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The dynamics of foreland basin carbonate platforms: tectonic and eustatic controls

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ABSTRACT

A numerical model linking a coral growth algorithm and an algorithm for flexural subsidence reproduces many of the characteristics of drowned foreland basin carbonate platforms. This model successfully matches the observed distribution and drowning age of drowned carbonate platforms in the Huon Gulf, Papua New Guinea, a modern submarine foreland basin. Analysis of equations describing flexural subsidence and eustatic sea-level variations suggest that there are minimum convergence rates and periodicities of sea-level variation required to drown foreland basin carbonate platforms. For convergence rates on the order of a few millimetres per year, sea-level must vary on time-scales of about 10^5 years in order to induce a rate of relative sea-level rise great enough to drown an otherwise healthy foreland basin carbonate platform.

INTRODUCTION

Underfilled peripheral foreland basins commonly display a characteristic, three-phase stratigraphic evolution (Sinclair, 1997). The earliest stage of sedimentation in many underfilled foreland basins is characterized by shallow-water carbonate platform development. A particular characteristic of this phase in many foreland basins is the development of discrete, backstepping carbonate platforms (Barnolas & Teixell, 1994; Galewsky *et al.*, 1996). While the clastic phases of foreland basin evolution have been the subject of several numerical modelling studies (Jordan, 1981; Flemings & Jordan, 1989; Sinclair *et al.*, 1991), and there have been numerical models of carbonate sedimentation (Read *et al.*, 1986), there have been few quantitative studies linking foreland basin development and carbonate sedimentation. Here I present a numerical model for the development of backstepping foreland basin carbonate platforms and use this model to explore the tectonic and eustatic controls on the evolution of the carbonate platforms in the Huon Gulf, Papua New Guinea, an active submarine foredeep associated with the Finisterre Mountains (Galewsky *et al.*, 1996). I conclude by considering the role of the convergence rate and the periodicity of sea-level fluctuations on the evolution of foreland basin carbonate platforms.

Foredeeps are asymmetric, flexurally controlled basins that form adjacent to collisional orogens (Price, 1973). They are deepest adjacent to the orogen, which acts to load the lithosphere underlying the foredeep, and shallowest in the foreland (Fig. 1). Clastic sedimentation tends to be focused in the deeper parts of the basin, which are closer to sources of clastic sediment, while the shallow, distal part of the basin may remain in clear water, thus favouring carbonate platform development in the shallow part of the basin (Pigram *et al.*, 1989). As the orogen migrates toward the foreland, the basin geometry also migrates toward the foreland. Sites of active carbonate deposition may therefore drown due to rapid submergence beneath the photic zone (Schlager, 1981) as active carbonate platform development shifts further toward the foreland.

Carbonate platform drowning is a complex process that potentially involves a wide range of environmental factors (Schlager, 1989; Vogt, 1989; Drzewiecki & Simo, 1997), but it is essentially controlled by the maximum upward growth potential of the platform-building corals and the rate of sea-level rise relative to the platform, which is the sum of the tectonically induced basement subsidence rate (referred to here as the tectonic subsidence rate) and the rate of eustatic sea-level rise. When the rate of sea-level rise relative to the platform exceeds

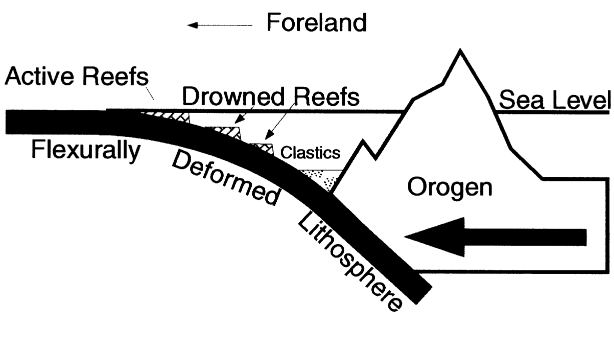

Fig. 1. (A) Cross-section through a foredeep (not to scale), illustrating the links between orogenic loading, flexural subsidence of the basin, clastic deposition and carbonate platform development.

the upward growth potential of a platform, the platform will drown. The maximum upward growth rate of modern platform-building corals is on the order of 10 mm yr^{-1} (Grigg & Epp, 1989), although this rate may have been lower in the past (Bosscher & Schlager, 1993) and environmental degradation may act to lower this growth potential. Furthermore, long-term sediment accumulation rates tend to be lower than short-term rates (Sadler, 1981), suggesting that the growth potential of carbonate platforms may vary depending on the time-scale of the observation.

THE NUMERICAL MODEL

The numerical model reported here links coral growth with the flexural subsidence of an elastic plate. The upward growth of platform-building corals is critically linked to the amount of available light, which is dependent on water depth (Bosscher & Schlager, 1992). The coral growth algorithm used in this model combines the physics of depth-dependent extinction of photosynthetically active light with the biology of photosynthesis (Fig. 2) (Chalker, 1981; Bosscher & Schlager, 1992). Subsidence is modelled as the flexural deformation of a one-dimensional semi-infinite elastic plate subjected to a line load (Turcotte & Schubert, 1982). The flexural effects of sediment accumulation and eustatic sea-level variations are not considered. The governing equations for the model are given in Table 1. The model space is 100 km long, divided into 100-m cells. During each 2000-year time step, the position of the line load advances toward the foreland at a predefined convergence rate.

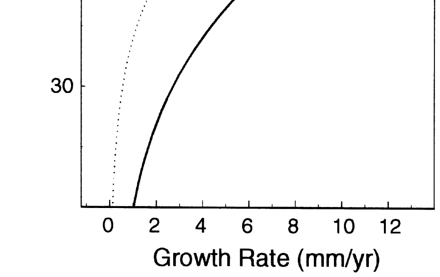

Fig. 2. Upward growth rates of platform-building corals, as calculated from the algorithm of Bosscher & Schlager (1992). See Table 1 for the parameters used in this algorithm. Parameters for the solid line: G_m, 12.5 mm yr^{-1}; k, 0.1 m^{-1}; I_0, 2000 μE m^{-2} s^{-1}; I_k, 450 μE m^{-2} s^{-1}; for the dotted line: G_m, 7.5 mm yr^{-1}; k, 0.15 m^{-1}; I_0, 2000 μE m^{-2}s^{-1}; I_k, 300 μE m^{-2} s^{-1}.

The tectonic subsidence due to the encroaching load is calculated using the equation for elastic plate flexure, and the new depth of the plate relative to eustatic sea-level during that time step is calculated. The upward growth of the carbonate platform is calculated, based on the depth of the platform during that time step, and new growth is added to the platform.

I first illustrate the model using a sinusoidal sea-level history. Figure 3 shows the evolution of a single point in a foreland basin and its relationship to sea-level. This reference point begins 100 km away from a load characterized by a 10-km maximum deflection. The elastic plate has a flexural rigidity of 5×10^{22} N m and the load advances toward the reference point at 8 cm yr^{-1}. The carbonate platform is characterized by a maximum upward growth potential of 14 mm yr^{-1} and a light extinction coefficient of 0.15 m^{-1}. Until 284 ka, the tectonic subsidence is balanced by growth of coral to sea-level (Fig. 3A) because the upward growth rate of the carbonate platform is at least equal to the total subsidence rate. Because the sea-level history used in this example is purely sinusoidal, the maximum rate of eustatic sea-level rise is the same for each cycle; however, this cycle is superimposed on an accelerating tectonic subsidence (Fig. 3B). At 284 ka, the carbonate platform drowns due to the interactions between tectonic subsidence, eustatic sea-level rise and the growth characteristics of the reef. The drowning arises naturally from the interaction of the model parameters and is not controlled by a predetermined set of drowning conditions.

Figure 4 shows the evolution of the entire profile under the same sinusoidally varying sea-level in 100-kyr time steps. During periods of rapid sea-level rise, those regions of active carbonate growth closest to the encroaching load will be subjected to the highest subsidence rates and will drown, while those regions further in the foreland will be subjected to a lower subsidence rate and will survive the period of rapid sea-level rise. The net result of the interplay between eustatic sea-level rise and tectonic subsidence is the generation of a series of backstepping drowned coral terraces, each terrace representing a period of rapid eustatic sea-level rise.

APPLICATION TO THE HUON GULF, PAPUA NEW GUINEA

This general quantitative model can be applied to the Huon Gulf, Papua New Guinea (Fig. 5), an active submarine foredeep associated with the Finisterre Mountains, a 250-km-long mountain chain uplifting in response to the ongoing collision between the Bismarck Arc and the Australian continental margin (Pigram & Davies, 1987; Abbott *et al.*, 1994). A series of at least four drowned coral terraces have been recognized in the Huon Gulf (Galewsky *et al.*, 1996) at depths of 190–460 m (von der Borch, 1972), 1250 m, 1420 m and 2000 m. The 2000-m terrace has been dated at 348 ± 10 ka using the ^{230}Th method (Galewsky *et al.*, 1996).

Table 1. Equations used in model.

Equation for upward growth rate of platform-building corals (Bosscher & Schlager, 1992)
$G = G_m \tanh(I_0 e^{-kz}/I_k)$

Parameters and range of published values:
- G_m: maximum upward growth rate (10–15 mm yr^{-1})
- k: extinction coefficient (0.04–0.16 m^{-1})
- I_0: surface light intensity (2000–2250 μE m^{-2} s^{-1})
- I_k: saturating light intensity (50–450 μE m^{-2} s^{-1})
- z: depth (m)

Equations for the flexure of a semi-infinite elastic plate subjected to a line load (Turcotte & Schubert, 1982)
$w = w_0 e^{-(x/\alpha)} \cos(x/\alpha)$
$\alpha = [4D/\rho_m - \rho_w)g]^{1/4}$
- w_0: maximum deflection
- x: distance from load to point of measurement
- α: flexural parameter

Parameters and range of values:
- D: flexural rigidity (1×10^{19} to 1×10^{24} N m)
- ρ_m: density of mantle (3300 kg m^{-3})
- ρ_w: density of sea water (1030 kg m^{-3})
- g: acceleration of gravity (9.8 m s^{-2})

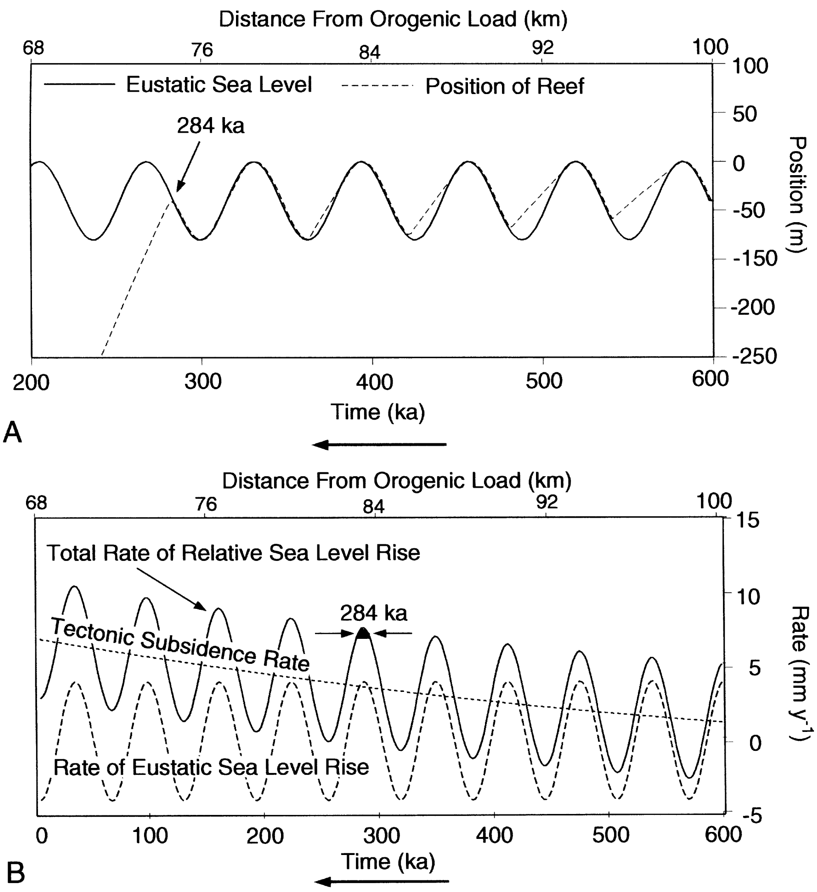

Fig. 3. The evolution of a single point of a carbonate platform subjected to sinusoidal sea-level variations and progressive flexural subsidence. (A) The position of the reference point relative to sea-level. Beginning at 600 ka, the platform grows to sea-level and maintains its position at sea-level despite sea-level rise and tectonic subsidence. During periods of sea-level fall, the platform is briefly stranded above sea-level. At 284 ka, growth of the carbonate platform cannot keep up with the rate of relative sea-level rise and the platform drowns. (B) The components that make up the rate of relative sea-level rise. The maximum rate of eustatic sea-level rise is constant for each cycle, while the tectonic subsidence rate slowly accelerates. At 284 ka, the sum of eustatic sea-level rise and tectonic subsidence exceeds 8 mm yr^{-1}, and the platform drowns.

The model results are shown in Fig. 6. For these models, sea-level history is derived from a linear transformation of the oxygen isotope record (Imbrie *et al.*, 1984; Chappell & Shackelton, 1986), digitized at 2000-yr intervals. The model results are compared to data from a profile normal to the strike of the orogen. The range of lateral positions of the drowned terraces reflects embayments and re-entrants in the reef fronts. The best-fitting model predicts four drowned coral terraces for the Huon Gulf, including a terrace at 2000 m depth predicted to have drowned during a period of rapid sea-level rise at 338 ka (Fig. 6A). This result very closely matches the

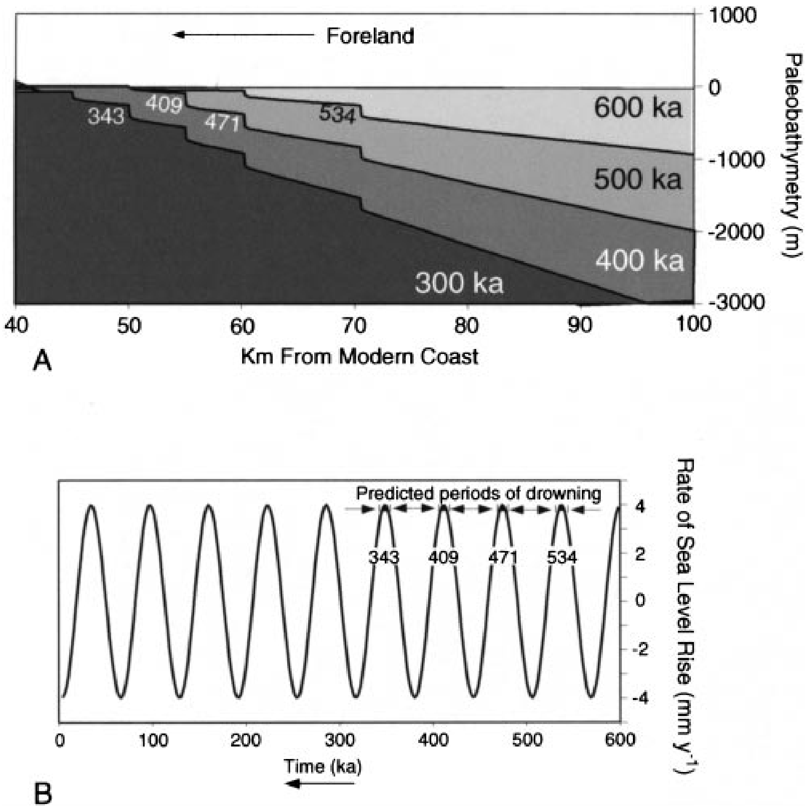

Fig. 4. The evolution of part of a 100-km-long profile showing the formation of backstepping coral terraces in a foredeep. (A) The bathymetric evolution of the profile in 100-kyr time steps. The number under the terraces refers to drowning age of the platform (in ka). The terraces are younger toward the foreland. (B) The rate of eustatic sea-level rise. The predicted periods of drowning correspond to periods of rapid sea-level rise. The creation of discrete, back-stepping terraces is due to the superposition of a prograding, accelerating tectonic subsidence on sea-level variations.

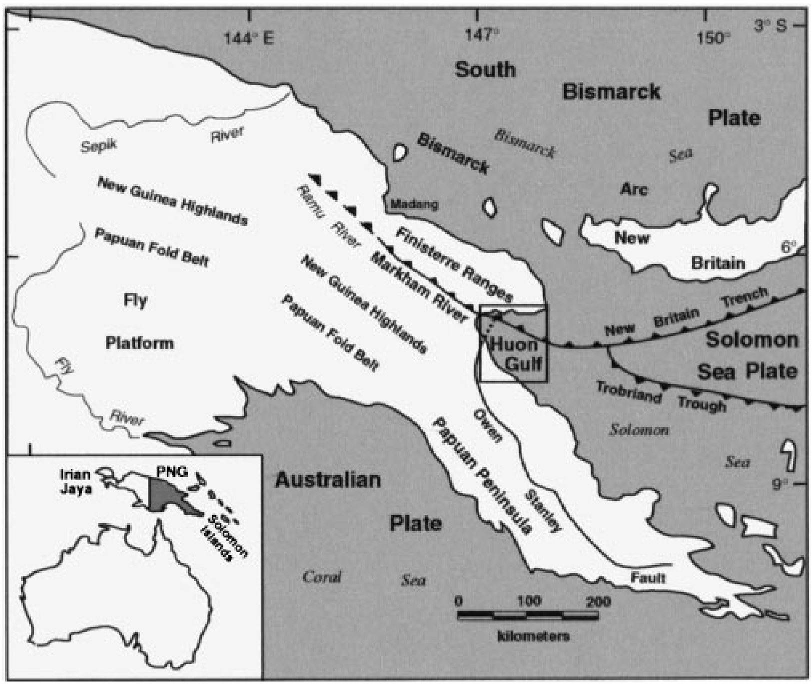

Fig. 5. Location of the Huon Gulf, Papua New Guinea. The black box indicates the study area. The Huon Gulf is the modern submarine foredeep associated with the ongoing collision between the Bismarck arc and the Australian continental margin.

coral terrace dated at 348 ± 10 ka and 2000 m depth (Galewsky *et al.*, 1996) and the model is in good agreement with the positions and depths of the other coral terraces. The model predicts that the terraces drowned during discrete periods of rapid eustatic sea-level rise, with rates between 7.5 and 13.5 mm yr^{-1} (Fig. 6B).

The tectonic parameters required to match the observed data are in good agreement with independent measurements. The convergence rate between the Bismarck Arc and the Australian continental margin is at least 8 cm yr^{-1} and possibly as high as 15 cm yr^{-1} (Taylor, 1979; McClusky *et al.*, 1994). Models using convergence rates less than 8 cm yr^{-1} fail to match the observed data. The models are extremely sensitive to the flexural rigidity: only those models with flexural rigidities between 4×10^{22} N m and 6×10^{22} N m match the observed data, which is consistent with previous measurements from the region (Galewsky *et al.*, 1992; Abers &

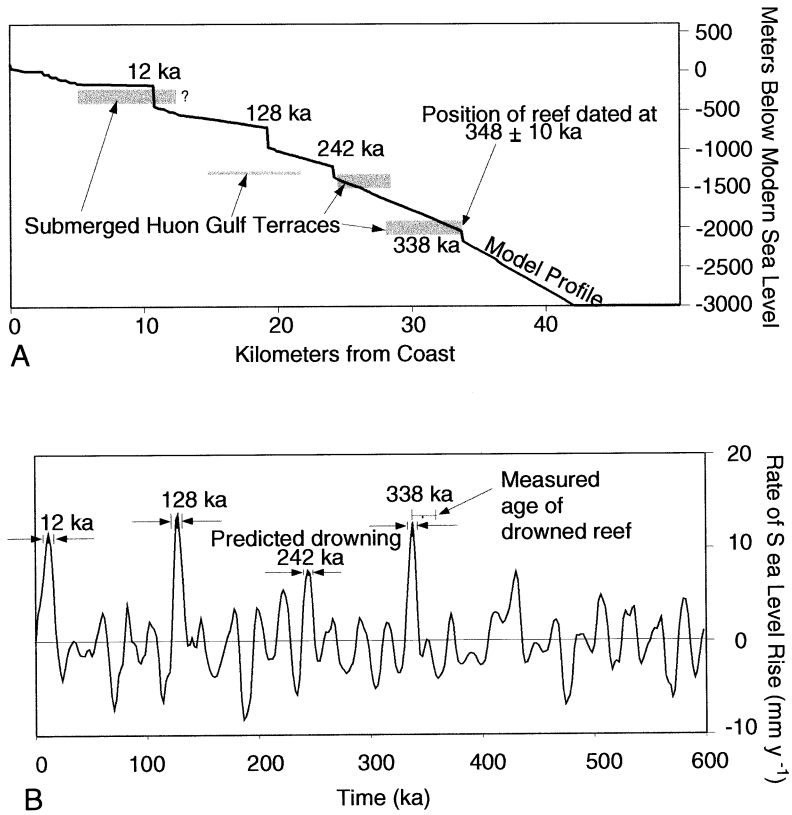

Fig. 6. Modelling results from the Huon Gulf, Papua New Guinea. (A) The best-fitting model profile is shown by the solid line. The ranges in depth and lateral position of submerged coral terraces from the Huon Gulf are given by the shaded bars (von der Borch, 1972; Galewsky *et al.*, 1996). The lateral positions of the reefs are presented as a range because of re-entrants and embayments in the reef fronts. Although the lateral position of the shallowest terrace is not well constrained, the depth range spans about 300 m (von der Borch, 1972). The other terraces have about 150–200 m of relief (Galewsky *et al.*, 1996). The terrace at 2000 m has been dated at 348 ± 10 ka using the ^{230}Th method (Galewsky *et al.*, 1996). The model predicts a terrace at a modern depth of 2000 m and a drowning age of 338 ka. The parameters for this model are: flexural rigidity: 5×10^{22} N m; maximum deflection: 17 km; final position of the line load: 107 km from the southern coast of the modern Huon Gulf; convergence rate: 10 cm yr^{-1}; maximum rate of upward reef growth: 14 mm yr^{-1}; extinction coefficient: 15 m^{-1}; surface light intensity: 2100 μE m^{-2} s^{-1}; saturating light intensity: 400 μE m^{-2} s^{-1}. (B) The rate of sea-level rise, derived from the oxygen isotope record (Imbrie *et al.*, 1984; Chappell & Shackelton, 1986). The predicted periods of drowning correspond to maximum rates of sea-level rise.

McCaffrey, 1994). The position of the elastic plate's maximum deflection is open to some debate, but almost certainly lies between the southern coast of the Huon Peninsula and the Bismarck volcanic arc, 100–200 km from the southern coast of the modern Huon Gulf. This is also in good agreement with model parameters.

Environmental and biological parameters are more difficult to determine, but the model parameters are all within the range of published values (Bosscher & Schlager, 1992). The extinction coefficient exerts significant control over the depth-dependent decay of the maximum growth rate. The extinction coefficient used in the final model (0.15 m^{-1}) corresponds to a lower limit of coral growth at about 40 m and maximum growth in the upper 10–15 m of the water column. Models using an extinction coefficient below 0.13 m^{-1} fail to match the observed data. The model is not as dependent on the other environmental parameters, and will match the observed data using maximum growth rates of 10–15 mm yr^{-1}, surface light intensities of 2000–2250 μE m^{-2} s^{-1} and saturating light intensities of 50–450 μE m^{-2} s^{-1}.

The sea-level history used is a linear transformation of the oxygen isotope record (Imbrie *et al.*, 1984; Chappell & Shackelton, 1986) and is digitized at a 2000-yr interval. Periods of very rapid sea-level rise (>45 mm yr^{-1}) may occur on time-scales shorter (<300 years) than is resolved by this record (Blanchon & Shaw, 1995). While the drowning of the Huon Gulf reefs may have occurred on such time-scales, such events are not resolvable given the resolution of the oxygen isotope record used.

DISCUSSION

The evolution of the Huon Gulf was characterized by two particularly distinctive conditions, a high convergence rate and rapid sea-level variations. The convergence rate between the Finisterre Mountains and the Australian continental margin is on the order of 10 cm yr^{-1} (McClusky *et al.*, 1994). This is approximately an order of magnitude greater than the long-term average convergence rates reported from other settings (Homewood *et al.*, 1986; Pigram & Symonds, 1991). The convergence rate exerts significant control over the rate of tectonic subsidence, as can be seen from the time derivative of the equation for elastic plate flexure. The equation for plate flexure can be written as a function of convergence rate, c, and time, t:

$$\text{flex}(t) = w_0 \cdot \exp\left[\frac{-(c \cdot t)}{\alpha}\right] \cdot \cos\left[\frac{(c \cdot t)}{\alpha}\right]$$

where α is the flexural parameter (see Table 1). The derivative of this function is:

$$\frac{d}{dt}\text{flex}(t) = c \cdot \alpha^{-1} \cdot w_0 \cdot \exp\left(-c \cdot \frac{t}{\alpha}\right) \times \left(-\cos\left(c \cdot \frac{t}{\alpha}\right) - \sin\left(c \cdot \frac{t}{\alpha}\right)\right). \quad (1)$$

The subsidence rate due to plate flexure is therefore directly proportional to the convergence rate. Calculations using the flexural parameters from the Huon Gulf model indicate that tectonic subsidence rates are about an order of magnitude less than the convergence rate. Thus, the relatively high convergence rate in the Finisterre mountains, about 10 cm yr^{-1}, is expected to yield a tectonic subsidence rate of several millimetres per year, while a convergence rate of a few millimetres per year would yield a tectonic subsidence rate of less than 1 mm yr^{-1}. These calculations suggest that tectonic subsidence alone would probably be insufficient to drown a healthy, active carbonate platform in a foreland basin associated with a slowly converging orogen.

During the last half million years, the period of the Huon Gulf's evolution, sea-level has varied quite rapidly, by tens of metres over time-scales of tens of thousands to hundreds of thousands of years. Because eustatic sea-level variations play such a key role in controlling the accommodation space available for carbonate platform development, the rate of eustatic sea-level variation clearly plays a key role in the evolution of foreland basin carbonate platforms. The impact of the periodicity of sea-level variation on the rate of sea-level rise can be calculated if we consider a purely sinusoidal sea-level history, characterized by an amplitude, A:

$$\text{sea-level}(t) = A \cdot \sin\left(2 \cdot \pi \cdot \frac{t}{\text{period}}\right).$$

The time derivative of this function is:

$$\frac{d}{dt}\text{sea-level}(t) = \text{period}^{-1} \cdot A \cdot 2 \cdot \pi \cdot \cos\left(2 \cdot \pi \cdot \frac{t}{\text{period}}\right). \quad (2)$$

For a given amplitude, the rate of sea-level rise is inversely proportional to the period of sea-level variations. We can investigate how sea-level periodicity influences the rate of sea-level rise by using eqn 2 with an amplitude of sea-level variation of 50 m. Sea-level periodicities of 10^4–10^5 yr yield rates of sea-level rise of about 10 mm yr^{-1}, while sea-level periodicities on the order of 10^6 years yield a rate of sea-level rise of about 1 mm yr^{-1}.

These calculations suggest that the conditions in the Huon Gulf, characterized by a high convergence rate and rapidly changing sea-level, created conditions highly favourable for carbonate platform drowning, i.e. a very high rate of relative sea-level rise (in excess of several millimetres per year). We can generalize these results by linking the equations for the rate of tectonic subsidence (eqn 1) and the rate of sea-level rise (eqn 2) to create a general equation that describes the rate of relative sea-level rise in a foreland basin:

$$r(t) = \frac{d}{dt}\text{flex}(t) + \frac{d}{dt}\text{sea-level}(t)$$

$$r(t) = c \cdot \alpha^{-1} \cdot w_0 \cdot \exp\left(-c \cdot \frac{t}{\alpha}\right) \cdot \left(-\cos\left(c \cdot \frac{t}{\alpha}\right) - \sin\left(c \cdot \frac{t}{\alpha}\right)\right) + \text{period}^{-1} \cdot A \cdot 2 \cdot \pi \times \cos\left(2 \cdot \pi \cdot \frac{t}{\text{period}}\right).$$

This equation is represented graphically in Fig. 7.

For low convergence rates (about 1 mm yr^{-1}), sea-level must vary on time-scales of $10^5 - 10^6$ yr to generate 1 mm yr^{-1} of relative sea-level rise in the foreland basin, while sea-level must vary on time-scales of 10^4–10^5 yr^{-1} to generate 10 mm yr^{-1} of relative sea-level rise in the foreland basin. For high convergence rates (5–10 cm yr^{-1}), the convergence rate alone will induce rates of relative sea-level rise of 1 mm yr^{-1} in the foreland, while sea-level must vary on time-scales of perhaps 10^6 years to generate a 10-mm-yr^{-1} rate of relative sea-level rise in the foreland. There is a limit, however, to which purely sinusoidal sea-level fluctuation can substitute for flexural subsidence. In cases of very low flexural subsidence rates, the platform may drown during rapid sea-level rise only to revive as sea-level falls again. Permanent drowning is only possible when the flexural subsidence is rapid enough to submerge the platform such that it is not revived during subsequent sea-level falls.

These results suggest that there are minimum rates of convergence and sea-level periodicity required if carbonate platform drowning in an ancient foreland basin is to be attributed to tectono-eustatic controls. In ancient foreland basins that were characterized by a low average convergence rate and long-period sea-level variations, these results invite investigation into the possibility of higher short-term convergence rates or more rapid sea-level variations on short time-scales.

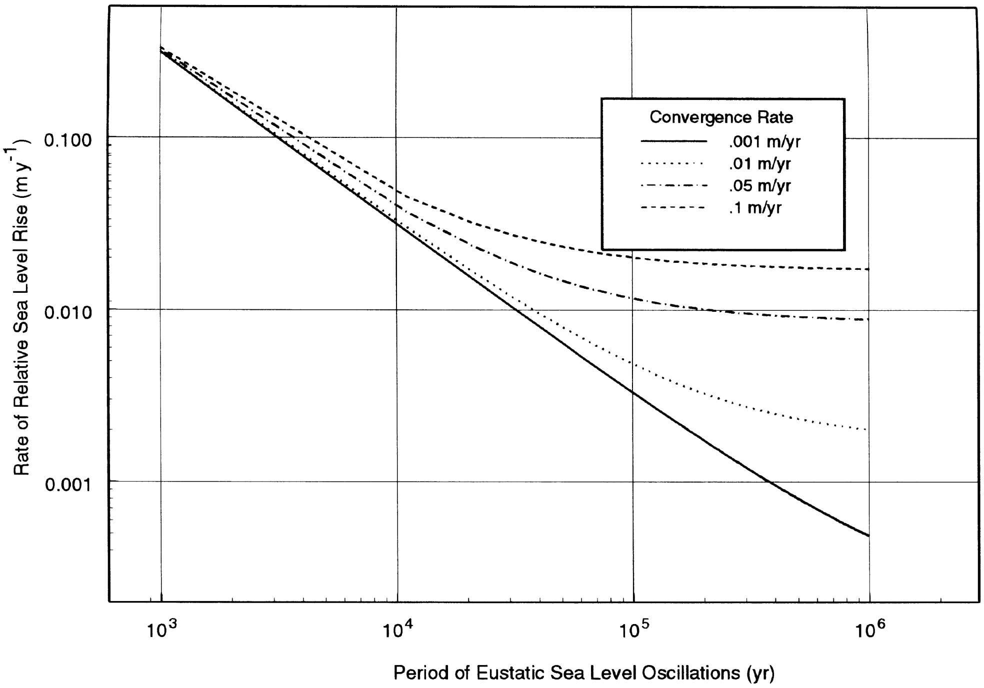

Fig. 7. Relationships between the rate of relative sea-level rise and periodicity of sea-level variation for a range of convergence rates. Sea-level variations control the rate of relative sea-level rise when sea-level varies rapidly. At higher convergence rates, tectonics control the rate of relative sea-level rise. Calculations are for a site 30 km from the orogen. The amplitude of sea-level variation is 50 m; flexural rigidity is 5×10^{21} N m; maximum deflection of the elastic plate is 10 km.

CONCLUSIONS

1 A numerical model linking expressions for coral growth and flexural subsidence can reproduce many of the characteristics of drowned foreland basin carbonate platforms.

2 The history of the Huon Gulf carbonate platforms is well explained by this numerical model. Furthermore, the model provides testable predictions for the drowning ages of the Huon Gulf carbonate platforms.

3 Generalizations of this model suggest that foreland basins characterized by low long-term convergence rates and long-period sea-level variations may require higher short-term convergence rates or more rapid sea-level variations to explain the evolution of their carbonate platforms.

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