Foredeep tectonics and carbonate platform dynamics in the Huon Gulf, Papua New Guinea

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ABSTRACT

HAWAII MR1 side-scan sonar and six-channel seismic reflection data reveal a history of carbonate platform growth, drowning, and back stepping in the Huon Gulf, Papua New Guinea. This is one of the few modern sites where active carbonate platform development and foredeep subsidence are linked. ^{230}Th methods date aragonitic shallow-water corals, recovered from a modern depth of 2000 m, at 348 ± 10 ka. This documents rapid subsidence of the Huon Gulf in response to the encroaching Finisterre Mountains at an average rate of 5.7 mm/yr for the past 348 k.y., the highest subsidence rate reported from any foredeep setting. Carbonate deposition has moved toward the foreland at an average rate of 110 mm/yr over the same period. Comparisons of the measured age with sea-level history (derived from the oxygen isotope record) suggest that the reefs may have formed during sea-level lowstands and drowned during rapid rates of sea-level rise.

INTRODUCTION

Drowned carbonate platforms are common in ancient foredeeps (Pigram et al., 1989; Allen et al., 1991; Barnolas and Teixell, 1994) where the tectonics and sedimentology were particularly conducive to platform formation and subsequent drowning. Foredeeps are flexurally controlled basins dynamically linked to collisional orogens. They have characteristic asymmetric profiles, deepest near the orogen and shallowing toward the foreland. Carbonate platforms tend to develop in the shallow, clear water in the foreland part of the basin, while most clastic sediments are channeled into the deeper, proximal part of the basin. As the orogen advances, the characteristic basin geometry and associated depocenters also migrate toward the foreland. As previously active sites of carbonate formation are submerged beneath the photic zone and buried beneath clastic sediments, reef growth shifts toward the foreland as subaerial regions become submerged.

Despite many ancient examples of back-stepping carbonate platforms (Pigram et al., 1989; Barnolas and Teixell, 1994) and the qualitative understanding of the links between tectonics and carbonate depositional processes developed from studying modern carbonate platforms (Mullins et al., 1991, 1992), there is little quantitative understanding of these processes. Such an understanding can only come from further study of modern foredeeps where the processes of foredeep tectonics and carbonate platform development are still active. We present new data indicating that the southern Huon Gulf, Papua New Guinea (Fig. 1), is one such setting and is the site of active and recently drowned carbonate platforms. Our data suggest that the Huon Gulf has a history of carbonate platform growth, drowning, and back stepping as the Australian continental margin subsides in response to the ongoing collision with the Bismarck arc. Because we can place quantitative constraints on the rates of these processes, the Huon Gulf represents a prime site for studying the processes that link foredeep tectonics and carbonate platform evolution.

REGIONAL SETTING

In northern Papua New Guinea, the active arc-continent collision between the Bismarck arc and the Australian continental margin began about 3.0–3.7 Ma near Madang and has propagated 300 km to the southeast (Abbott et al., 1994). The modern collision tip lies in the western Solomon Sea (Davies et al., 1987). East of the collision tip, the Solomon Sea plate is subducting beneath the New Britain trench at about 90 mm/yr (Taylor, 1979), and slow convergence (~6 mm/yr) between the Solomon Sea and Australian plates is accommodated along the Trobriand trough (Kirchoff-Stein, 1992). West of the collision tip, the Bismarck fore arc overthrusts the Australian continental margin. The Finisterre Mountains, with elevations of 4 km, have been built in response to this collision. The foredeep associated with the Finisterres is located in the Markham Valley (Abers and McCaffrey, 1994) and extends offshore into the Huon Gulf.

MARINE GEOPHYSICAL OBSERVATIONS

Seismic reflection and HAWAII MR1 sidescan sonar data (Fig. 2) show three northwest-trending terraces, 8–10 km wide, in water depths of 2000 m, 1750 m, and 1250 m. The vertical relief on each terrace averages about 200 m. Seismic reflection profiles show

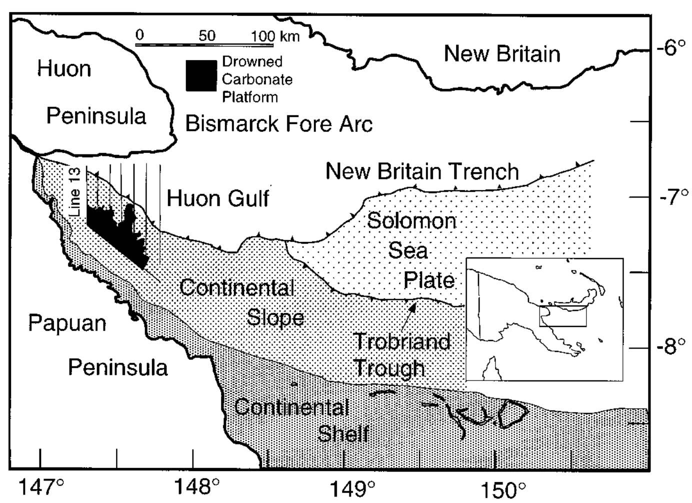

Figure 1. Map of major geographic features in Solomon Sea region, Papua New Guinea, discussed in text. Inset shows broader location of this map. Drowned carbonate platform in Huon Gulf is marked in black. Side-scan and seismic lines also shown, and line 13 (Fig. 3) is labeled. Major thrust fronts in Solomon Sea are mapped triangular teeth on upper plates.

Data Repository item 9644 contains additional material related to this article.

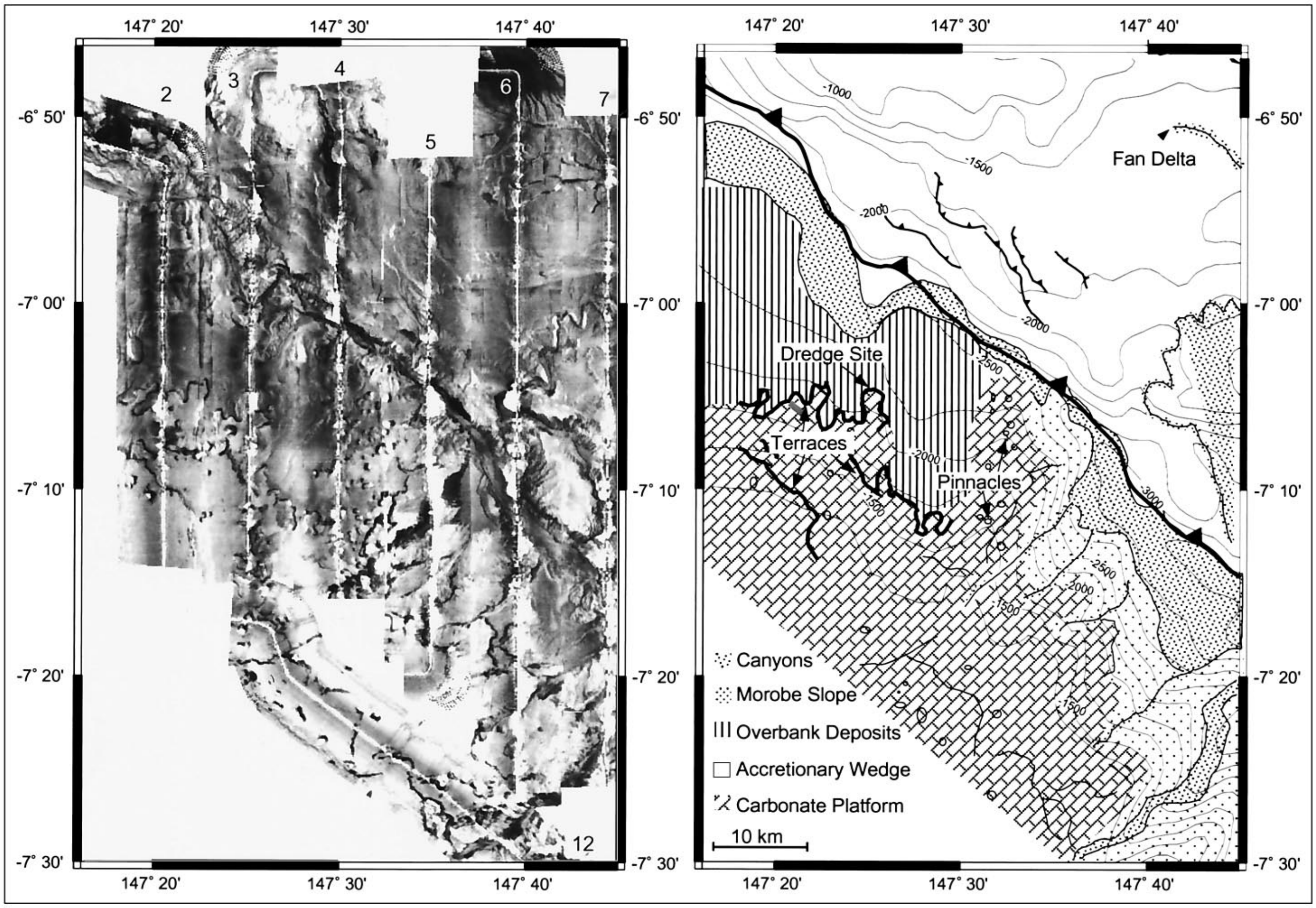

Figure 2. HAWAII MR1 side-scan sonar image (left) and interpretation (right) from Huon Gulf, located in Figure 1. Light lines through image are locations of ship's track. Three carbonate terrace fronts are labeled, as is location of dredge haul. Thrust faults are marked; teeth are on upper plates.

raised platform rims along the terraces, which are characteristic of drowned carbonate platforms (Schlager, 1981) (Fig. 3). Previous studies reported shallower drowned reefs at the modern shelf break (109–117 m) and on the upper slope (192–457 m) (von der Borch, 1972). Living fringing reefs exist along most of the Morobe coast (Loffler, 1977), suggesting foreland-prograding carbonate deposition. To determine whether the deep terraces are drowned carbonate platforms, we dredged the steepest part of the 2000 m terrace to obtain, as much as possible, in situ samples. The dredge recovered several kilograms of shallow water corals, indicating that the deepest terrace is a drowned carbonate platform. Because the morphology and side-scan reflectivity of the two shallower terraces are similar to the deepest terrace, we interpret the two shallower terraces to also represent drowned carbonate platforms. Regardless of the nature of the two shallower terraces, our observation that the deepest terrace is a drowned carbonate platform, coupled with previous observations of living fringing reefs along the Morobe coast, documents an episode of carbonate platform drowning and back stepping in the Huon Gulf.

BIOLOGICAL ANALYSIS

We examined 11 dredged corals (54–970 g) before and after cleaning by ultrasound in water. Each was assigned to one of seven genera (*Acropora*, *Favia*, *Cyphastrea*, *Galaxea*, *Porites*, *Goniopora*, *Pavona*) and four of the corals were identified to species. Patterns of differential erosion and deposition of black precipitates (possibly Mn or Fe oxides) on upper surfaces indicate that at least five were probably dredged from in situ growth positions on the reef. The whole collection, morphologically and taxonomically, is characteristic of a shallow-water coral assemblage in a high-energy environment. In particular, the species *Acropora robusta* and the growth forms of *Galaxea fascicularis* and *Cyphastrea microphthalma* in the collection are usually restricted to such habitats on living reefs today (Veron et al., 1977; Veron and Pichon, 1979; 1982; Veron and Wallace, 1984; Veron and Kelley, 1988). In addition, several specimens

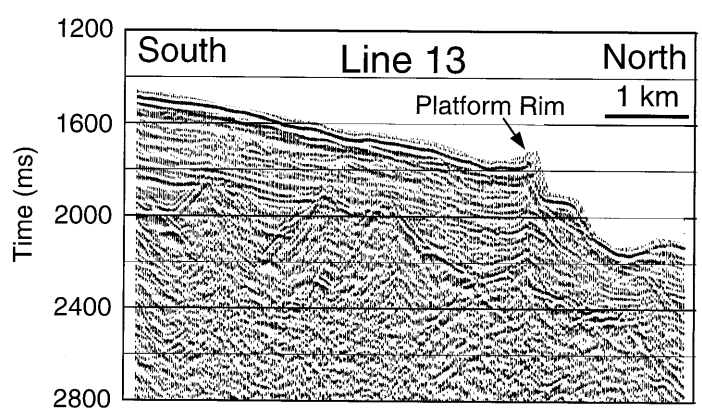

Figure 3. Migrated six-channel seismic reflection profile from line 13, located in Figure 1. Raised platform rim is shown on this figure. Vertical scale is in milliseconds of two-way traveltime. 1000 ms in seawater is ~750 m of depth.

had attached barnacles, polychaete tubes, and forams similar to those now living in shallow-water reef environments. The *Porites* specimens appear to be massive forms typical of shallow environments. We conclude that these corals lived in <5–10 m of water on a high-energy reef.

Six unattached fragments had marked indications of diagenesis (discoloration, sediment penetration, possible secondary calcification, and mineral replacement), but the five apparently in situ corals had many fewer signs of diagenesis. In at least two cases, RD01-8 (*Cyphastrea microphthalma*) and RD01-15 (*Porites* sp.), fine skeletal details on the upper surface were preserved in exquisite condition under the black precipitate. This suggests that subsidence to a level of low biological activity occurred too rapidly for damage by overgrowth or bioerosion to occur.

ISOTOPIC MEASUREMENTS[1]

Two of the corals were selected for ^{230}Th dating because they had the least amount of discoloration, leaching, or cementation. X-ray diffraction analysis shows that the samples consist almost exclusively of aragonite. Subsamples of 1 g were taken by breaking the corals in a rock press and then using a chisel to isolate the least-altered carbonate. Uranium and thorium isotopic compositions and concentrations were determined at the University of Minnesota Isotope Laboratory using thermal ionization mass spectrometric techniques (Gallup et al., 1994). Two separate samples from RD01-2 (*Acropora robusta*) were analyzed, because the sample's color and texture were somewhat heterogeneous. Replicate mass-spectrometric analyses of the thorium fraction of RD01-2 (2) and the uranium fraction of RD01-3 (*Favia maxima*) agreed within analytical error. ^{230}Th ages, initial δ^{234}U values and Uranium concentrations for RD01-2 (1) are 393 ± 10 ka, 226 ± 7, and 3.58 ppm, for RD01-2 (2) are 365 ± 10 ka, 218 ± 7, and 3.57 ppm, and for RD01-3 are 348 ± 10 ka, 146 ± 5, and 2.21 ppm (using the weighted averages of the replicates). The two samples have very different initial δ^{234}U values: that of RD01-3 is within error of the modern seawater value of 149.3 ± 1.5 (Edwards et al., 1993; Gallup et al., 1994; Cheng et al., 1995), whereas the two values measured for RD01-2 are significantly higher than the modern value. Though the marine δ^{234}U value may have differed in the past, fossil corals from Barbados indicate that it was within 2 per mil of the modern value at 83 and 200 ka (Gallup et al., 1994). Simple models of marine inputs and residence time for uranium (Ku et al., 1977) indicate that the marine δ^{234}U value should not vary by more than 20 per mil over 10^5 yr (Edwards, 1988; Hamelin et al., 1991; Richter and Turekian, 1993). Thus, we would expect that a 350 Ka, unaltered fossil coral should have an initial δ^{234}U value within ~20 per mil of 149.3. Sample RD01-3 fits well within this criteria, which suggests that its ^{230}Th age is accurate and that the age of the drowned reef is 348 ± 10 ka.

DISCUSSION

Seismic and side-scan sonar data indicate that the Huon Gulf has a history of carbonate platform growth and drowning during subsidence induced by the encroaching Finisterre Mountains. Isotopic measurements indicate that part of the Huon Gulf has subsided 2000 m within the past 348 k.y. at an average rate of 5.7 mm/yr. During carbonate platform drowning, relative sea-level rise (eustatic sea-level rise plus tectonic subsidence) outpaces carbonate accumulation rates until the platform is submerged beneath the photic zone of maximum carbonate deposition (Schlager, 1981).

[1]GSA Data Repository item 9644, U and Th isotopic composition and ^{230}Th ages of corals, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

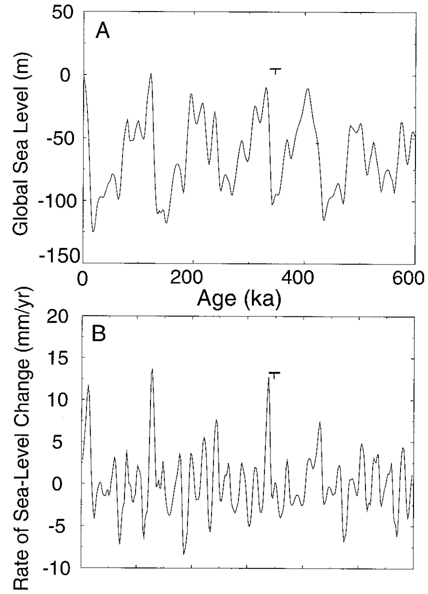

Figure 4. Relation of global sea-level changes to the dredged and dated coral. A: Global sea-level variations based on linear transformation of oxygen isotope record from deep sea cores (Imbrie et al., 1984). Vertical line corresponds to ^{230}Th age of drowned reef sample, and uncertainties are shown by horizontal line. B: Rate of sea-level change, which is determined by taking derivative (slope) of sea-level curve in A. Note that ^{230}Th age and its uncertainties encompass time of very rapid rate of sea-level change, exceeding 10 mm/yr.

Conditions necessary for platform drowning can be met by a variety of mechanisms. Brief pulses of rapid eustatic sea-level rise superimposed on background tectonic subsidence may have drowned a series of coral reefs on Hawaii (Ludwig et al., 1991). Other suggested mechanisms include various environmental stresses that inhibit growth of coral reefs, including local variations in nutrient supply (Hallock and Schlager, 1986) and water turbidity, as well as regional and global environmental factors (e.g., Vogt, 1989). Although the maximum upward growth rate for individual corals may be greater, the accumulation of reefal carbonates rarely exceeds 10 mm/yr (Grigg and Epp, 1989).

The average subsidence rate of 5 mm/yr in the Huon Gulf is approximately half the maximum upward growth rate for platform-building reefs, so a moderate sea-level rise of a few millimetres/year, possibly coupled with small changes in the local environment that persisted for a few decades, would be enough to drown an otherwise active platform. The relationships between eustatic sea-level history, as inferred from the deep-sea oxygen isotope record (Imbrie et al., 1984), and our ^{230}Th age suggest that the corals were alive during oxygen-isotope stage 10, a sea-level lowstand (Fig. 4A), and may have drowned during a rapid (>10 mm/yr) sea-level rise (Fig. 4B). Recent studies indicate that brief (<500 yr), extremely rapid (>20 mm/yr) pulses of sea level rise may accompany deglaciation (Blanchon and Shaw, 1995; Edwards et al., 1993; Fairbanks, 1989), and these pulses are not resolvable on the sea-level history derived from the oxygen isotope record.

These observations suggest a scenario for carbonate platform evolution in the Huon Gulf (Fig. 5). During sea-level lowstands, a carbonate platform develops on the tectonically subsiding Australian continental margin (Fig. 5A). Rapid sea-level rise coupled with tectonic subsidence yields a rate of relative sea-level rise that is greater than the platform maximum upward growth rate, the platform drowns, and active carbonate deposition back steps to the south (Fig. 5B). The net effect of this sequence is that active carbonate deposition migrates toward the foreland over time. Because reefs are currently active along the modern Morobe coast and other reefs were active about 40 km to the north at 348 ka, we estimate that the locus of active carbonate deposition has migrated to the south at about 110 mm/yr, close to the overall convergence rate between the Bismarck arc and Australia. Back stepping of carbonate deposition is consistent with a foredeep origin for the Huon Gulf.

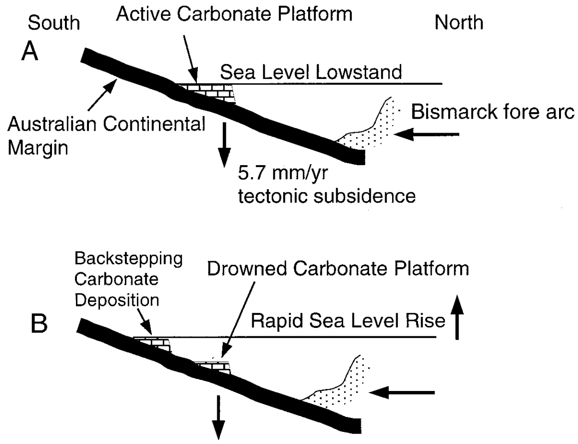

Figure 5. Proposed scenario for formation of Huon Gulf carbonate platform. Average of 5.7 mm/yr subsidence, induced by encroaching Bismarck fore arc, is superimposed on sea-level fluctuations. A: During sea-level lowstands, reefs form an active carbonate platform. B: Platform drowns during rapid rise in sea level and subsidence is rapid enough to remove earlier reef from photic zone before next reef forms. At next major lowstand, new carbonate platform develops south (toward foreland) of drowned platform.

The 5.7 mm/yr subsidence rate in the Huon Gulf is the highest subsidence rate reported from a foredeep setting. Most foredeep subsidence rates are about an order of magnitude lower than in the Huon Gulf (Jordan, 1981; Cross, 1986; Homewood et al., 1986; Abers and McCaffrey, 1988; Pigram and Symonds, 1991). The only exception may be the Timor trough (Audley-Charles, 1986), where subsidence rates are thought to be at least 1 mm/yr. Slowly subsiding foredeeps (~0.1 mm/yr) invariably have slowly converging orogens (~1 mm/yr), whereas rapidly subsiding foredeeps (~1 mm/yr) have rapidly converging orogens (>10 mm/yr). This is a consequence of the link between the orogen and the foredeep, because the flexural profile of the basin migrates at roughly the same rate as the orogen.

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