GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G45994.1

Manuscript received 2 January 2019
Revised manuscript received 15 May 2019
Manuscript accepted 15 May 2019

Published online 6 June 2019

Miocene start of modern carbonate platforms

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ABSTRACT

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INTRODUCTION

Many carbonate platforms are edifices formed by carbonate growth in the tropical photic zone. The high sediment production of a tropical neritic carbonate factory can accumulate several thousand meters of shallow-water platform deposits (Schlager and Ginsburg, 1981). Reefs may build a rim at the platform edges, separating more protected lagoonal water bodies from the open sea (Purdy and Gischler, 2005). Other platforms have margins with oolitic and skeletal grainstone (Enos, 1974). Carbonate platforms may develop steep rims, either with reef boundstone or with cemented and/or microbially bound grainy deposits (Ginsburg et al., 1991; Della Porta et al., 2004, 2013; Reolid et al., 2017). Some carbonate platform edges migrate basinward, with bank-margin facies progradation as the stratigraphic result of this process. Often, the leeward side of platforms progrades as shallow-water components are transported off the platform, mainly by wind-driven currents. In contrast, the windward edge of the platform displays an aggradational pattern with a steep, sediment-starved flank. A typical example of leeward progradation and coeval windward aggradation is Great Bahama Bank (GBB, Atlantic Ocean; Eberli and Ginsburg, 1987, 1989). The light dependency of sediment production close to sea level and steep slopes around carbonate platforms have driven the notion that fluctuating sea level and mass gravity flows are the main controls on platform and slope architecture (Kendall and Schlager, 1981; Playton et, al., 2010).

Ocean currents are, however, an additional major controlling factor of carbonate platform slope sedimentation (Mullins et al., 1980; Betzler et al., 2014, 2016a, 2016b; Lüdmann et al., 2016). Currents have proven to be a major contributor to carbonate platform drowning (John and Mutti, 2005; Eberli et al., 2010; Betzler et al., 2016b). In fact, with the exception of GBB, all large isolated carbonate platforms (ICPs) or carbonate complexes in the world's oceans (Fig. 1), like the Maldives in the Indian Ocean, the South China Sea (SCS) carbonate banks, and the Queensland and the Marion Plateaus (QP and MP) offshore northeast Australia, have mainly been shrinking, as they have been subjected to the action of currents through the Neogene and Quaternary.

Currents may directly or indirectly reduce or suppress coral reef growth and thus contribute to carbonate platform drowning. These processes include erosion and resuspension (Storlazzi et al., 2011), topographically induced upwelling and concomitant increase of nutrients that displace hermatypic algae and corals (Fig. 2; Hallock and Schlager, 1986), and negative effects on coral larval settlement by strong ocean currents (Hata et al., 2017). Upwelling is not affecting the GBB, the leeward flank of which is bathed by surface and contour currents in the Straits of Florida and the Santaren Channel, inducing downwelling (Lüdmann et al., 2016).

The physical transport capacity of currents induces selective deposition, sediment winnowing, and redistribution along platform flanks (Fig. 2A). In areas of lower contour current velocity, extensive periplatform drifts form, irrespective of the orientation of the wind-driven surface currents (Fig. 2B; Mullins et al., 1980; Betzler et al., 2014; Chabaud et al., 2016). Because carbonate platforms grow into the photic zone, they are affected by both the shallow surface currents and the bottom currents. The position where the surface current is most effective fluctuates with sea level, but sweeping of the upper slope can lead to prolonged hardground formation, i.e., on the Miami Terrace (Gomberg, 1976), along the western GBB (Kenter et al., 2001), and on the MP (Eberli et al., 2010). Contour current acceleration and concomitant sediment reduction lead to slope undercutting and oversteepening, or slope starvation (Betzler et al., 2016a; Principaud et al., 2016; Wunsch et al., 2018). Another consequence of contour current activity is a grain-size increase at the toe-of-slope that would not be produced by gravity-driven deposition (Wunsch et al., 2018).

In short, the effect of bottom currents is at least as important as gravitational sedimentation processes. This amends the concept of line shedding, wherein a constant sediment influx along the edge of carbonate banks and component grain size (Playton et al., 2010) are the controlling factors for slope facies and thickness distribution. The record of current processes is documented by seismic and hydroacoustic surveys and sediment sampling (Betzler et al., 2014, 2016a, 2016b). By comparing stratigraphic stacking patterns of ICPs around the world, we show that these processes leave diagnostic signatures in the stratigraphy, facies, and sediment

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CITATION: Betzler, C., and Eberli, G.P., 2019, Miocene start of modern carbonate platforms: Geology, v. 47, p. 771–775, https://doi.org/10.1130/G45994.1

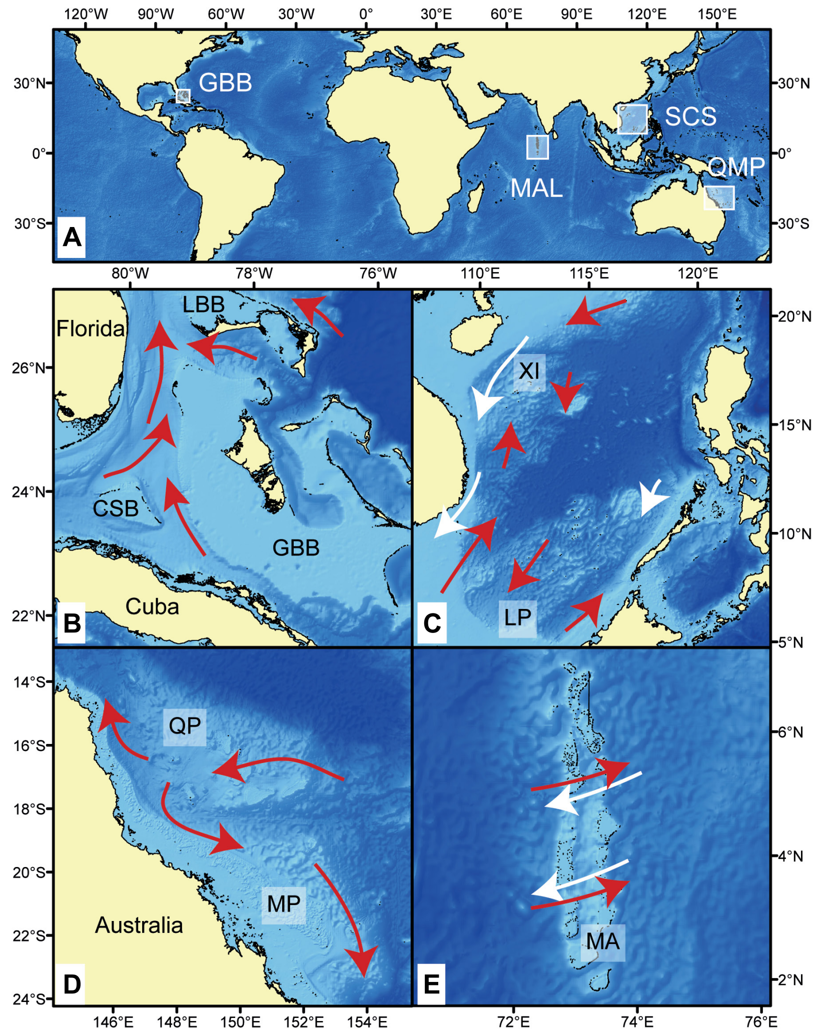

Figure 1. A: Major isolated carbonate platforms discussed in the text: Great Bahama Bank (GBB), Maldives (MAL), South China Sea (SCS), Queensland Plateau (QP), and Marion Plateau (MP). B: Bahamas, with GBB, Little Bahama Bank (LBB), and Cay Sal Bank (CSB). C: South China Sea with Xisha carbonate banks (XI) and Luconia Province (LP). D: Northeast Australian carbonate province with Queensland Plateau and Marion Plateau. E: Maldives (MA) in the Indian Ocean. Arrows mark surface current flows. Red arrows in C and E indicate flow during the summer monsoon; white arrows indicate flow direction during the winter monsoon. Red arrows in B and D indicate the main year-round currents.

composition of carbonate platforms that allow us to define the contemporaneous start of the modern carbonate platform growth mode.

METHODS

Multichannel seismic lines from the GBB, Maldives, and northeast Australia were acquired for Ocean Drilling Program (ODP)/International Ocean Discovery Program (IODP) campaigns (Anselmetti et al., 2000; Isern et al., 2004; Lüdmann et al., 2013) and were assessed with regard to stratigraphic stacking patterns of carbonate platform successions and adjacent basinal deposits. We used well-to-seismic correlations at ODP/IODP sites to resolve the age and lithology of the deposits, as well as the geometrical changes imaged in the seismic lines. For this correlation, the two-way traveltimes of seismic reflections were converted to depth using the interpolated time-depth curve from the first-arrival data of the vertical seismic tool. To assign ages, the converted depths of the seismic sequence boundaries were then plotted in a depth-versus-age graph (Eberli et al., 2002, 2010; Betzler et al., 2018). The SCS seismic and stratigraphic data were taken from the cited literature and evaluated accordingly.

MIOCENE INITIATION OF MODERN CARBONATE PLATFORMS

Many of the elements that distinguish the modern climate and ocean circulation system were established during the Neogene. Major ice sheets established in East Antarctica led to a globally steeper meridional temperature gradient, intensifying pressure systems and ocean circulations (Flower and Kennett, 1994). The North Atlantic became an important circulation component during the middle Miocene, complementing the persistent southern source of deep-water circulation (Poore et al., 2006). There are now several lines of evidence indicating that the current-controlled carbonate platform mode started between 13 and 10 Ma, i.e., at this time of middle to late Miocene stepwise global cooling (Holbourn et al., 2013) and onset of modern ocean circulation (Fig. 3).

In the Straits of Florida, this onset led to the formation of large contourite drift complexes that started at 12.5–12 Ma (Fig. 3A; Anselmetti et al., 2000; Bergman, 2005; Principaud et al., 2016; Wunsch et al., 2018; Paulat et al., 2019). In this case, the contour currents were different branches of the Florida Current, which is the main contributor to the Gulf Stream. The onset of the currents is recorded in the establishment of drift bodies and moats surrounding the platforms (Fig. 3A). Coincident with the inception of these currents, the leeward flank of GBB started to change from a ramp profile into a platform with a steep flank (Beach and Ginsburg, 1980; Betzler et al., 1999). Schlager and Camber (1986) related carbonate platform steepening to increasing shelf erosion and the increasing height of the platform. Adams and Hasler (2010) discussed the effect of aggradation and increased sediment budgets, which are required to retain slope geometries. Slope steepening is also a consequence of toe-of-slope sediment winnowing by bottom and contour currents (Rendle and Reijmer, 2002; Betzler et al., 2014; Wunsch et al., 2018). Currently available data allow this process to be traced back at least through the Pleistocene (Wunsch et al., 2018).

The establishment of a vigorous current system affecting isolated carbonate banks and platforms between 12 and 10 Ma in the SCS has been outlined in several studies (Fig. 3B). The influence of currents on the Xisha carbonate banks in the northwestern SCS was documented by Shao et al. (2017), who reported the onset of wind-driven cooling and nutrient input into the shallow-water realm at around 11 Ma. In the southern SCS, drift and moat formation around the Luconia province carbonate platforms started at 10.5–10 Ma (Vahrenkamp et al., 2004; Koša et al., 2015; Bracco Gartner et al., 2004), shortly before major parts of the carbonate banks drowned. Today, the current system in the SCS is controlled by the monsoonal winds (Hu et al., 2000).

The East Australian carbonate province encompasses the Great Barrier Reef, the MP, and the QP. The isolated carbonate banks of the MP and QP record a major middle Miocene turnover of the stratigraphic architecture and facies. Both plateaus lie in the flow of the North Caledonia Jet (Kessler and Cravatte, 2013). The wind regime is dominated by trade

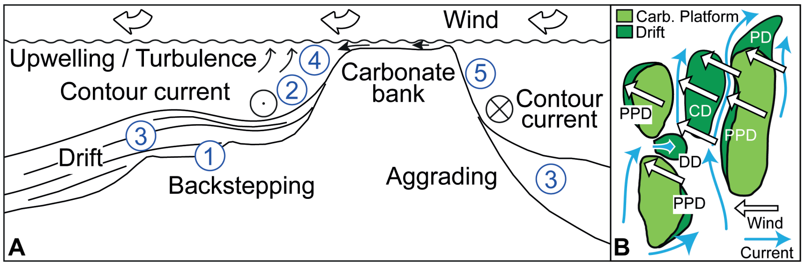

Figure 2. Effects of currents on sedimentation of isolated carbonate platforms. A: Backstepping of bank margins (1) can be linked to upwelling and turbulence (4). Contour currents shape the flanks of carbonate banks and sculpt moats at the toe-of-slope of banks (2); carbonate drifts (3) form in basins adjacent to banks. Current-swept flanks are characterized by hardgrounds (5). B: Map view of drift depocenters around isolated carbonate platforms, modified after Eberli and Betzler (2019). PPD—periplatform drift, PD—patch drift, CD—confined drift, DD—delta drift.

winds, which intensified at 12 Ma (Groeneveld et al., 2017). The surface and upper thermocline waters flow from east to west until reaching the Great Barrier Reef, where the currents divide into a north-flowing and a south-flowing branch. The south-flowing limb of the current system is the one linked to the Miocene drowning of the MP (Eberli et al., 2010). The active reef and banks of the QP, which form tower-like structures elevated above the plateau area, act as obstacles and divert these currents. These banks are relicts of a larger Miocene carbonate platform that covered ~64,000 km^2 (Betzler et al., 1995). The shrinking of these banks was achieved through the backstepping of the down-current margin, which was preceded by a geometrical turnover from a rimmed platform to a carbonate ramp (Betzler, 1997). The turnover at ca. 12 Ma has been interpreted as a response to the cooling of surface waters and a higher nutrient influx, as well as a changed current and energy regime (Betzler et al., 1995). A viable and simple explanation for this pattern is that a wind-driven current system was established during the late middle Miocene and that the backstepping developed on the leeward side of the carbonate banks as upwelling cells injected either more nutrients or colder waters in the wake of the banks.

At the MP, from the late middle Miocene (ca. 13.6 Ma) onward, sea-level changes were coupled with increased activity of the southward-flowing East Australian Current (Isern et al., 2004; John and Mutti, 2005; Eberli et al., 2010). As a result, depositional sequences developed a characteristic mounded geometry of large drift deposits from ca. 11 Ma onward (Fig. 3C). Coincident with the onset of this current, the MP carbonate platform partially drowned, which has been attributed to the combined effect of a sea-level rise and subsequent sweeping of the platform by strong currents that prevented the reestablishment of a shallow-water carbonate factory (Eberli et al., 2010). The southern MP "survived" the initial onset of the current intensification, but a shift of the current axis also helped to drown this platform at around 7 Ma (Eberli et al., 2010).

In the Maldives (Indian Ocean), the current system is related to the monsoon (Betzler et al., 2016a). The start of current-controlled slope sedimentation is documented at ca. 13 Ma, as recorded by the first appearance of drifts (Fig. 3D; Betzler et al., 2016a). Like on the MP, the onset of current activity induced a partial drowning of carbonate banks, and the depositional regime at the flanks of the remaining carbonate banks changed from a prograding to an aggrading/backstepping system (Betzler et al., 2016b). This aggrading/backstepping pattern is attributed to the toe-of-slope winnowing and erosion by contour currents and is reminiscent of the evolution of the flanks of GBB when the current regime started there.

These examples show that the late middle Miocene was a major global break for ICP evolution. This break separates the carbonate platform depositional systems, which until 13–10 Ma thrived under relatively moderate current conditions, from the younger platforms, which were affected by a more vigorous current system that was established when the modern ocean circulation started.

Concurrent with the onset of current control of carbonate platform slope deposition, different types of carbonate drift deposits accumulated in the seaways and the adjacent basins, supplied with sediment from off-bank–transported material (Fig. 2B). Periplatform drifts line the platform flanks (Betzler et al., 2014), confined drifts comparable to their siliciclastic counterparts form in seaway or passages separating isolated carbonate platforms (Anselmetti et al., 2000; Isern et al., 2004; Lüdmann et al., 2016), and delta drifts form at the mouths of passages separating platforms (Lüdmann et al., 2018).

CONCLUSIONS AND IMPLICATIONS

Many factors control the facies and stratigraphic stacking pattern of carbonate platforms. Sea level and subsidence determine ac-

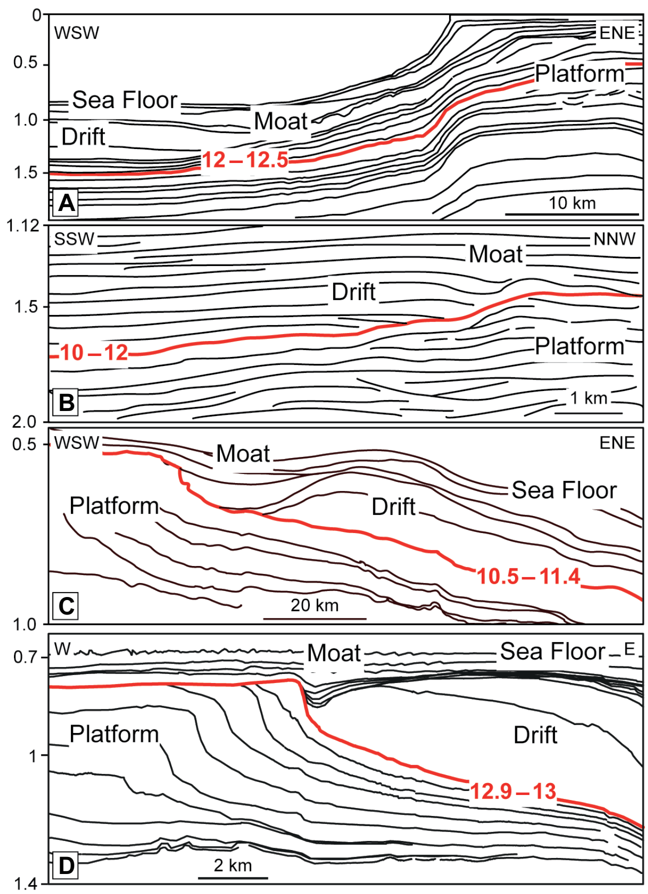

Figure 3. Line drawings of selected seismic lines from carbonate platforms, which show abrupt onset of current activity along their slopes. Red lines correspond to positions of reflections that delimit the base of current-controlled packages with corresponding ages. A: Great Bahama Bank, Caribbean (after Eberli et al., 1997). B: Sarawak, South China Sea (geometry after Bracco Gartner et al., 2004; age after Vahrenkamp et al., 2004). C: Marion Plateau, northeast Australia (after Isern et al., 2004). D: Maldives, Indian Ocean (after Betzler et al., 2016b). Vertical axes in A–D are two-way traveltime in seconds.

commodation, nutrients and water temperature influence the carbonate factory, and currents, driven either by winds or tides, stir and redistribute sediment particles in the platform interior. Tides and gravity-driven currents transport sediment off bank, but ocean contour currents distribute the off-bank–transported sediments along the slopes and in the adjacent basin. All these controlling factors interact during the growth of the carbonate edifices and are also the processes that are evoked when reconstructing and interpreting shallow-water carbonate successions. Based on our evaluation of ICPs growing today and during the Neogene, the physical action of along-slope currents is a major factor that acts in carbonate platform successions younger than 13–10 Ma, i.e., carbonate platforms evolving in the icehouse world. The current action leaves characteristic signatures in the platform slope architecture. Currents shape carbonate slopes by sediment removal, starvation, and creation of hardgrounds along slopes, by formation of moats at the toe of slope, formation of carbonate drifts around carbonate platforms, and by effects related to topographically induced upwelling and turbulence, such as backstepping of the bank margins or slope steepening (Fig. 3).

The recognition of the influences of currents on platform slope architecture also allows a potential way to estimate current activity in ancient times, especially from the early Paleozoic backward, when the pelagic record is missing. For example, the commonly observed evolution from a ramp to a rimmed shelf is likely to be associated with an intensification of ocean currents. Such a change occurred in the Permian carbonate system of west Texas (USA), where the Wolfcampian ramp developed into the Leonardian shelf (Silver and Todd, 1969). In contrast, many Devonian and Cretaceous ICPs display an aggradational to progradational platform growth that is related to relative sea-level changes (Whalen et al., 1999; Eberli et al., 1993). Interrogating the stratigraphic record in detail is, however, necessary to comprehensively extract the history of currents in deep time from the carbonate slope architecture.

ACKNOWLEDGMENTS

Betzler acknowledges funding from different projects by the Deutsche Forschungsgemeinschaft and the Federal Ministry of Education and Research, Germany. Eberli acknowledges financial support from the industrial associates to the Comparative Sedimentology Laboratory and Center for Carbonate Research at the University of Miami (Florida, USA). We thank our colleagues Thomas Lüdmann, Dick Kroon, Sebastian Lindhorst, John Reijmer, Christian Hübscher, and Jim Wright for the many discussions that helped us to sharpen our concept. The constructive and helpful reviews by Erwin Adams and two anonymous reviewers are gratefully acknowledged. We thank *Geology* Editor James Schmitt for his very helpful comments.

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