

## Neogene evolution of the mixed carbonate-siliciclastic system in the Gulf of Papua, Papua New Guinea

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[1] This paper outlines the evolution of the late Cenozoic mixed carbonate-siliciclastic depositional system in the Gulf of Papua (GoP), using seismic, gravity, multibeam bathymetry, well data sets, and Landsat imagery. The deposition of the mixed sedimentary sequences was influenced by dynamic interplay of tectonics, eustasy, in situ carbonate production, and siliciclastic sediment supply. The roles of these major factors are estimated during different periods of the GoP margin evolution. The Cenozoic mixed system in the GoP formed in distinct phases. The first phase (Late Cretaceous–Paleocene) was mostly driven by tectonics. Rifting created grabens and uplifted structural blocks which served later as pedestals for carbonate edifices. Active neritic carbonate accumulation characterized the second phase (Eocene–middle Miocene). During this phase, mostly eustatic fluctuations controlled the large-scale sedimentary geometries of the carbonate system. The third phase (late Miocene–early Pliocene) was characterized by extensive demise of the carbonate platforms in the central part of the study area, which can be triggered by one or combination of several factors, such as eustatic sea level fluctuations, increased tectonic subsidence, uplift, sudden influx of siliciclastics, or dramatic changes in environmental conditions and climate. The fourth phase (late Pliocene–Holocene) was dominated by siliciclastics, which resulted in the burial of drowned and/or active carbonate platforms, although some platforms still remain alive until present-day.

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### 1. Introduction

[2] Mixed carbonate-siliciclastic systems are sedimentary environments characterized by lateral juxtaposition and/or vertical stacking of carbonate and siliciclastic sediments [Doyle and Roberts, 1988; Budd and Harris, 1990; Lomando and Harris, 1991; Handford and Loucks, 1993; Ferro et al., 1999]. These systems provide important information for understanding sediment origin, transport

pathways, and ultimate sinks during different periods of the Earth's evolution. In many cases, spatial and temporal interactions of carbonate and siliciclastic sediments in the mixed systems can provide significantly more information on such processes as eustatic sea level fluctuations, global and regional tectonics, and climate than studying either pure carbonate or pure siliciclastic systems. The Cenozoic mixed systems often result from a complex interplay between several geological factors (tectonics, eustasy, in situ carbonate production, and siliciclastic sediment supply). A detailed analysis of the spatial and temporal interactions between carbonate and siliciclastic sediments can help in estimating the role of the major factors influencing the system. For example, significant siliciclastic supply can rapidly terminate the carbonate system, and the timing and the geographical distribution of the siliciclastic influx can be related to several factors such as active tectonic uplift, weathering, and erosion in the adjacent regions, and to modifications of the ocean base level. At the same time, specific carbonate-producing biota can often sustain and adapt to very high turbidity conditions which can be reflected in the geometrical configuration of the depositional sequences [Wilson and Lokier, 2002]. The mixed systems become also valuable in

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the context of hydrocarbon exploration because carbonate and siliciclastic components of mixed systems play very different roles in the formation of petroleum source rocks, traps, and seals, in oil migration, and evolution of petroleum reservoirs (e.g., Gulf of Mexico, South China Sea, and Indonesia).

[3] The Gulf of Papua (GoP), encompassing southern Papua New Guinea (PNG) and northeastern Australia (Figure 1), is considered to be one of the largest Cenozoic mixed carbonate-siliciclastic systems. In this rather unique depositional system, large isolated carbonate platform and shelf environments have interacted in space and time with the unusually large influx of siliciclastic sediments produced from the 3–4 km elevated PNG mountain chains [Davies *et al.*, 1989; Pigram and Symonds, 1993; Harris *et al.*, 1996; Sarg *et al.*, 1996]. The Cenozoic depositional evolution of the GoP represents an excellent example of a gradual transition from a pure carbonate to a mixed carbonate-siliciclastic system.

[4] Previous studies along the northeastern Australian margin mostly focused on the Oligocene-Neogene evolution of the pure carbonate system on the Queensland and Marion plateaus [Davies *et al.*, 1989; McKenzie *et al.*, 1991; Isern *et al.*, 2002]. The mixed carbonate-siliciclastic system of the Great Barrier Reef (GBR) was primarily studied regarding the timing and causes of its establishment during the Brunhes [International Consortium for Great Barrier Reef Drilling, 2001; Webster and Davies, 2003; Braithwaite *et al.*, 2004] and its evolution during the last deglaciation [Dunbar *et al.*, 2000; Page *et al.*, 2003; Dunbar and Dickens, 2003]. The GoP was studied in terms of hydrocarbon exploration and general understanding of the tectonic evolution of the area [Stewart and Durkee, 1985; Durkee, 1990; Sarg *et al.*, 1996; Gordon *et al.*, 2000; Jablonski *et al.*, 2006]. Using a sequence stratigraphic approach, Morgan [2005] analyzed the Eocene and Miocene evolution of the pure carbonate Mendi and Darai formations in the northern part of the GoP. The spatial and temporal interactions of carbonate and siliciclastic sediments have not been yet studied in the context of the changing degree of influence of such factors as tectonics, eustasy, carbonate production, siliciclastic sediment supply, and their complex combination.

[5] The southern PNG and the adjacent GoP were selected to become a National Science Foundation-funded MARGINS source-to-sink (S2S) focus area chosen for reasons that include juxtaposition of large siliciclastic and carbonate sediment sources and sinks. This study integrates the seismic and well data sets, acquired mostly across the GoP shelf through the past 30 years by the oil industry, with the data collected from the shelf, slope, and basin of the GoP during the MARGINS PANASH 2004 and International Marine Global Change Study (IMAGES) PECTEN 2005 research cruises on the R/V *Melville* and R/V *Marion Dufresne*, respectively. This study sheds new light on the Cenozoic depositional history of the GoP and offers an essential framework to place into longer timescale the results of more recent MARGINS S2S studies particularly focusing on depositional processes, sediment sources, sinks, and transport pathways within the GoP. It will also provide

an analog for active or ancient mixed systems in other areas of the world.

## 2. Data Sets and methodology

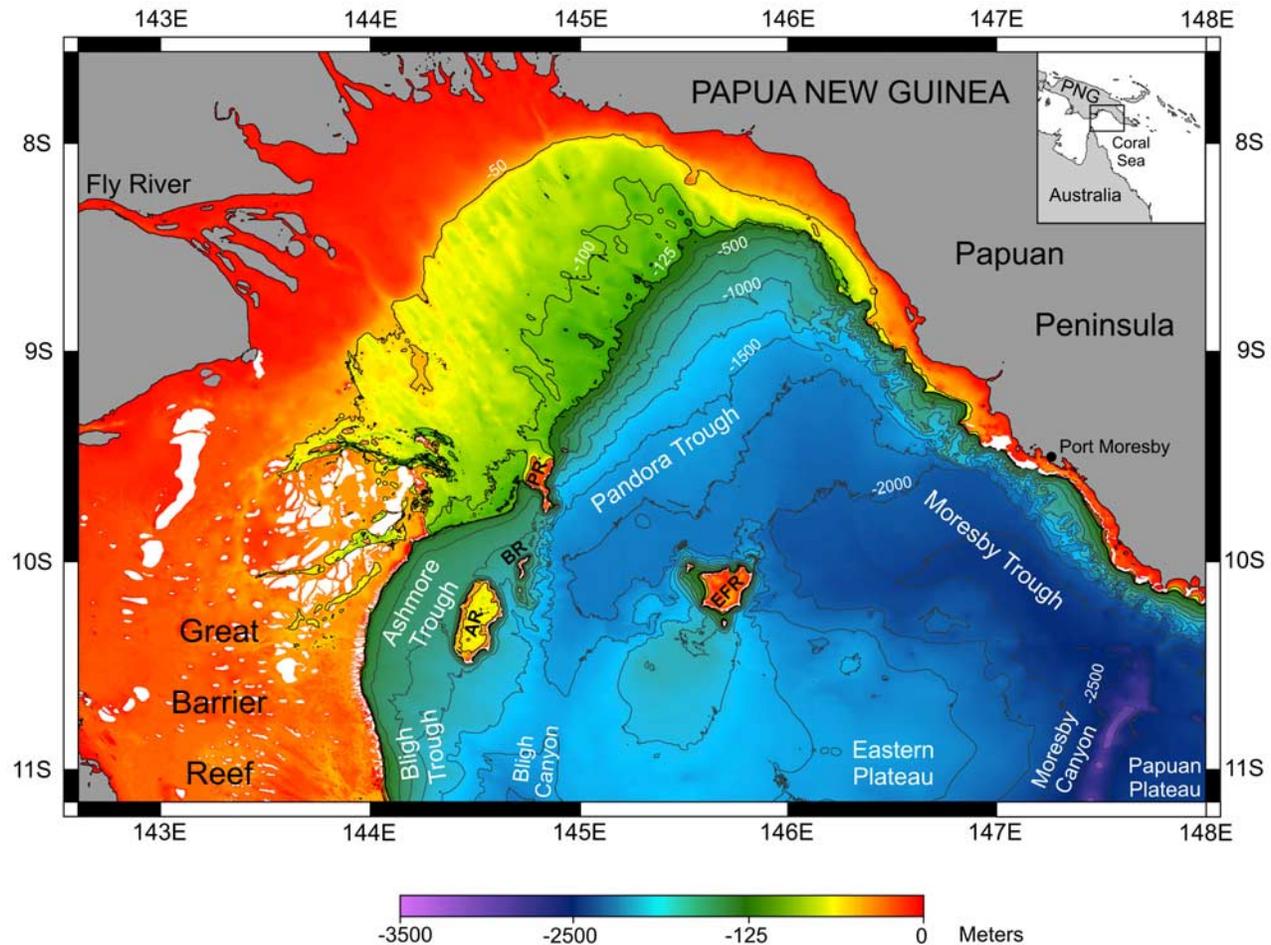
[6] The industrial well and seismic data sets used for the interpretation (Figure 2) comprised 26 wells drilled on the GoP shelf and about 30,000 km of two-dimensional seismic data recently reprocessed by Fugro Multi Client Services, Inc. The data sets also included gravity map provided by ConocoPhillips, and public domain Landsat imagery used for detailed mapping of the modern coral reefs in the GoP.

[7] Multibeam bathymetry data sets and 3.5 kHz seismic profiles were collected from the GoP shelf edge to Eastern Plateau, including several troughs (e.g., Ashmore, Pandora, and Moresby) seaward of the modern shelf break. Modern and recent depositional features, once observed and interpreted, provide valuable information to establish comparisons and analogies between the most recent and possibly identical Miocene-Pleistocene sedimentary features buried beneath the modern GoP shelf.

[8] Two recent 2004 PANASH and 2005 PECTEN cruises provide a new perspective on the present-day bathymetry and mixed carbonate-siliciclastic sedimentation during the last glacial cycle in the GoP. During the 2004 cruise, about 8000-line-km of multibeam bathymetry and 3.5 kHz seismic profiles, 33 jumbo piston cores (up to 14 m in length), 29 trigger cores, 4 gravity cores, 30 multicores, 4 box cores, and 5 dredge samples were collected in the GoP from the modern shelf edge to adjacent troughs, spanning water depths between 65 and 2300 m. The 2005 cruise retrieved 22 CALYPSO, Casq, and gravity cores ranging from 8 to 47 m in length, with 8 CALYPSO cores exceeding 30 m in length. These long cores are crucial for constraining sedimentary sinks in areas of high accumulation or during early periods of the last sea level cycle. About 1500 km of multibeam and 3.5 kHz seismic profiles were also collected during the 2005 cruise [Jorry *et al.*, 2008; Muhammad *et al.*, 2008; Febo *et al.*, 2008; J. M. Francis *et al.*, Deep-water geomorphology of the mixed siliciclastic-carbonate system, Gulf of Papua, submitted to *Journal of Geophysical Research*, 2007, hereinafter referred to as Francis *et al.*, submitted manuscript, 2007; L. J. Patterson *et al.*, Petrological and geochemical investigations of deep sea turbidite sands in the Pandora and Moresby troughs: Source to sink Papua New Guinea focus area, unpublished manuscript, 2007].

## 3. General Geology of the Gulf of Papua

[9] The GoP is located in the northern Coral Sea and occupies more than 50,000 km<sup>2</sup> of the modern continental margin off northeastern Australia and southern PNG (Figure 1). The area represents the offshore portion of the Papuan Basin, which has developed during the Mesozoic and Cenozoic [Home *et al.*, 1990; Pigram and Symonds, 1993]. This present-day structural basin is filled with Triassic to Holocene sedimentary successions as thick as 10 km. The regions of PNG to the east and northeast of the GoP are among the most tectonically active areas of the world, where large lateral displacements are locally associated with either exceptionally deep subsidence or extreme



**Figure 1.** Bathymetry map of the Gulf of Papua. Modern shelf edge is at  $\sim$ -125 m. Note wide shelf in the northwest and very narrow shelf in the northeast. White areas on the shelf represent modern live reefs. Active isolated carbonate platforms (atolls) seaward of the shelf edge include Eastern Fields Reef (EFR), Ashmore Reef (AR), Boot Reef (BR), and Portlock Reef (PR). Contour interval is 250 m seaward of the shelf edge. Inset shows location of Papua New Guinea (PNG).

uplift rates [Bird, 2003; Webster et al., 2004]. These regions contrast with the GoP study area which, sitting on the northeast corner of the Australian Plate, is currently very stable tectonically, illustrated by a lack of historical earthquakes [Bird, 2003].

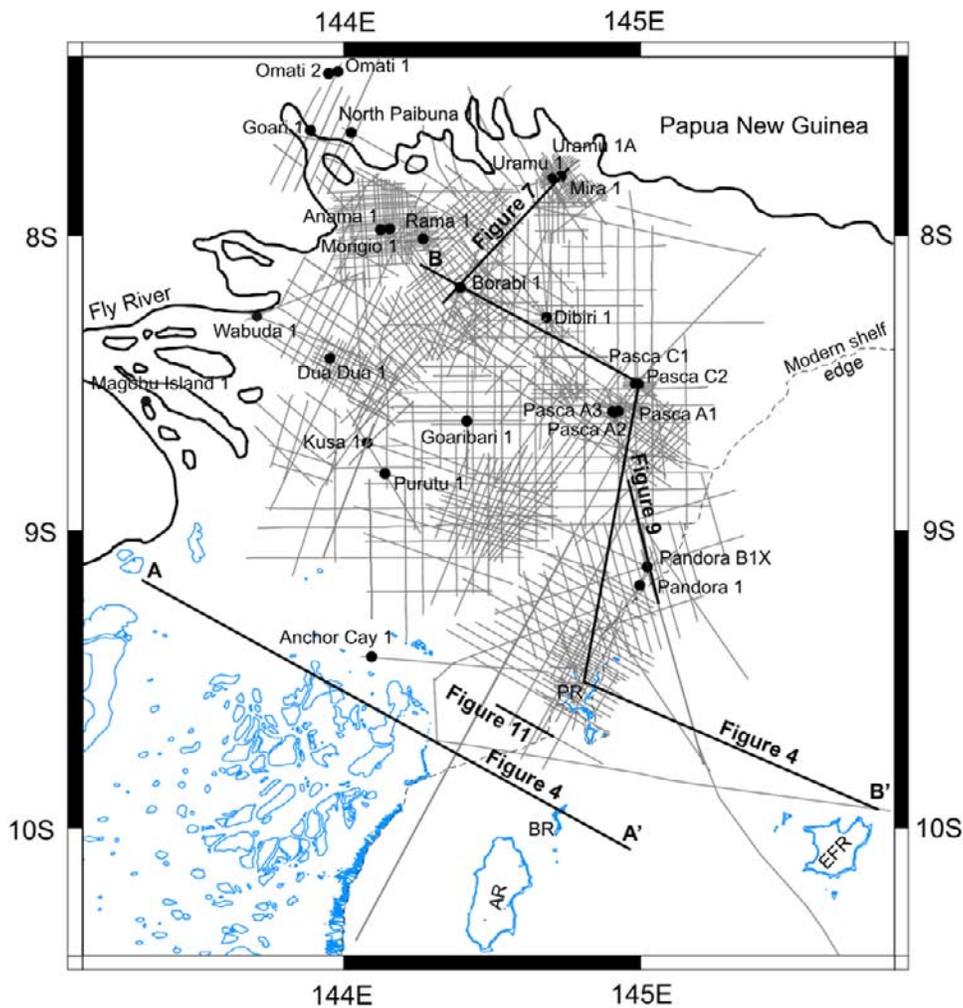
[10] The overall evolution of the carbonate-siliciclastic systems in the GoP and on the northeastern Australian margin was influenced by eustasy [Davies et al., 1989; Sarg et al., 1996; Jorry et al., 2008], tectonics [Hamilton, 1979; Hall, 2002; Quarles van Ufford and Cloos, 2005], siliciclastic influx, climate, and oceanic currents [Feary et al., 1991; Wolanski et al., 1995]. Rifting determined the size, shape, orientation, and location of a series of northeast oriented troughs and ridges, on top of which isolated carbonate platforms were established and evolved [Davies et al., 1989]. Sea level changes are reflected in large-scale sedimentary stacking patterns such as back stepping, aggradation, progradation, and reflooding [Schlager, 2005, and references herein]. The northward motion of the Australian Plate during the Cenozoic influenced the distribution of climate-related facies along the northeastern Australian

margin where older temperate and subtropical carbonate facies are overlain by younger tropical facies [Davies et al., 1989; Feary et al., 1993; McKenzie et al., 1991; Isern et al., 2002]. Moreover, the early Miocene expansion of the neritic carbonate facies in the GoP was influenced by the development of a foreland basin often referred to as Aure Trough (Figure 3), serving as a depocenter and/or bypass for large volumes of siliciclastic sediments and therefore indirectly protecting the development of the neritic carbonates in the more distal part of the depositional system.

## 4. Results

### 4.1. Gulf of Papua Bathymetry

[11] The modern bathymetry of the Gulf is shown in Figure 1 [Daniell, 2008; Francis et al., submitted manuscript, 2007]. A significant portion of the study area represents a modern siliciclastic and mixed carbonate-siliciclastic shelf ranging in water depth from 0 to 125 m, which formed as a result of voluminous siliciclastic supply and intensive carbonate production during the Cenozoic.



**Figure 2.** Seismic and well data set used in the study was provided by Fugro Multi Client Services, Inc. Modern reefs were digitized using georeferenced Landsat imagery in ArcGIS.

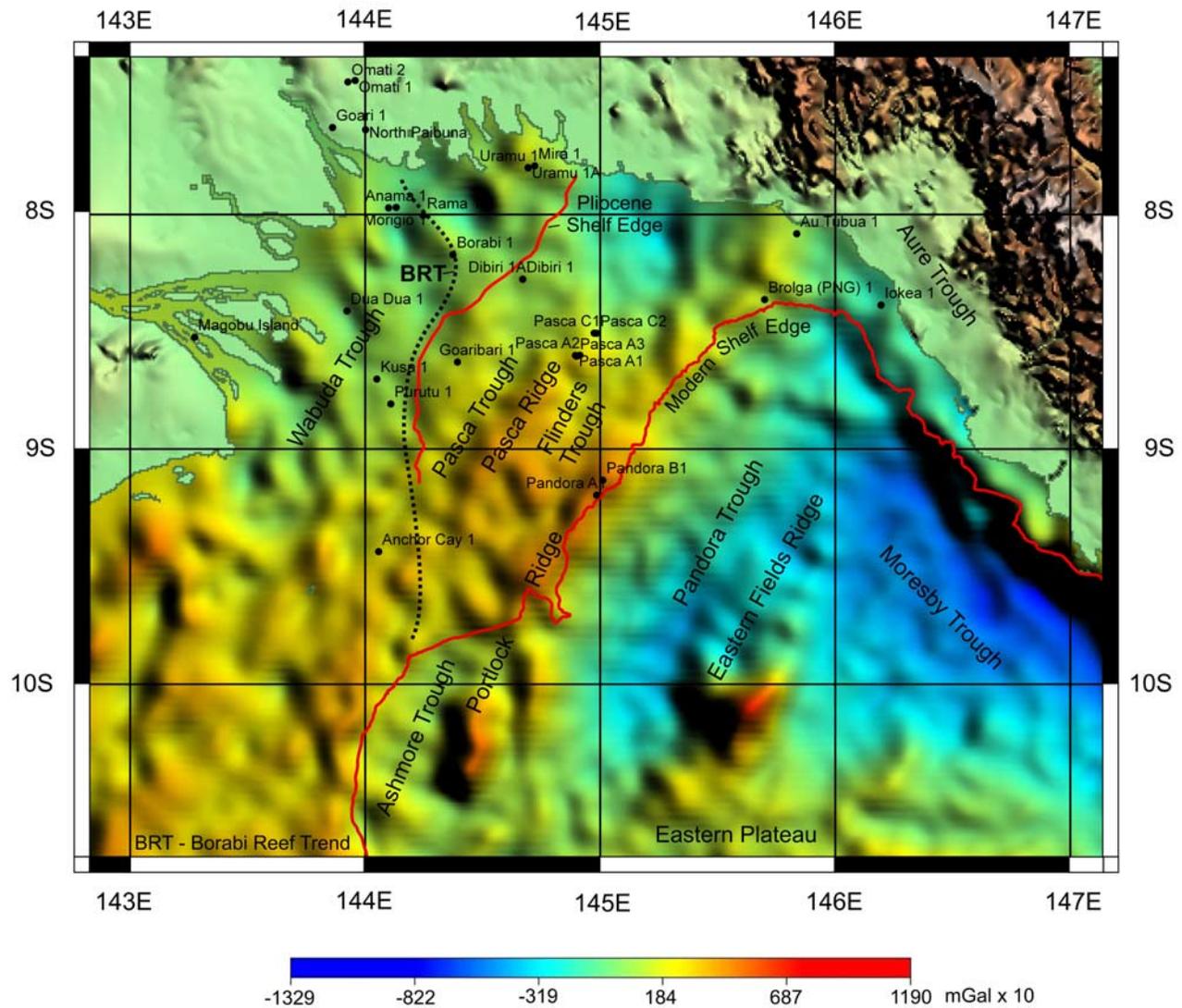
The GoP area seaward of the modern shelf edge consists of elongated active and partially drowned isolated carbonate platforms (Eastern Fields Reef (EFR) and Ashmore-Boot-Portlock reefs) separated by a series of subparallel intervening troughs (Ashmore and Pandora), roughly oriented in the northeastern direction, and ranging in water depth from a couple of hundreds to almost 2000 m. Unlike these reefs and troughs, Moresby Trough, the deepest basin in the GoP, with depths reaching 2500 m, is oriented in the northwestern direction, parallel to the Papuan Peninsula.

[12] The GoP shelf is predominantly siliciclastic in the northern part (~north of 9°S) and carbonate or mixed carbonate-siliciclastic in the southern part (approximately south of 9°S), where almost continuous, live or drowned, barrier reefs and reef complexes occupy the modern shelf. The GoP shelf is about 200 km wide in the west and northwest and narrows down to ~10–20 km in the northeast and east. The narrow northeastern shelf can be explained by the modern structural elements and perhaps by a relatively smaller volume of siliciclastic input in comparison with the northwestern shelf. The Papuan Peninsula has been and still acts as a large source of siliciclastics, because it includes a fold and thrust belt,

intensively eroded under wet tropical climate conditions. The southwestern front of this fold and thrust belt forms the offshore steep margin of the Papuan Peninsula, explaining the high gradient slope, and therefore the narrow shelf, which is mostly bypassed by terrigenous sediments. The edge of this narrow shelf is rimmed by an almost continuous barrier reef stretching as far north as ~8°40'S. In the northwestern part of the GoP shelf, the Fly River along with several relatively smaller rivers discharge huge volume of siliciclastic sediments, which play a major role in the formation of a very wide modern shelf in this part of the GoP. Several rivers deliver annually about 200–300 megatons of terrigenous siliciclastic and volcanoclastic material to the GoP inner shelf [Milliman, 1995; Harris *et al.*, 1996]. This huge volume of clastic sediments is juxtaposed with many neritic carbonate sources and sinks, including the northern extremity of the GBR.

#### 4.2. Evolution Phases in the Gulf of Papua Mixed System

[13] On the basis of the analysis of seismic and well data (Figure 2), and the data acquired during the 2004–2005 cruises, the general evolution of the mixed system in the



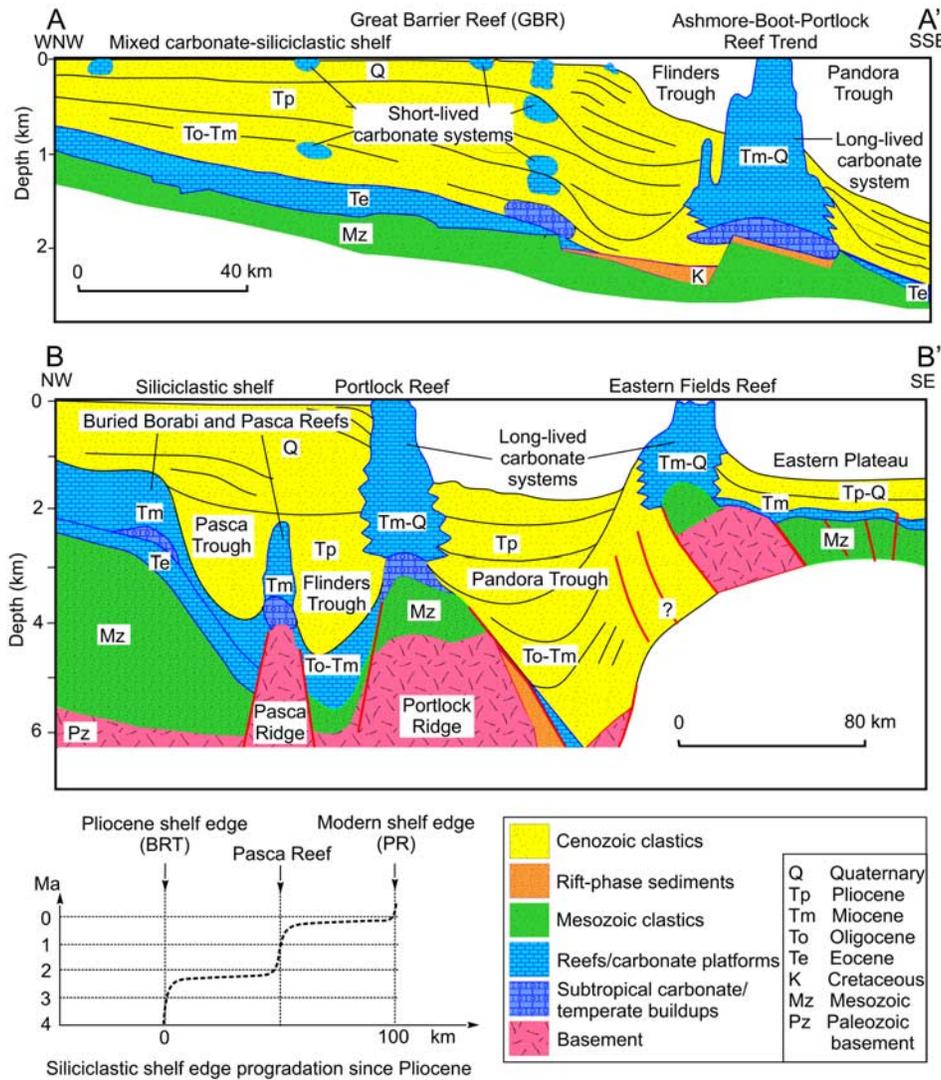
**Figure 3.** Gravity map of the GoP showing the overall distribution of major structural features. Note a series of northeast oriented troughs and ridges which influenced the depositional history of the mixed system. The modern shelf edge location is also controlled by structural highs. The map is courtesy of K. A. Soofi of ConocoPhillips, based on radar altimeter-derived free-air gravity anomaly (offshore) while onshore topography is from the Shuttle Radar Topography Mission. The free-air gravity anomaly derivation is based on algorithms developed by *Sandwell and Smith* [1997]. Pliocene shelf edge position is obtained from *Sarg et al.* [1996].

GoP is outlined with an emphasis on which processes can be considered predominant and which processes are minor in the system development during different Cenozoic time intervals. Four major phases can be distinguished in the geological evolution of the Cenozoic mixed GoP system based on the balance between tectonics, eustasy, carbonate production, and clastic sediment supply.

#### 4.2.1. Tectonic Control of the System Evolution (Phase 1)

[14] The first phase in the mixed system evolution was mostly driven by large-scale tectonics, represented by periods of active rifting, subsidence, and uplift. This phase corresponds to the last stage of the Coral Sea spreading in the late Cretaceous-Paleocene and subsequent uplift resulted

in intensive erosion (so-called base tertiary unconformity, BTU) [*Hamilton, 1979; Symonds et al., 1991; Pigram and Symonds, 1993; Hall, 2002; Quarles van Ufford and Cloos, 2005; Morgan, 2005*]. The gravity map of the GoP (Figure 3) helps to characterize the overall tectonic grain presently buried under the modern shelf and seaward of the modern shelf edge. The early physiography, molded by tectonics, displays two sets of preferential northeast and northwest trending orientations, which have influenced the GoP evolution throughout the entire Cenozoic. The first structures consist of a series of three northeast trending relatively continuous ridges (Pasca, Portlock ridges, and Eastern Fields Ridge (defined as such in this paper)) separated by intervening paleotroughs and modern troughs (Pasca, Flinders,



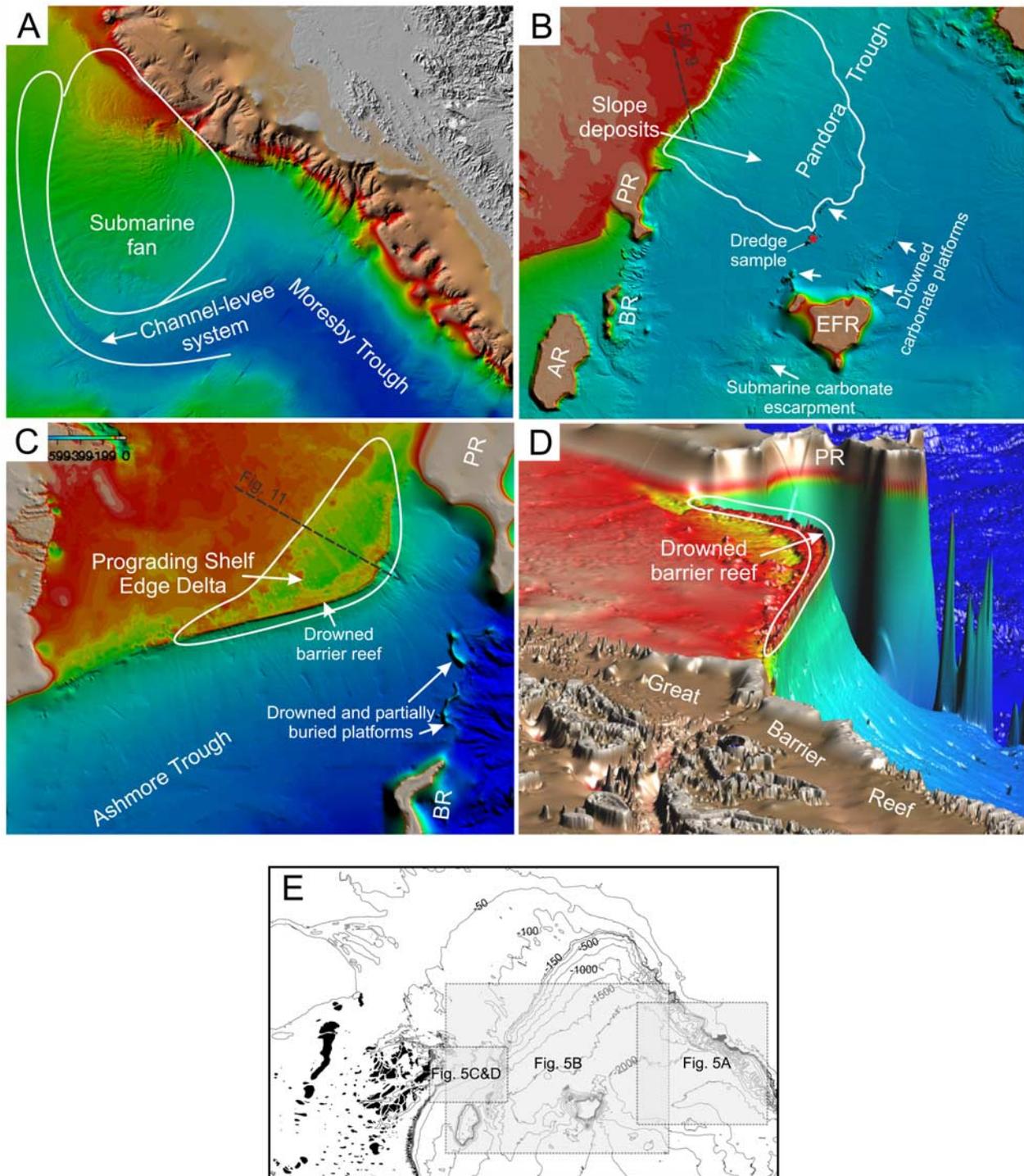
**Figure 4.** Schematic cross sections showing generalized structures and sedimentary sequences in the GoP (modified from *Davies et al.* [1989]). Note long- and short-lived carbonate systems and mixed carbonate-siliciclastic and pure siliciclastic parts of the GoP shelf. Shelf edge position is controlled by the distribution of long-lived carbonate platforms and structural features. Siliciclastic shelf edge did not prograde, being “anchored” along Borabi Reef Trend (BRT) or Pasca Ridge, until the next adjacent troughs (Pasca and Flinders Troughs, respectively) were infilled (see graph). High gradient slope of the curve shows low rate of shelf edge progradation, while low gradient curve shows high rate progradation of the shelf edge per million years. In this model, the modern shelf edge is “anchored” along Portlock Ridge including Portlock Reef (PR) and will not prograde until Pandora Trough is infilled.

Ashmore, and Pandora). The second set of structural features includes northwest oriented deep troughs (ancient Aure and Moresby) which served and currently act as major conduits for siliciclastic sediment transfer through Moresby Canyon down to the Coral Sea basin, the ultimate sediment sink for the sediments not stored on the shelf and slope of the GoP. The gravity map and two schematic geological cross sections (Figure 4) illustrate that the morphology of paleoridges and troughs buried beneath the GoP shelf under several kilometers thick late Pliocene-Pleistocene siliciclastics is almost identical to the morphology in the deep-water part of the GoP directly adjacent to the shelf (Ashmore and Pandora Troughs adjacent to Portlock and Eastern Fields

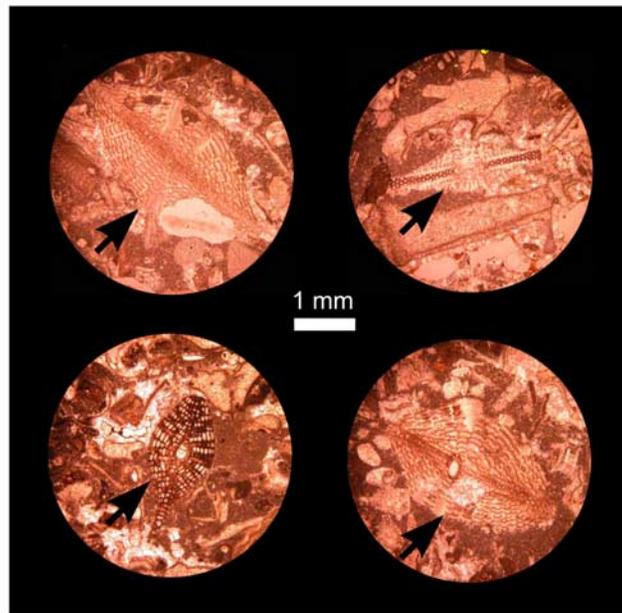
ridges). This tectonic morphology later influenced the late Oligocene-early Miocene establishment and distribution of the Miocene carbonate platforms as well as the invasion of the late Miocene-Holocene clastics.

**4.2.2. Carbonate Deposition and Eustatic Control (Phase 2)**

[15] In general, during the Cenozoic, two types of carbonate systems can be identified in the GoP, long-lived and short-lived systems (Figure 4). The long-lived systems include several large isolated long-lived carbonate platforms which have evolved since the late Oligocene-early Miocene, and observed today as typical large atolls (e.g., Ashmore, Boot, Portlock, and EFR). Over longer times, these or



**Figure 5.** High-resolution multibeam bathymetry maps of different portions of the GoP, showing modern analogs of vertically stacked sedimentary features interpreted in the Miocene-Pleistocene infilling of Pasca and Flinders paleotroughs (see Figure 9). (a) Submarine fan and channel-levee system in deep-water Moresby Trough. (b) Ponded turbidites and slope deposits in Pandora Trough. Drowned isolated platforms serve as barriers for siliciclastics. (c) Prograding lowstand shelf edge delta deposits in Ashmore Trough. (d) Three-dimensional perspective of the transgressive drowned barrier reef on the modern shelf break in northern Ashmore Trough. (e) Location map. Depositional features in Figures 5a–5c demonstrate a lateral trend which is comparable to the vertical stacking of the Pliocene-Pleistocene depositional environments, observed in the prograding several kilometers thick siliciclastic sediment pile infilling the paleotroughs and burying the drowned carbonate platforms.



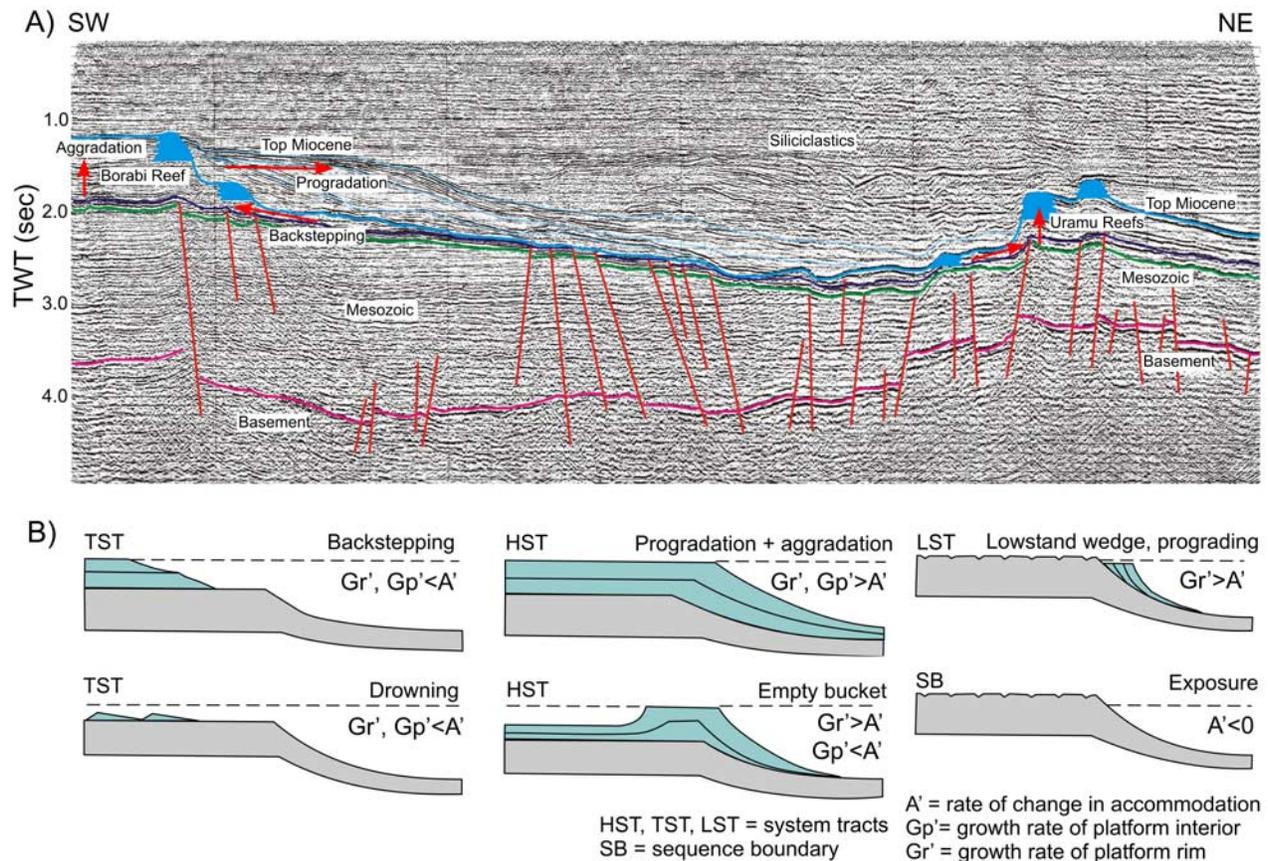
**Figure 6.** Thin sections showing early Miocene larger foraminifera (*Lepidocyclina* (*Nephrolepidina*) and *Spirochypena margaritatus*) (upper (u)Te) zone, ~20 Ma) observed in dredge samples collected from the slope of a drowned carbonate platform in Pandora Trough (dredge sample is located in Figure 5b).

similar long-lived carbonate edifices, buried under the GoP shelf, appear to act as compartments, controlling the GoP margin evolution, guiding and restraining siliciclastic sediment fluxes from the continent. This has been clearly the case in the recent past for Portlock Reef and the Miocene drowned reefs on the northeastern extension of EFR in Pandora Trough (Figure 5b), where drowned platforms directly interact with the slumping masses along the slope of the central Pandora Trough. Some of the isolated carbonate platforms were drowned starting in the early Miocene and were subsequently buried by siliciclastics (e.g., Pasca and Pandora reefs) [Sarg *et al.*, 1996; Morgan, 2005], while others (the Ashmore-Boot-Portlock Reef complex and EFR) remained active and not buried from the late Oligocene until present. On the other hand, short-lived carbonate systems represent buildups of much smaller size that lived over short periods of time (Figure 4). These include the northern extension of the GBR, which covers the western shelf and, like its more southern counterpart (e.g., Ribbon Reef 5 on the GBR), is probably not older than mid-Brunhes in age (<0.5 Ma) [International Consortium for Great Barrier Reef Drilling, 2001; Webster and Davies, 2003]. Moreover, during the 2004 and 2005 cruises, a series of early transgressive barrier reefs was discovered (Figures 5c and 5d), established on top of coastal Last Glacial Maximum siliciclastic deposits. Because of short life of these reefs, they are considered to be ephemeral sources and sinks of neritic carbonates.

[16] Carbonate deposition in the mixed GoP system was initiated during the Eocene. Interpretation of the seismic and well data suggests that during the late Oligocene-early Miocene, the initial distribution of major carbonate sources and sinks in the GoP was controlled by a system of preexisting northeast oriented structural ridges. Such carbonate platforms as Uramu, Pasca, Pandora, Ashmore-Boot-

Portlock, and EFR reefs were established during this time on the uplifted blocks (Figures 3 and 4). The northeast trending Borabi Reef rimmed a large carbonate shelf in the western part of the GoP by the middle of the early Miocene [Pigram *et al.*, 1989, 1990; Carman, 1993]. We assume that a late Oligocene-early Miocene overall sea level transgression [Vail *et al.*, 1977; Haq *et al.*, 1987, 1988; Billups and Schrag, 2002] triggered the large-scale establishment of major carbonate platforms in the GoP. Although the New Guinea mountain chains possibly started emerging at that time, the area of neritic carbonate production was not influenced by siliciclastics, because their accumulation was mostly restricted in Aure Trough (Figure 3), the foreland basin located in the early Miocene further northeast from the carbonate province.

[17] Our study reveals that the evolutionary history of the neritic carbonate system in the GoP was very similar to the evolution of the pure carbonate systems along the northeastern Australian margin and particularly on the Queensland and Marion plateaus [McKenzie *et al.*, 1991; Droxler *et al.*, 1993; Feary *et al.*, 1993; Betzler *et al.*, 1993, 2000; Brachert *et al.*, 1993; Isern *et al.*, 2002; John and Mutti, 2005]. We observe that during the overall late Oligocene and early Miocene sea level transgression, most of the platforms in the GoP experienced a general back stepping of environments, resulting in a systematic decrease of the surface area of neritic carbonate production. Some of the platforms were partially or completely drowned at that time. For example, EFR platform started as a much larger system extending toward the southwest and northeast relative to the modern EFR (Figures 1 and 5b) and later partially drowned in the early Miocene. On the basis of newly acquired high-resolution bathymetry data, several narrow, drowned, isolated, high-relief carbonate platforms were discovered to the northeast of EFR in the central Pandora Trough. Analyses of



**Figure 7.** (a) Seismic profile showing different geometries of the Miocene carbonate system in the GoP (back stepping, aggradation, progradation, reflooding). TWT, two-way traveltime. (b) Basic geometries of tropical platforms as a response to rates of change in accommodation space and platform carbonate growth rates [Schlager, 2005].

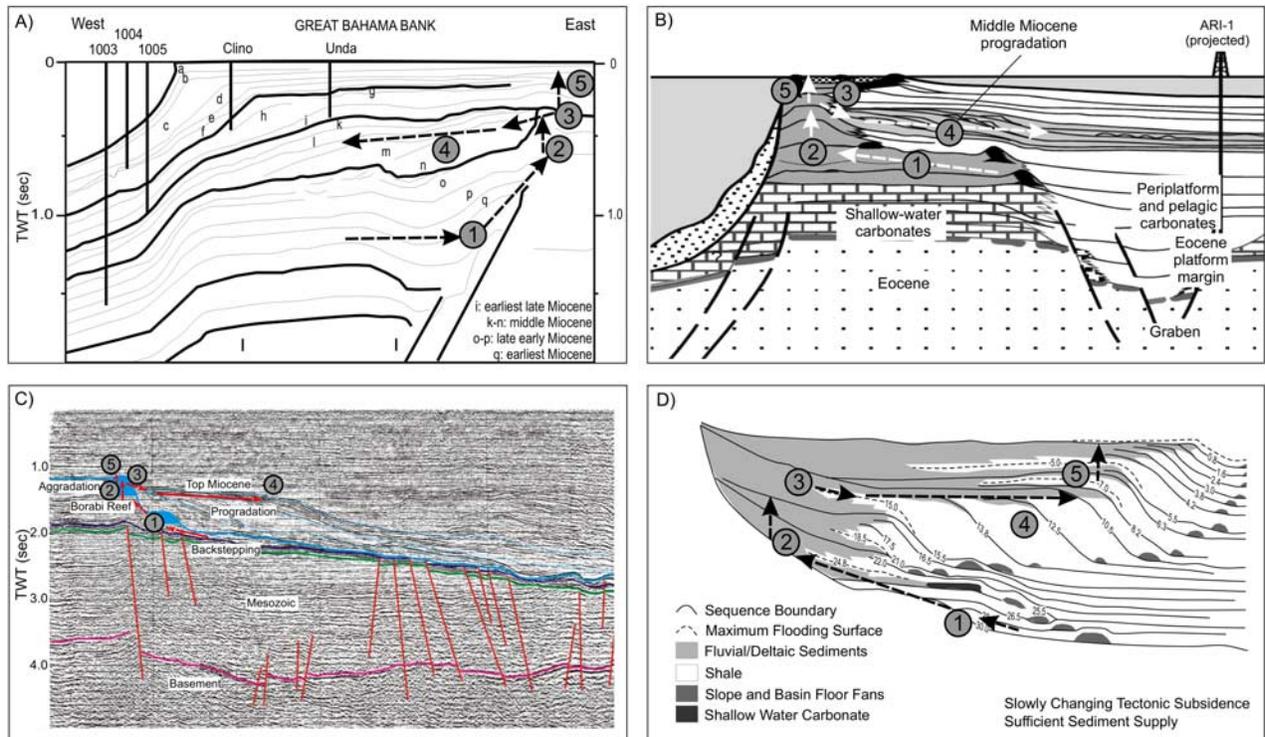
dredge samples from one of them (Figures 5b and 6) demonstrated that the original EFR platform was drowned as early as 20 Ma [Droxler *et al.*, 2004].

[18] An overall back stepping pattern of the carbonate system during the early Miocene is also shown on Borabi platform (Figure 7). During the end of the early Miocene and the earliest middle Miocene, Borabi platform, as many carbonate platforms in the GoP, vertically aggraded and therefore was able to keep up with the rise of sea level. In the middle Miocene, the carbonate deposition on the north-eastern Borabi margin shifted downward which most likely signals a systematic sea level lowering [Billups and Schrag, 2002]. Subsequent deposition resulted into well developed progradational patterns. The platform was then reflooded during a major transgression at the very beginning of the late Miocene.

[19] The late Oligocene-middle Miocene stacking patterns observed in the seismic profiles crossing the Borabi Reef trend (Figures 7a and 8) correspond to the identical and contemporaneous pattern of back stepping, aggradation, downward shift, progradation, and reflooding observed in other pure carbonate systems such as the Bahamas (Figure 8a) [Eberli and Ginsburg, 1987; Eberli *et al.*, 1997], the Maldives (Figure 8b) [Belopolsky and Droxler, 2003, 2004a, 2004b], and also in pure siliciclastic system on

the New Jersey continental margin [Miller *et al.*, 1996]. This so-called Neogene global stratigraphic signature [Bartek *et al.*, 1991] is represented in the schematic diagrams shown in Figure 8d by (1) aggradation and back stepping and partial drowning in the late Oligocene-early Miocene, (2) vertical growth or aggradation in the latest early Miocene and earliest middle Miocene, (3) a downward shift of deposition in the middle Miocene, (4) systematic lateral growth or progradation in the middle Miocene, and (5) reflooding and aggradation from the late Miocene until the early Pliocene. Because the Maldives and the Bahamas platforms, as well as the New Jersey margin are considered to be tectonically stable during the Oligocene-Neogene, the common sedimentary geometries observed in these different systems must be produced by eustatic sea level fluctuations.

[20] The Neogene signature is also observed in the GoP, and therefore eustatic sea level fluctuations apparently influenced the major carbonate sources and sinks in the GoP during maximum development of the carbonate system in the late Oligocene-Miocene. Our interpretation of the seismic data shows that in general the study area had relatively stable tectonics with the exception of some local zones of late Oligocene and earliest Miocene extensional faulting and more intensive differential subsidence (e.g., Pasca Trough). Accommodation space was produced by a



**Figure 8.** (a) Overall sequence stratigraphic signature observed in the interpretation of the Bahamas western line (modified from Eberli *et al.* [1997]). (b) Neogene stratigraphic signature along the West Maldives Inner Sea carbonate margin (modified from Belopolsky and Droxler [2003, 2004a, 2004b]). (c) Neogene stratigraphic signature on the Borabi platform margin and adjacent slope in the GoP. (d) Stratigraphic signature of the Neogene (modified from Bartek *et al.* [1991]). Numbers in circles: 1, late Oligocene-early Miocene aggradation, back stepping and partial drowning; 2, latest early Miocene-earliest middle Miocene vertical growth or aggradation; 3, middle Miocene downward shift of deposition; 4, latest middle Miocene systematic lateral growth or progradation; and 5, late Miocene-early Pliocene reflooding and aggradation.

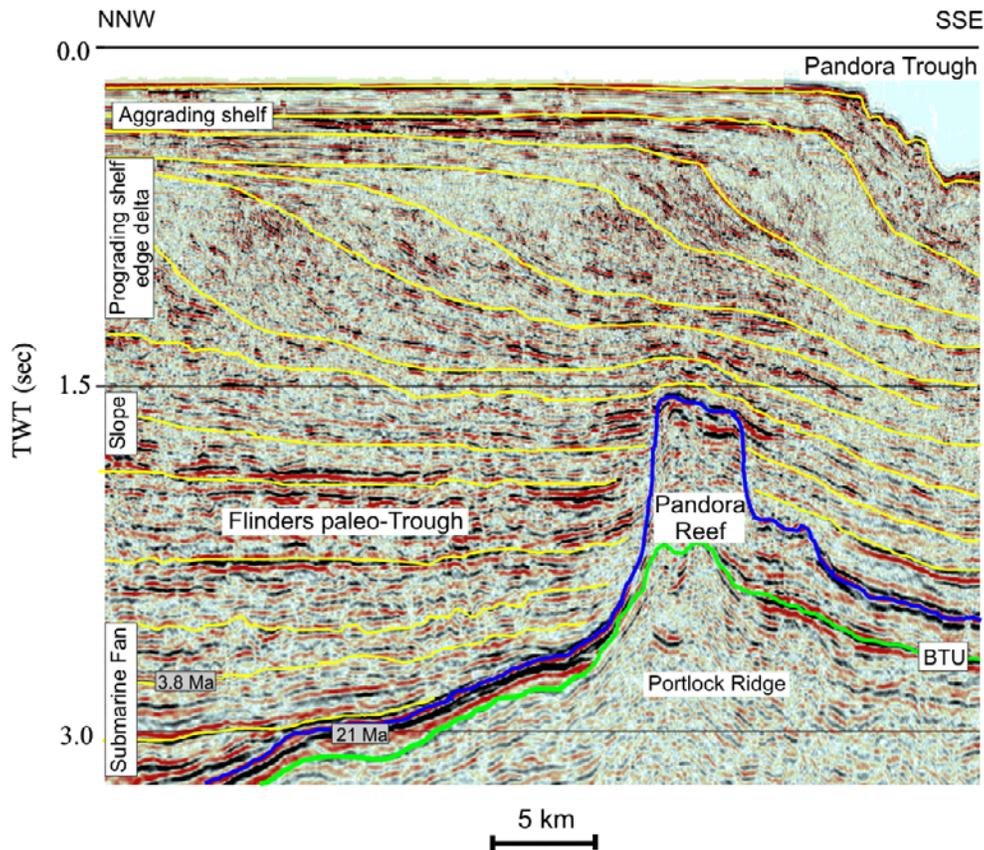
combination of a low subsidence rate and eustatic sea level fluctuations. The stacking pattern of sedimentary sequences (Figures 7 and 8c) observed in the GoP carbonate system (back stepping, vertical aggradation, downward shift, progradation, reflooding) is identical to the contemporaneous pattern identified in the Bahamas and Maldives and can only be explained by eustasy influencing the neritic carbonate production. Siliciclastics did not influence the system, since at that time they were isolated to the east in the deepest part of the foreland basin referred to as Aure Trough. The late Oligocene-Miocene evolution of the GoP mixed system therefore was preferentially controlled by intensive carbonate production and eustasy that resulted in thick carbonate successions with sequence geometries identical to the well-established Neogene global stratigraphic signature observed worldwide.

#### 4.2.3. Partial Demise of Carbonate Platforms (Phase 3)

[21] The demise of carbonate systems in either pure carbonate or mixed carbonate-siliciclastic environments can be caused by one or a combination of several factors such as significant eustatic sea level changes, increased tectonic activity, siliciclastic burial, and/or climatic/environmental changes. Tectonic activity in the PNG region increased during the late Miocene-early Pliocene with intensive fold and thrust belt development which resulted

in significant crust loading and related subsidence [Home *et al.*, 1990; Quarles van Ufford and Cloos, 2005]. This increased subsidence was probably a major reason explaining the partial demise of a large part of the carbonate system in the northern part of the GoP. Although the early partial demise (drowning) of the neritic carbonate system at some locations of the GoP was probably already initiated in the early Miocene, the late Miocene-early Pliocene interval was the time of maximum drowning of the carbonate platforms, when such large systems as Borabi and Uramu platforms drowned.

[22] When the ages of the drowning of Pandora Reef and the first major influx of siliciclastic sediments into Flinders paleotrough are compared (Figure 9) [Sarg *et al.*, 1996], it is clear that a time gap of 10–15 Ma occurred between the carbonate demise and major siliciclastic arrival. This suggests that siliciclastics did not cause the cessation of the carbonate production, but the platforms possibly drowned due to eustatic sea level rise enhanced by increased tectonic subsidence and changes in ocean environment conditions. During this phase, two specific times, at the beginning of the late Miocene (Tortonian) and beginning of the early Pliocene, were characterized by high rates of eustatic sea level rise. These episodes, most likely enhanced by contemporaneous basin subsidence, related to the loading effect



**Figure 9.** Interpreted seismic profile showing depositional features infilling Flinders paleotrough and Pandora slope and burying drowned early Miocene Pandora Reef. The features include submarine fans, ponded turbidite, slope, prograding shelf edge deltas, and aggrading shelf deposits. These vertically stacked depositional environments are observed as modern analogues laterally juxtaposed in the Moresby Trough, central Pandora Trough, Pandora slope, and northern Ashmore shelf edge (Figures 5a–5c). BTU is base tertiary unconformity. Dates are obtained from *Sarg et al.* [1996]. The seismic profile is courtesy of Fugro Multi Client Services, Inc.

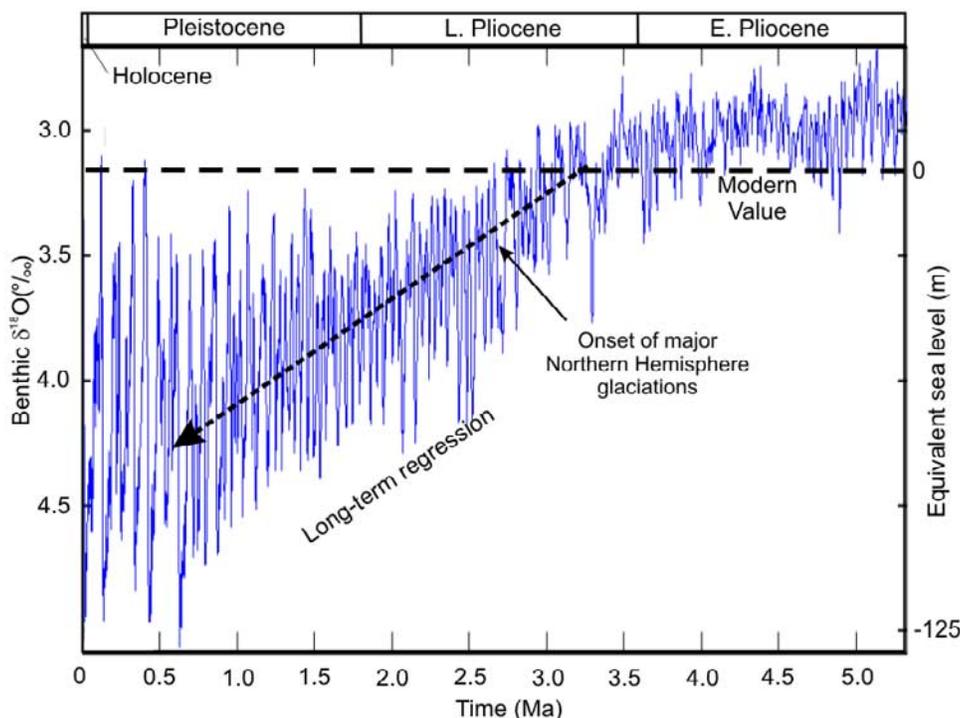
of the PNG mountain belt forming at that time, correspond to the intervals of ultimate demise of several carbonate platforms.

#### 4.2.4. Siliciclastic Influx in the Mixed System (Phase 4)

[23] Since the late Pliocene, siliciclastics have dominated the deposition in the GoP mixed system. This interval is considered to be an overfilled phase in the evolution of the foreland basin. As a main result, the proximal foredeep (Aure Trough) was infilled by clastic sediments and many carbonate platforms in the distal part of the foreland basin (e.g., Uramu, Pasca, Pandora reefs) already drowned for 5–15 Ma [Pigram *et al.*, 1989, 1990] became buried by the prograding siliciclastics. During this phase, the huge influx of siliciclastic sediments, originating from the denudation of the New Guinea uplifted mountains, was linked to the intensified tectonical uplift during the last 3 Ma and associated monsoonal wet tropical climate. The wet climate generated high rainfall resulting in high rates of weathering and erosion as well as high levels of runoff. Since the Pliocene, the siliciclastic shelf edge has prograded about 80 km to the southeast (Figures 3 and 4). Seismic interpretation shows that the rate of progradation was lower when the shelf edge was located on top of the preexisting northeast oriented ridges and carbonate platforms where it

was temporarily anchored until the adjacent trough filled. The rate accelerated when the shelf edge was prograding over previously infilled trough (Figure 4).

[24] In addition, the long-term (~2 Ma) late Pliocene to mid-Brunhes sea level regression and more than 120 m cyclic sea level fluctuations characteristic of the late Pleistocene (Figure 10) influenced the volume and spatial distribution of siliciclastics, accumulating in the GoP, possibly following the reciprocal model of mixed carbonate-siliciclastic sedimentation [Wilson, 1967; Dolan, 1989; Handford and Loucks, 1993; Schlager *et al.*, 1994; Jorry *et al.*, 2008]. According to this model, during sea level regressions and lowstands, the neritic carbonate production in the GoP was minimized or completely ceased, and the slope and basins became starved of neritic carbonate sediments. River channels incised the exposed continental shelf, and siliciclastic sediments bypassed it, initiating prograding lowstand shelf edge deltas and thick basinal deposits. Unconsolidated siliciclastic sediments accumulated during previous sea level highstands on the inner shelf (e.g., modern prograding clinoforms) were reworked and transported to the slopes and basin floor during the early parts of regressions. During regressions and lowstands, siliciclastic sediment fluxes to the basin floor significantly increased



**Figure 10.** Graph constructed from 57 stacked, globally distributed benthic  $\delta^{18}\text{O}$  records. This curve is the best proxy for ice volume changes and therefore eustatic sea level fluctuations during the last 5 Ma. The record demonstrates an overall long-term increase of global ice volume or sea level regression from 2.7 to 0.5 Ma and high-amplitude  $\sim 120$  m sea level (ice volume) cyclic changes at a frequency of 100 ka during the last 0.5 Ma (modified from *Lisiecki and Raymo* [2005]).

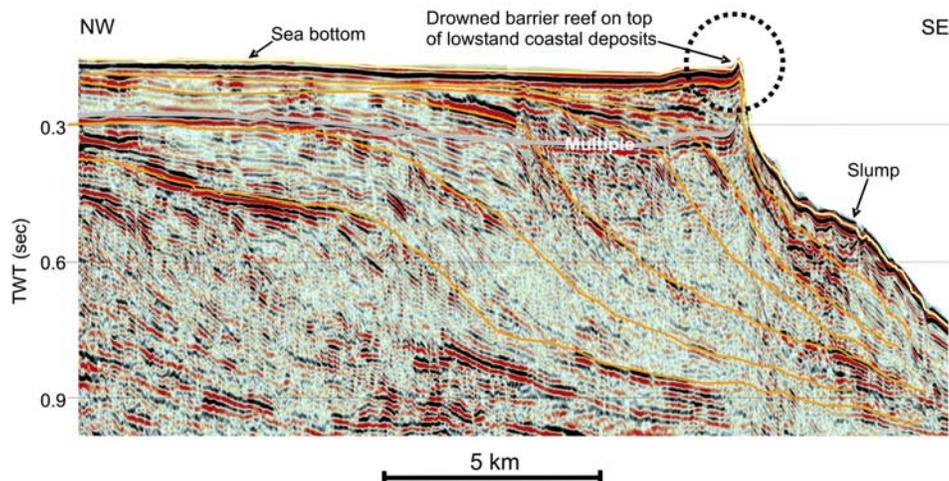
whereas the neritic carbonate fluxes dwindled [*Jorry et al.*, 2008]. During sea level transgressions, the accommodation space on the reflooded shelf increased, and siliciclastics accumulated on the continental inner shelf, along the coast, and in the fluvial plains. As a result, siliciclastic sedimentation on the slope and in the basin floor adjacent to the shelf edge was dramatically reduced. Carbonate bank tops exposed during lowstands reentered the photic zone and neritic production was reinitiated, resulting in greatly increased carbonate exports to the slope and basin floor. In the GoP, the discovery of relict barrier reefs existing along the modern shelf edge [*Droxler et al.*, 2004; *Dickens et al.*, 2006], demonstrates that early transgressions can be optimum intervals for neritic carbonate accumulation on low-latitude siliciclastic shelves (Figures 5c, 5d, and 11). During highstands of sea level, the carbonate factory production on isolated carbonate platform tops and back barrier and barrier reefs on the mixed shelves is still very high, maximizing the carbonate deposition on the surrounding slopes and basin floor.

[25] The several kilometers thick siliciclastic sediments deposited during different periods of phase 4 also include a series of ephemeral (short-lived), thin, laterally limited neritic carbonate lenses (Figures 4, 5c, 5d, and 11). These ephemeral carbonate deposits are interpreted to have lived over relatively short time intervals, and are much smaller in size when compared with the long-lived carbonate platforms which originated already during the late Oligocene–early Miocene and were able to survive until today (e.g., EFR and Portlock reefs). These ephemeral neritic carbonate

accumulations were often first established during early transgression on top of lowstand coastal deposits on the shelf edges, drowned during late transgression, and then were buried by prograding siliciclastics during late highstand, regression and lowstand. Short-lived transgressive carbonate banks buried in thick siliciclastic pile of sediment are not uncommon in low-latitude siliciclastic passive margins. They have been described, for instance, by *Belopolsky and Droxler* [1999] along the south Texas shelf edge offshore Corpus Christi.

[26] One of the best examples of ephemeral carbonate accumulations in the GoP is the drowned barrier reef established on top of the lowstand shelf edge delta deposits in the northern Ashmore Trough (Figures 5c, 5d, and 11). This transgressive barrier reef was first established during the early part of the last transgression ( $\sim 14.5$  ka) on top of lowstand siliciclastic coastal features such as beach coastal ridges. Once established, the reef grew 30 to 80 m high as it kept up with the rising sea level during one of the periods of rapid melting of the Northern Hemisphere ice sheets (Meltwater Pulse 1A) [*Droxler et al.*, 2006]. Finally, this transgressive barrier reef drowned, most likely during Meltwater Pulse 1B ( $\sim 11$  ka). The transgressive origin of ephemeral (short-lived) carbonate systems on top of lowstand coastal deposits is a simple mechanism that would explain the initiation, often contemporaneous, of many modern and ancient barrier reefs in the world [*Droxler et al.*, 2003].

[27] In the GoP, distinct siliciclastic depositional environments, juxtaposed laterally from the deepest to the shallowest settings, are observed seaward of the modern shelf edge.



**Figure 11.** Interpreted seismic profile showing prograding shelf edge delta and drowned transgressive barrier reef, which formed at the beginning of the last transgression on top of last lowstand coastal beach ridges and subsequently drowned during the end of the transgression. The seismic profile is courtesy of Fugro Multi Client Services, Inc.

They are represented by the submarine fan and deep sea channels in Moresby Trough, the flat seafloor of the ponded turbidite basin in the central Pandora, the muddy slope slumping deposits in Pandora Trough, and the prograding lowstand shelf edge delta in the northern Ashmore Trough (Figures 5a–5c). Identical environments can be interpreted in the kilometers thick siliciclastic infill of Flinders paleotrough. In this trough, more than 3 km thick siliciclastic deposits of the late Pliocene–Pleistocene represent a vertically stacked succession of depositional environments representing deep sea fans, flat floored ponded turbidite basin, slumping slope, prograding lowstand shelf edge delta, and aggrading shelf (Figure 9).

## 5. Conclusions

[28] The depositional environments and sedimentary features, observed seaward of the modern shelf edge, represent modern analogs of different episodes of the establishment of the late Oligocene–Miocene long-lived carbonate system and its later infilling and burial by siliciclastic sediment invasion. Interpretation of multibeam bathymetry, seismic, and well data sets from the GoP demonstrated close analogy of the modern and late Oligocene–Holocene processes during the long-term evolution of the GoP passive margin. The overall evolution of the mixed system in the GoP was controlled by a dynamic interaction of several major factors, which include tectonics, eustasy, in situ carbonate production, and siliciclastic sediment supply. Four different phases can be distinguished in the evolution of the mixed system based on the balance between these factors.

[29] Tectonics played the most important role during the first phase (late Cretaceous–Paleocene), creating accommodation space and pedestals on top of which major neritic carbonate systems were established and developed. The troughs and ridges influenced the spatial distribution of long-lived carbonate platforms and later along with existing carbonate platforms influenced and guided the invasion of

siliciclastics. During the second phase (Eocene–middle Miocene), tectonic control became a minor factor and large platforms were established during a late Oligocene–middle Miocene overall transgression. A late middle Miocene overall sea level regression limited the accumulation of neritic carbonate sediment in localized well-developed prograding complexes. These complexes and early Miocene bank tops were reflooded during a high-amplitude transgression during the earliest part of the late Miocene. During this phase, large-scale carbonate systems and especially their sedimentary geometries were regulated mostly by eustatic sea level fluctuations. The study area represented a pure carbonate system, because the siliciclastics remained isolated in the foreland deep-water trough proximal to the emerging fold and thrust belt. During the third phase (late Miocene–early Pliocene), intensified tectonics and enhanced subsidence associated with two transgression intervals during the late Miocene and early Pliocene, resulted in the drowning of the carbonate platforms in the northern part of the GoP. Drowned carbonate platforms remained unburied and therefore stayed exposed in the water column for 5–15 Ma. At the same time, some of the platforms located in the southern part of the study area, further from the deformation front, were able to keep up with relative sea level rise. Finally, during the fourth phase (late Pliocene–Holocene), existing deep basins were infilled by siliciclastic sediments, originated from intensified uplift of the fold and thrust belt during the late Pliocene–Holocene. Drowned platforms were buried by prograding siliciclastics, migrating southward by more than 80 km during the last 3.5 Ma. This four-phase model is not unique to the GoP mixed margin and can explain the general long-term evolution of low-latitude mixed passive margins. Similar evolution (rifting, intensive development and then termination of the neritic carbonate system, and its ultimate burial by prograding siliciclastics) can be observed in many other low-latitude regions of the world over geological time.

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