene (~3.0 Mya) shelf-edge flattop carbonate edifices. The five Pleistocene boundaries, identified by high-amplitude reflections and some small mound-like features, cap five packages characterized by a series of downstepping prograding units recording forced regressions. The high-amplitude boundaries correspond to systematic reflooding events during transgressions (maximum flooding surfaces in the sequence stratigraphic nomenclature). The last transgression since the LGM corresponds to the high-amplitude reflections observed on today's outer shelf and the relict drowned reef on the shelf edge itself (**Figures 6**, **8**, and **13**).

The geometries observed in the Pleistocene packages most likely correspond to a series of intervals when sea level systematically fell punctuated by shorter intervals of unusually high-amplitude sea-level rise. These geometries can be linked to a sea-level curve based on Pliocene–Quaternary stacked $\delta^{18}O$ records corrected for temperature and, therefore, an ice-volume (sea-level proxy) curve (Miller et al. 2005). In **Figure 13**, the oldest package (PLE-1) could correspond to the first forced regression during the latest Pliocene–earliest Pleistocene, from 2.7 to 1.6 Mya; the second package (PLE-2) could correspond to another forced regression, from approximately 1.5 to 1.1 Mya; and the third package (PLE-3) could correspond to the next forced regression, from approximately 1.0 to 0.6 Mya. Each of these packages is bounded by high-amplitude reflectors (PLE1–PLE-4) and sometimes by small mound-like seismic facies in up-dip locations that could correspond to transgressive intervals leading to the interglacial MIS 47, MIS 31, and MIS 11 periods; the packages are characterized by unusually light $\delta^{18}O$ values (minimum ice-volume–sea-level highstand) relative to other interglacials. The most obvious boundary (PLE-3), which has the most continuous and highest-amplitude seismic character, would correspond to the first high-amplitude (120–140-m) transgressions between MIS 16 and MIS 11 in the mid-Brunhes.


a
Sea level
Purutu-1
well
PLE-5
PLE-4
PLE-3
PLE-2
PLE-1
L_PLI-8
L_PLI-7
L_PLI-6
L_PLI-5
L_PLI-4
L_PLI-3
Ashmore
Trough
Top carbonates
Base carbonates
Two-way travel time (s)
1.0
2.0
b
Drowned shelf-edge
transgressive barrier reef
MIS 47/MIS 49 reefs
MIS 31 reefs
MIS 11 reefs
Late-Pliocene reefs
Drowned Miocene
pinnacle reef
c
Seismic unconformities
MIS 11
reefs
MIS 31/MIS 33
reefs
MIS 47/MIS 49
reefs
Late-Pliocene
reefs
Eustatic sea level
30
10
–10
–30
–50
–70
–90
–110
–130
2-million-year-long
early/late-Pliocene
sea-level highstand
(+20–30 m)
Prograding late-Pliocene–Pleistocene shelf-edge deltas
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (millions of years)
Onset of
Northern Hemisphere
glaciations

The PLE-4 and PLE-5 packages, which are separated by the PLE-4 high-amplitude boundary (MIS 9), are not as voluminous and do not display clear downstepping geometries, as the PLE 1–PLE-3 packages do.

In summary, the late-Pliocene–Pleistocene successions of mixed siliciclastic-carbonate sequences are uniquely imaged in the building of the GoP continental shelf and can be interpreted in the context of the sea-level fluctuations of the last 3–4 million years (Miller et al. 2005, Tcherepanov et al. 2010). Few low-latitude mixed margins have been seismically imaged with such clarity. Contemporaneous late-Neogene mixed sequences have been recently described in a series of outcrops in the island of Hispaniola, Dominican Republic (Braga et al. 2012, McNeill et al. 2012). Similar to what we observed in the southwest part of the GoP shelf, McNeill et al. (2012) described a cyclic pattern in the Pliocene shelf mixed sediment accumulation; coralgal deposition occurred during times of transgression and highstand, whereas siliciclastics were preferentially deposited during times when sea level fell. As we reported earlier, Gischler et al. (2010) also observed in boreholes from the area of the Rhomboid Reefs in Belize [as it has been interpreted in the southwest part of the GoP shelf by Tcherepanov et al. (2010)] that a carbonate interval at ∼1.1–1.0 Mya was underlying a clay-rich unit corresponding to a time of forced regression and lowstand at approximately 0.9–0.6 Mya, or roughly the early Brunhes. The switch from siliciclastics to the observed stacked coralgal units separated by several exposure horizons in the Rhomboid Reefs area during the middle and late Brunhes would then correspond to the initial high-amplitude (120–140-m) transgressions between MIS 16 and MIS 11 in the middle Brunhes.

6. DISCUSSION AND FUTURE CONSIDERATIONS

All data sets presented in this review focus on the relative importance of eustatic sea level, climate changes, and tectonics to gaining a better understanding of the evolution of mixed continental margins. For a time of relatively well-established climatic and eustatic sea-level records, our observations therefore address crucial questions on sedimentary processes, responses, causes, and effects in the context of carbonate platform/reef establishment, growth, (partial) demise, and rebirth along mixed siliciclastic-carbonate margins.

During the ∼2-million-year Pliocene interval, the climate was warmer and more stable than it was during the late Miocene and the following Quaternary (Ravelo 2010, Ravelo et al. 2004). This golden age (in terms of climatic conditions) was likely a period when the neritic carbonate systems, such as those offshore of the Belize margin, flourished. The Pliocene ended with the onset of the main glaciations in the Northern Hemisphere approximately 2.7–2.5 Mya (Willis et al. 1999 and references therein). In the context of the Mesozoic and Cenozoic, the late Pliocene and Quaternary were unique because both hemispheres were partially and intermittently covered by major continental ice sheets at high latitudes. Once bipolar ice caps became established, the climate gradually cooled and became rather unstable through the Quaternary.

Based on visual observations of several 5-million-year-long $\delta^{18}O$ records (e.g., Lisiecki & Raymo 2005) (**Figures 3** and **12**), it is clear that the most significant change in the climate record in the past 3 million years occurred at the transition from MIS 12 to MIS 11. This

Figure 13

(*a*) Seismic profile showing late-Pliocene (L_PLI) and Pleistocene (PLE) sequences developed along the Gulf of Papua shelf edge (after Tcherepanov et al. 2010). (*b*) Interpreted seismic profile. (*c*) Relative sea level (from Miller et al. 2005). The high-amplitude reflections, which were considered sequence boundaries, are interpreted as carbonate sequences deposited during transgressions (note the peaks on the curve corresponding to the sequences). Abbreviation: MIS, marine isotope stage.

transition marks the end of the gradual deterioration of the climate and is clearly illustrated by the 0.6‰–0.8‰ $\delta^{18}O$ increase in the glacial and interglacial MIS values from approximately 3.0 to 0.5 Mya (**Figure 3**). In summary, the late-Quaternary transition from glacial MIS 12 (which, along with MIS 16, had the heaviest glacial values of any MIS period) to interglacial MIS 11 (which had the lightest values) is unique because of its extreme amplitude.

In the past 10 years, barrier reefs such as the Australian GBR (Peerdeman & Davies 1993, Webster & Davies 2003), Florida Keys barrier reef (Cunningham 1998, Multer et al. 2002), and New Caledonian barrier reef (Cabioch et al. 2008, Montaggioni et al. 2011) were discovered to be relatively thin and young late-Quaternary carbonate deposits, corresponding to four or five stacked mid-to-late-Brunhes coralgal units, separated by exposure horizons. These stacked coralgal units overlie mostly early-Brunhes or earlier siliciclastic sediments.

A similar scenario has been observed for the Rhomboid Reefs in the back barrier of the central BBR (Gischler et al. 2010) and has been suggested to explain the evolution of the BBR itself (Carson 2007, Droxler et al. 2003, Ferro et al. 1999). Although it is difficult to give a precise time for the mid-Brunhes establishment of modern barrier reefs, the unique mid-Brunhes sea-level transgression leading to interglacial MIS 11 has become an excellent candidate (Droxler et al. 2003).

The initial establishment of several globally distributed barrier reefs can be explained by the flooding of early-middle-Pleistocene lowstand tropical paleofluvial plains during the unique sea-level transgression leading to interglacial MIS 11. This exceptionally high-amplitude (>120-m) sea-level transgression—the first such transgression since the onset of the main Northern Hemisphere glaciations 2.7–2.5 Mya—and the unusually long MIS 11 (Raynaud et al. 2003) dramatically contrast with the overall early-middle-Pleistocene lowering of the marine base level, which was tied to the establishment and expansion of the major continental ice sheets in the Northern Hemisphere.

Because they archived two complementary sets of information within a single margin area, mixed siliciclastic-carbonate margins have probably recorded Pliocene–Quaternary sea-level fluctuations better than either pure carbonate systems or pure siliciclastic systems in terms of timing and to a certain extent amplitude. Further drilling programs dedicated to mixed margins will ground-truth our current understanding of how mixed systems have evolved since the early Pliocene and, in particular, will provide a unique opportunity to fully test the model that the origin of modern barrier reefs is linked to the mid-Brunhes MIS 12–MIS 11 high-amplitude sea-level transgression that followed the long-term early-middle-Pleistocene sea-level regression (Droxler et al. 2003).

The Belize margin would constitute an ideal location to address such fundamental questions for several reasons, among which two stand out. The first is that the Belize margin can be considered a unique natural laboratory. In spite of its modest extent, it is highly diverse in terms of reef systems thriving in close proximity to a mostly siliciclastic coastal zone. Fringing reefs are established close to the coast and are devoid of siliciclastic sediments in the northern part of the margin. The BBR proper, approximately 250 km in length, stretches 20–35 km offshore along the central and southern parts of the margin.

The second reason is that, in the past several decades, the Belize margin has been the ground for offshore oil and gas exploration because it was (and still is) thought that the Cretaceous part of the margin could have oil plays similar to those discovered and exploited around the Yucatan peninsula (Morrice 1993a,b). In the central and southern parts of the Belize margin in particular, a series of multichannel seismic grids of different vintages were acquired that provided good imaging of the Cenozoic evolution of the margin. Those seismic images have been ground-truthed by a series of deep industrial wells, nine of them drilled in the central part of the margin, and based on these a general chronological framework was developed (Esker et al. 1998, Ferro 2000, Ferro et al.

1999, Lara 1993, Purdy & Gischler 2003, Purdy et al. 2003, and references therein). Moreover, our understanding of the late-Pleistocene–Holocene evolution of the shallow carbonate system was greatly improved once numerous vibracores and rotary cores were collected and studied in the offshore atoll lagoons and along the BBR (Gischler 2003; Gischler & Hudson 1998, 2004; Gischler et al. 2010). The northern extremity of the GBR in the GoP would be another excellent locale for drilling to test the model of the last mid-Brunhes phase of modern barrier reef establishment and potentially older late-Pliocene and Pleistocene phases of establishment on top of lowstand siliciclastic coastal deposits such as beach ridges and delta fronts during unusually high-amplitude sea-level transgressions that reflooded lowstand fluvial plains (**Figure 13**).

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Errata

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