A dynamic process for drowning carbonate reefs on the northeastern Australian margin

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ABSTRACT

Drowned carbonate reefs on passive margins are puzzling because of their enormous growth potential compared to typical rates of passive margin subsidence and moderate sea-level fluctuations. A possible solution to this paradox is that slow processes acting over geologic time weaken reefs and contribute to their ultimate demise. The Australian northeastern marginal plateaus, known for their drowned reefs, underwent a period of accelerated tectonic subsidence during the late Miocene to Pliocene that, combined with a sequence of second-order global sea-level rises, outpaced reef growth and drowned the once-thriving Miocene carbonate platforms. However, the mechanism for the observed anomalous subsidence of this relatively mature passive margin 1000 km from the nearest plate boundary is uncertain. We use a coupled plate, kinematic mantle flow model to show that in the late Miocene northeastern Australia overrode subducted slabs from Eocene Melanesian subduction north of Papua New Guinea. We find that the rate of surface subsidence induced by the sinking slabs increases the likelihood that relative sea-level rises outpaced late Miocene reef growth. In addition to the well-known effects of long-term plate processes and short-term global sea-level and climate change, our results demonstrate that deep Earth processes can play a substantial role in driving the evolution of passive margins and coral reefs.

INTRODUCTION

The destruction of coral reefs is usually attributed to processes that act over short time intervals (Natawidjaja et al., 2007; Pomar and Ward, 1994; Taylor et al., 1982; Wallace et al., 2002; Webster et al., 2008). Understanding the human contribution to reef demise through the alteration of the environment is of particular importance to the preservation and protection of these valuable and rare ecosystems (Vitousek et al., 1997). However, these rapid changes may only provide the final environmental degradation for reefs that have been progressively weakened by processes acting over much longer time scales. Indeed, long-term processes can cause the progressive deterioration of optimal reef growth conditions, making reef ecologies more susceptible to rapid sea-level and environmental changes (Sadler, 1981; Schlager, 1981, 1999).

Until recently the abundance of ancient drowned reefs on tectonically quiescent passive margins represented a paradox because the enormous growth potential of reefs should ensure that reef growth keeps pace with passive margin subsidence and the rates of moderate sea-level change (Schlager, 1981). Schlager (1999) estimated that reef growth potential for intervals of 10^5–10^8 yr is greatly reduced to ~40 m/m.y. due to the long-term changes in environmental factors such as water depth (Sadler, 1981; Schlager, 1999). This observation solves the paradox of drowned reefs on continental rift margins since long-term growth potential rates are of the same order of magnitude as rift margin subsidence.

The Australian northeastern marginal plateaus are located on a passive rift margin, but represent a new challenge to explain the drowned reef paradox. Here we explore the Marion Plateau, which is south of the Queensland Plateau offshore of the Great Barrier Reef (Fig. 1B). Marion Plateau basement is thinned continental crust rifted during the Late Cretaceous (Exon et al., 2006; Gaina et al., 1998), and is capped with fossil carbonate platforms (Isern et al., 2002). There is no evidence for major faulting on the plateau during the Neogene (Isern et al., 2002), indicating that the plateau was tectonically quiescent; furthermore, very little post-rift thermal subsidence is expected on the northeastern margin since the late Miocene (<30 m; calculations described in the following). However, the Marion Plateau records sudden reef drowning during the late Miocene–early Pliocene (Betzler, 1997; Isern et al., 2002, 1996; Müller et al., 2000). The Marion Plateau is located more than 1200 km south of the Pacific-Australia plate boundary and thrust loading associated with this margin is unable to account for the subsidence (Müller et al., 2000). In this case, mantle processes might be an attractive alternative mechanism to drive subsidence and cause long-term weakening of the reefs. Here we aim to demonstrate the contribution of mantle flow to the drowning of the Marion Plateau reef. We use a high-resolution regional geodynamic model, coupled to a global model, to track the rate of dynamically driven subsidence beneath the northeastern marginal plateaus. The models incorporate the history of plate motions and subduction with a crust and mantle wedge (DiCaprio, 2009).

DYNAMIC CONTRIBUTION TO RELATIVE SEA-LEVEL RISE SINCE THE EOCENE

We use the finite element package CitcomS Version 2.2 (Tan et al., 2006; Zhong et al., 2000), available from the Computational Infrastructure for Geodynamics (CIG, http://geodynamics.org), to solve the equations of mantle convection. The models couple the higher resolution regional model to the global flow field. Plate motions and the reconstructed age of the ocean floor (Müller et al., 2008) are assimilated into the models. For a detailed description of the models and methods for assimilating data, see DiCaprio (2009).

The models start with subducting slabs on the Australian-Pacific margins at 50 Ma. The initial slabs extend from the surface to a depth of 400 km to the east of New Caledonia and dip southwest beneath the reconstructed location of the Melanesian arc (Fig. 1A). The position and polarity of these subduction zones are based on tectonic reconstructions of the southwest Pacific. During the early Eocene northeast-dipping subduction may have been located to the northeast of New Caledonia (Crawford et al., 2003; Schellart et al., 2006) and continued southward into the Norfolk Basin along the Three Kings Ridge (DiCaprio et al., 2009b; Mortimer et al., 2007; Schellart et al., 2006). Southwest-dipping subduction at the Melanesian arc was initiated between 45 and 50 Ma (Gaina and Müller, 2007; Hall, 2002).

From 50 until ca. 12 Ma subduction continued at the Melanesian arc (Gaina and Müller, 2007). The slab was eventually overridden by northeastern Australia and is currently sinking within the transition zone beneath the northeastern plateaus (Fig. 1D) (Hall and Spakman, 2003). Fast velocity perturbations are also observed beneath the northeast margin in global tomography (Ritsema et al., 1999) (Fig. 1C). Our model is consistent with global tomography on a 1000 km scale that shows an accumulation of material within the transition zone beneath the plateaus (Fig. 1C). Our models show that since the Miocene, the northeastern margin has been progressively tilted down toward the northeast (Fig. 1D), consistent

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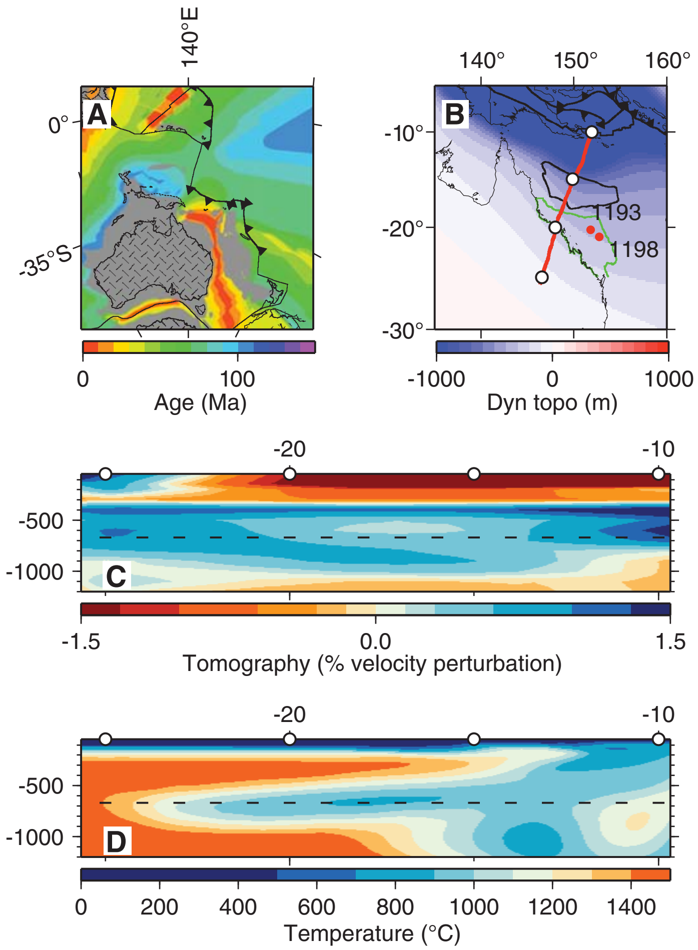

Figure 1. A: Reconstructed age of southwest Pacific Ocean at 50 Ma (Müller et al., 2008) with reconstructed plate boundaries. Location and polarity of subduction zones are used as initial conditions for geodynamic models. B: Present-day modeled dynamic topography (Dyn topo) from our preferred model, showing location of northeastern marginal plateaus (black outline is Queensland Plateau and the green outline is Marion Plateau). Ocean Drilling Program Leg 194 Sites 1193 and 1198 and cross sections taken through S-wave tomography model S20RTS (Ritsema et al., 1999) C, D: Temperature of preferred geodynamic model. Dashed line is at 660 km depth.

with a paleoshoreline (DiCaprio et al., 2009a). See the GSA Data Repository[1] (Movies DR1 and DR2) for movies of evolving dynamic topography and temperature.

We select a preferred model (M2) based on matching the magnitude and shape of dynamic subsidence on the Marion Plateau since the late Miocene with tectonic subsidence (Fig. 2). Model properties are provided in Table DR1. Backstripped tectonic subsidence was computed for Ocean Drilling Program Leg 194 Sites 1198 and 1193 using biostratigraphic and lithostratigraphic data (Table DR2) to remove the isostatic component of sediment and water loading.

Tectonic subsidence shows a pulse of rapid subsidence on the Marion Plateau during the middle Miocene followed by gradual subsidence of the plateau since the late Miocene (Figs. 2A and 2B). The rapid pulse of subsidence in the middle Miocene did not result in reef drowning. Unusual episodes of subsidence within the area have been identified and potential mechanisms described (Müller et al., 2000). Post-rift thermal subsidence on the Marion Plateau since the middle Miocene is 30 m, much less than tectonic subsidence during this time, and its contribution to reef drowning is negligible. The slope and magnitude of our modeled subsidence match tectonic subsidence since the late Miocene (Figs. 2A, 2B), and the plateau has subsided by 200 m since the late Miocene.

We analyze the contribution of dynamic subsidence to relative sea level by combining a global sea-level model (Haq and Al-Qahtani, 2005) with dynamic subsidence and post-rift thermal subsidence. Relative sea level is given by:

$$SL_{relative} = SL_{global} - (h_{thermal} + h_{dynaminc}), \quad (1)$$

where SL_{global} is the second-order global sea-level model (Haq and Al-Qahtani, 2005), $h_{dynamic}$ is the dynamic topography, and $h_{thermal}$ is the post-rift thermal topography calculated using $\beta = 1.2$, estimated by using post-rift crustal thickness of ~30 km and nearby nonextended crust as a proxy for pre-rift crustal thickness of 35 km (Heine and Müller, 2008). We use a rift period between 90 and 70 Ma (Exon et al., 2006). The modeled dynamic subsidence, post-rift thermal subsidence, and global sea level are referenced to the present-day global sea level of 0 m.

The result shows that although there is a long-term trend of global sea-level fall since the Miocene (red curve, Fig. 2C), the deepening topography due to dynamic subsidence (green curve, Fig. 2C) caused the regional relative sea level to rise since the Miocene (blue curve, Fig. 2C). The progressive deepening due to increased dynamic topography means that the relative sea level during the middle Miocene was on average 100 m shallower than it is today, even though global sea level was ~100 m higher (Fig. 2C).

We calculate the time derivative of global sea level (SL_{global}) and relative sea level ($SL_{relative}$) to explore the contribution of dynamic subsidence to the rate of change of relative sea level (Fig. 2D). The residual between the rate of change of global and relative sea level is the contribution of dynamic subsidence to the rate of relative sea-level change on the Marion Plateau (gray line, Fig. 2C). Until the late Miocene the contribution of dynamic subsidence to the rate of relative sea-level change is small, the modeled subsidence rate on the Marion Plateau is <10 m/m.y., and regional relative sea-level rate changes are similar to global sea-level rate variations (Fig. 2D). During the late Miocene the rate of dynamic subsidence increases from 10 m/m.y. to 17 m/m.y.. This causes the relative sea-level rise rate to increase and outpace global sea-level rise rate by 19 m/m.y. (Fig. 2D). The total rate of relative sea-level rise is >50 m/m.y. during the late Miocene and the increased divergence between these curves is coincident with the drowning of the Marion carbonate platform between 11 and 7 Ma.

Because dynamic subsidence increased since the Miocene, the rate of change of relative sea-level rise is faster than the rate of sea-level change alone. The corollary is that the rate of relative sea-level fall is also slower than the global sea-level fall. In summary, as the relative sea level on the Marion Plateau became progressively deeper since the late Miocene, relative sea-level rise rates occurred faster and the rate of relative sea-level fall was slower.

DISCUSSION AND CONCLUSIONS

The sudden drowning of the carbonate reef on the Marion plateau in the late Miocene is somewhat surprising since it followed a period of rapid sea-level rise in the middle Miocene and a peak in carbonate productivity (Ehrenberg et al., 2006; Isern et al., 2002). The contribution of post-rift thermal subsidence during the late Miocene is negligible, but reef drowning is coincident with a marked increase in the rate of dynamic subsidence. The contribution of dynamic subsidence to the relative sea level would have

[1]GSA Data Repository item 2010002, dynamic topography animation and evolving temperature, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

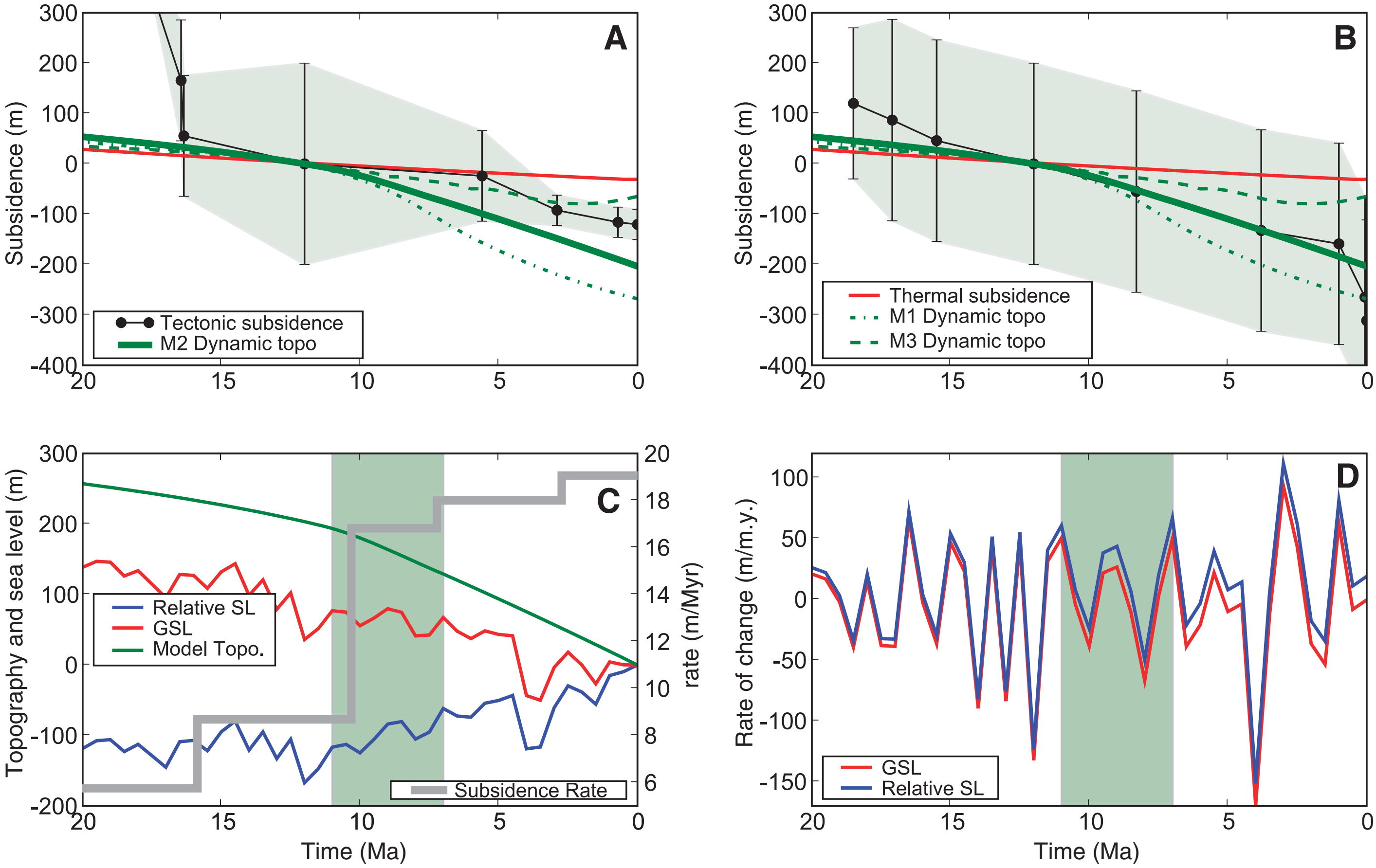

Figure 2. Calculated tectonic subsidence from Ocean Drilling Program Sites compared with dynamic subsidence (green curves) and post-rift thermal subsidence (red curves). A: Site 1193 on northern Marion Plateau. B: Site 1198 on the southern Marion Plateau. C: By including a component of modeled dynamic topography (green), relative sea level since Miocene (defined in Equation 1) (blue) has increased compared to sea level alone (global sea level, GSL, red) (Haq and Al-Qahtani, 2005). Subsidence rate of dynamic topography (gray) increased during late Miocene (green shaded box shows period of reef drowning). We use second-order global sea-level changes (Haq and Al-Qahtani, 2005) sampled in 0.5 m.y. increments. D: Rates of change of relative (blue) and global (red) sea level diverge since late Miocene. Relative sea level has faster rate of sea-level rise and slower rate of sea-level fall. Rate of relative sea-level rise is >50 m/m.y. during late Miocene.

magnified the impact of global sea-level rise on reef growth in northeastern Australia during the late Miocene, making it more difficult for carbonate bank productivity to keep pace with sea-level rise. The rate of relative sea-level rise during the late Miocene due to the addition of dynamic subsidence is >50 m/m.y. (Fig. 2D). This rate exceeds long-term reef growth potential (Schlager, 1999), and suggests that a geodynamic process may provide a valid candidate for the long-term weakening of the reefs.

Our model suggests that progressive subsidence on the northeastern margin of Australia since the late Miocene was likely a regional phenomenon. Several regional studies have proposed accelerated subsidence, which is coeval with platform drowning on the Marion Plateau (Davies et al., 1989; Müller et al., 2000). The principal reason the relationship between geodynamic processes and reef weakening has not been widely recognized is that it is difficult to match some geodynamic models with stratigraphic observations. Wheeler and White (2000) pointed out the inability of geodynamic models to match regional basin subsidence. However, our models demonstrate a convergence between surface dynamic topography with stratigraphy and depth anomalies of continental margins, resolving the controversies plaguing earlier geodynamic models.

The notion that reef and platform drowning is caused by a lethal combination of long-term and short-term factors is well established (Bertotti, 1993; Schlager, 1999; Wilson et al., 1998). However, for the first time we show that a significant contribution toward long-term decline in reef productivity can be attributed to a geodynamic process. We propose that reef drowning on the Marion Plateau was caused by a combination of weakening due to long-term dynamic subsidence and shorter-term factors such as sea surface temperature fall (Betzler, 1997; Isern et al., 1993, 1996) and global sea-level rise. Geodynamic processes played a significant role in long-term reef weakening on the northeastern plateaus. Consequently, the contribution of geodynamic processes to relative sea-level rise may affect the inferences of long-term climate and sea-level change that are drawn from ancient drowned reefs.

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