Coralgal composition of drowned carbonate platforms in the Huon Gulf, Papua New Guinea; implications for lowstand reef development and drowning

Jody M. Webster a,*, Laura Wallace a, Eli Silver a, Donald Potts b, Juan Carlos Braga c, Willem Renema d, Kristin Riker-Coleman e, Christina Gallup e

a Department of Earth Sciences, University of California, Santa Cruz, CA 95064, USA
b Department of Ecology and Evolutionary Biology, University of California, Santa Cruz, CA 95064, USA
c Departamento de Estratigrafía y Paleontología, Universidad de Granada, Spain
d Nationaal Natuurhistorisch Museum, Leiden, The Netherlands
e Department of Geological Sciences, Duluth, MN, USA

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Abstract

Collision between the South Bismarck plate and the northern edge of the Australian plate has produced an actively subsiding foreland basin in the western Huon Gulf. A series of drowned carbonate platforms and pinnacles are preserved on this margin due to a combination of this rapid subsidence and eustatic sea-level changes over the last 450 ka. We analyzed sedimentary and coralgal data from the platforms to better understand lowstand reef development and drowning in the Huon Gulf. The recovered limestones are divided into five main sedimentary facies: coral reef, coralline-foraminiferal nodule, coralline-foraminiferal crust, Halimeda, and planktonic foraminiferal limestones. Based on a comparison with modern analogues in the Indo-Pacific and elsewhere, we identified coral reef, deep fore-reef slope, deeper fore-reef slope, and pelagic/hemipelagic paleoenvironmental settings. An analysis of facies relationships and their paleoenvironmental meanings revealed lowstand corals reefs preserved at the top of the platforms that grew within ~10 m of sea level. Two different coral assemblages were identified within this facies: (1) a shallow, high energy reef community characteristic of windward margins and limited to the deep platforms (1947, 2121, 2393 m), and (2) another shallow community but indicative of more moderate lower energy reef conditions and limited to the middle (1113, 1217, 1612 m) and shallow platforms (823 m). The change from high to lower energy reef growth conditions suggests that oceanographic/climatic conditions in the Huon Gulf have changed substantially through time, primarily through the closure of the Gulf as a result of tectonic rotation and uplift of the Huon Peninsula over the last 450 ka. Despite major environmental perturbations (i.e. relative sea-level and temperature changes) the platforms and the shallow water coral reefs exposed at the top have been able to re-establish themselves time and time again over the last 450 ka. We also identified two different incipient drowning scenarios influenced by the rate of relative sea-level rise. More rapid drowning in the middle and deep platforms produced a thin veneer of coralline-foraminiferal nodule and Halimeda limestones over the shallow coral reef material while the slower
drowning experienced by the shallowest platforms allowed thick coralline-foraminiferal crust limestones to develop. We recognize three main stages of platform development: (1) initiation and growth characterized by shallow coral reef growth as the platforms grew close to sea level during the lowstands, (2) incipient drowning marked by a shift to coralline-foraminiferal nodule, crust and Halimeda limestones as the platforms began to drown during rapid eustatic sea-level rise and continued subsidence, and (3) the complete drowning of the platforms characterized by platform ‘turn off’, increased bioerosion, Fe–Mn precipitation and pelagic/hemipelagic sedimentation as the platform surfaces finally drop below the photic zone.

Keywords: carbonate platform drowning; Pleistocene reef development; sea-level changes; lowstand; Papua New Guinea; coralgal composition

1. Introduction

Our understanding of Pleistocene reef development in response to climatic and associated sea-level changes has been greatly enhanced over the last 30 years through extensive investigations of carbonate sequences on active margins in Barbados (Gallup et al., 2002), the Huon Peninsula (Chappell et al., 1996), East Indonesia (Hantoro et al., 1994), and the Ryukyu Islands (Nakamori et al., 1995a; Sagawa et al., 2001), rifted margins along the Red Sea (Gvirtzman, 1994; Plaziat et al., 1998), subsiding atolls (Camoin et al., 2001) and passive margins in the Great Barrier Reef (International Consortium for Great Barrier Reef Drilling, 2001; Webster and Davies, 2003) and the Florida Keys (Multer et al., 2002). For the most part, fossil reefs in these settings preserve a record of transgressive and highstand reef development, with lowstand growth either buried by subsequent reef growth or not preserved at all due to steep, shelf edge morphology. Submerged Pleistocene reefs on rapidly subsiding margins encapsulate a unique archive of lowstand reef development, drowning and associated climate change during transitions from glacial to interglacial conditions. Given the difficulties in access and the unique conditions required to preserve them there have been comparatively few comprehensive studies on such reefs (Hawaii: Moor and Campbell, 1987; Grigg et al., 2002; Jones, 1995; Fletcher et al., 2000; Papua New Guinea: Galewsky et al., 1996). To this end we imaged and sampled eight submerged platforms and pinnacles from the Huon Gulf on the north coast of Papua New Guinea (Fig. 1). These platforms represent the submerged counterpart to the uplifted terraces exposed on the Huon Peninsula, studied so extensively by Chappell and others (e.g. Chappell, 1974; Chappell and Polach, 1976; Chappell et al., 1996; McCulloch and Esat, 2000; Chappell, 2002).

Galewsky et al. (1996) and Galewsky (1998) suggested that the platforms preserved in the Huon Gulf drowned in response to a combination of rapid subsidence and eustatic sea-level rise. They calculated an average subsidence rate of 5.7 m/ka from a 348-ka shallow water coral dredged from the 1947-m platform. Using the last deglaciation as a model for older deglaciations, the average rate of sea-level rise was ~10 m/ky, close to the maximum sustained vertical accretion rate for shallow coral reefs (~10–14 m/ky; Buddemeier and Smith, 1988; Smith and Buddemeier, 1992). Furthermore, recent results from Barbados, the Huon Peninsula, and the Sunda Shelf indicate that the course of sea-level rise during the last deglaciation was in fact episodic, characterized by one, perhaps two very rapid, meter-scale (up to 20 m) sea-level rise events (meltwater pulse 1A and 1B) in excess of 45 m/ky in less than < 500 years (Fairbanks, 1989; Bard et al., 1990; Chappell and Polach, 1991; Bard et al., 1996; Blanchon and Shaw, 1995; Hanebuth et al., 2000). Therefore, assuming the rates of sea-level rise during earlier deglaciations were at least similar to the last deglaciation, any such rise (and associated meltwater pulses) combined with rapid subsidence could easily drown even the healthiest coral reef.

To better understand the relationship between carbonate platform development, subsidence and
climate change, we undertook a cruise to the Huon Gulf in August–September 2001. We mapped the drowned platforms using SeaBeam, side-scan sonar and then collected limestone samples using the Woods Hole ROV, Jason (Webster et al., 2002). The bathymetric data, side scan data and limited dates indicate: (1) the presence of eight major platforms and numerous pinnacles that likely grew ~450 and 60 ka in a backstepping fashion (Fig. 1A); (2) the morphology and

Fig. 1. (A) Regional map showing tectonic setting and location of the drowned platforms (after Wallace, 2002). The modern reefs (dashed line) fringe the Morobe coastline and extend east into the Solomon Sea forming the Trobriand platform. (B) Color 3-D bathymetry of the margin showing the structure and distribution of the platforms and pinnacles. The red arrows indicate the position of the ROV Jason dive sites. The yellow text represents the U/Th ages of the platforms currently dated.
age structure of the platforms is consistent with platform drowning as a result of rapid sea-level rise (and subsidence) during major deglaciations and other less dramatic interstadial events; (3) the platforms are composite features composed of pinnacles, banks and multiple terrace levels indicating an often complex history of platform growth and drowning; and (4) the platform tops preserve the signature and timing of platform drowning, despite experiencing substantial lateral modification.

Wallace (2002) used the additional data to develop a numerical model incorporating variable flexural subsidence, reef growth and eustatic sea-level changes (see methods for model details). From this model, Wallace (2002) estimated the timing of platform drowning (Fig. 2A) and suggested that the platforms and pinnacles drowned during early parts of the major deglaciations and smaller amplitude interstadial events (Fig. 2B) over the last 450 ka. U/Th dates from the 239-m (60.3 ± 0.5 ka) and 1947-m (348 ± 10 ka) platforms are close to the model ages.

In this paper we present new coralgal and sedimentary data to better understand the development and drowning of carbonate platforms on the rapidly subsiding margin in the Huon Gulf. Our objectives are: (1) to document the coralgal and sedimentary composition of the drowned platforms, (2) to reconstruct the paleoenviron-

![Fig. 2. (A) Depth and modeled age of the drowned carbonate platforms in the Huon Gulf, Papua New Guinea (after Wallace, 2002). (B) Eustatic sea-level for the last 500 ka showing the likely drowning ages (black circles) of the platforms. These times are based on a numerical model incorporating variable flexural subsidence, reef growth and eustatic sea-level changes (0–140 ka: Lambeck and Chappell, 2001; 141–350 ka: Lea et al., 2002; 351–500 ka: Imbrie et al., 1984). Note the Imbrie et al. (1984) curve is a deep marine δ¹⁸O record and not a direct measure of ice volume. Marine isotope stages (MIS) are after Imbrie et al. (1984).](MARGO 3438 4-2-04 Cyaan Magenta Geel Zwart)
mental settings prior to and during drowning, (3) to characterize and evaluate the coralgal and sedimentary signatures of platform drowning, and (4) to discuss implications of this record for platform development, drowning, tectonics and climate change over the last 450 ka in the Huon Gulf.

2. Location and methods

2.1. Geological setting

The study site is in the Huon Gulf located on the northern coast of Papua New Guinea (Fig. 1A). The Australian plate converges obliquely with the Pacific plate and has produced a complex and active system of micro-plates with associated vertical and lateral movements. In the Huon Gulf, the South Bismarck plate is colliding with and overriding the northern Australian continental margin (Pigram and Davies, 1987; Abbott et al., 1994) and a classic fore-deep has developed on the lower plate of the convergent zone in the Huon Gulf (Galewsky et al., 1996) (Fig. 1A). The resulting massive loading and subsidence has caused drowning of a series of carbonate platforms at 100–190 (von der Borch, 1972), 239, 625, 823, 1113, 1216, 1612, 1947, and 2121 m and pinnacles at 2393 m (Webster et al., 2002) (Fig. 1B).

2.2. Numerical model estimating platform drowning

We used a numerical model developed by Wallace (2002) incorporating: (1) flexural subsidence of the foredeep due to the foreland-migrating load, (2) coral growth on the subsiding plate, and (3) changing eustatic sea levels, to estimate the drowning age of each platform. Typical of a plate being consumed at a subduction zone, subsidence rates in the Huon Gulf increase dramatically closer to the New Britain trench (closer to the ‘load’), therefore the platforms experienced a variable subsidence history. In the numerical model we use margin bathymetry and the age and location of the 1950-m and 240-m drowned platforms to essentially ‘grow’ and ‘drown’ reefs on a realistic flexurally sinking substrate. Coral reef vertical growth rates as a function of water depth are calculated using equations presented by Bosscher and Schlager (1992) and estimates of eustatic sea-level change over the last 500 kyr (Lambeck and Chappell, 2001; Lea et al., 2002; Imbrie et al., 1984). The model predicts the drowning age of each platform during rapid sea-level rise events (Fig. 2), and is in agreement with the conceptual models of platform drowning proposed by Schlager (1981).

Wallace (2002) found that no single value for elastic thickness of the subsiding plate could explain both the flexural shape of the plate and the age and location of the 1950-m and 240-m platforms. Variable plate thickness can fit all the data quite well, with significant thinning towards the trench (from 16 to 10 km effective elastic thickness). This thinning has implications for the rate of subsidence experienced by the platforms during growth and prior to complete drowning. The flexural subsidence history presented by Wallace (2002) suggests that while within the photic zone (~100 m), the younger, shallow platforms (underlain by the elastically thicker plate) subsided more slowly than the deep platforms, which lie on top of a thinner, weaker elastic plate.

2.3. Modern climatic and oceanographic setting

The Huon Gulf lies within the influence of the NW monsoons (January–April) and SE trades (May–December) (von der Borch, 1972). However, there is no distinct energy regime with winds blowing from the SE and NE annually as well as in a diurnal local cycle (McAlpine et al., 1983). During the NW monsoon, seas are generally calm in the Huon Gulf. Although a short, choppy swell can develop during the SE trades, these prevailing conditions, plus the shape of the Gulf, and the positions of the Huon Peninsula and SE Trobriand platform, all act to shelter the Huon Gulf from much of the wave/wind energy from both NW and SE (Fig. 1A). Thus, the Huon Gulf usually experiences low to moderate energy conditions, particularly when compared with the more exposed Madang coast to the NW and the Trobriand platform to the SE.
Table 1
Coral, coralline algal and foraminifera species identified from the drowned carbonate platforms in the Huon Gulf, Papua New Guinea

<table>
<thead>
<tr>
<th>Corals</th>
<th>Coralline algal</th>
<th>Large benthic forams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Family ACROPORIDAE</td>
<td>Family FAVIIDAE</td>
<td>Family CORALLINACEAE</td>
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<tr>
<td>Acropora sp.</td>
<td><em>Leptoria phrygia</em></td>
<td>Subfamily Melobesioidae</td>
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<td>Acropora cytherea</td>
<td><em>Montastrea curta</em></td>
<td>Family Amphisteginidae</td>
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<td>Acropora grandis</td>
<td><em>Montastrea multipunctata</em></td>
<td>Amphistegina sp.</td>
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<td>Acropora hawkinsi</td>
<td><em>Montastrea sellabrosa</em></td>
<td>Amphistegina radiata</td>
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<td>Acropora humilis</td>
<td><em>Platygryra sp.</em></td>
<td>Amphistegina lessonii</td>
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<td>Acropora hyacinthus</td>
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<tr>
<td>Acropora longa</td>
<td><em>Family FAVIIDAE</em></td>
<td>Subfamily Litophyloidae</td>
</tr>
<tr>
<td>Acropora muricata</td>
<td><em>Family FAVIIDAE</em></td>
<td>Lithophyllum sp.</td>
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<td>Acropora palifera</td>
<td><em>Family FAVIIDAE</em></td>
<td>Lithophyllum incrassatum</td>
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<tr>
<td>Acropora sp. (robusta group)</td>
<td><em>Family FAVIIDAE</em></td>
<td>Lithophyllum gr. pustulatum</td>
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<td>Astreopora sp.</td>
<td><em>Family FAVIIDAE</em></td>
<td>Lithophyllum kotschyanum</td>
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<tr>
<td>Montipora sp.</td>
<td><em>Family FAVIIDAE</em></td>
<td>Subfamily Lithophyloidae</td>
</tr>
<tr>
<td>Montipora cf. venosa</td>
<td><em>Family FAVIIDAE</em></td>
<td>Lithophyllum sp.</td>
</tr>
<tr>
<td>Montipora cf. aequituberculata</td>
<td><em>Family FAVIIDAE</em></td>
<td>Lithophyllum incrassatum</td>
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<td>Montipora corbettiensis</td>
<td><em>Family FAVIIDAE</em></td>
<td>Lithophyllum gr. pustulatum</td>
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<td>Montipora monasteriata</td>
<td><em>Family FAVIIDAE</em></td>
<td>Lithophyllum kotschyanum</td>
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<td>Montipora foliosa</td>
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<td>Subfamily Mastophoroidea</td>
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<tr>
<td>Montipora informis</td>
<td><em>Family FAVIIDAE</em></td>
<td>Neogoniolithon sp.</td>
</tr>
<tr>
<td>Montipora tuberculosa</td>
<td><em>Family FAVIIDAE</em></td>
<td>Neogoniolithon concuum</td>
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<td>Montipora undata</td>
<td><em>Family FAVIIDAE</em></td>
<td>Neogoniolithon fosliei</td>
</tr>
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<td>Family AGARICIIDAE</td>
<td><em>Family FAVIIDAE</em></td>
<td>Hydroolithon reindoldtii</td>
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<td>Pachyseris speciosa</td>
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<td>Spongites sp.</td>
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<td>Heterostegina depressa</td>
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<td>Pavana explanulata</td>
<td><em>Family FAVIIDAE</em></td>
<td>Heterostegina operculinoides</td>
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<td>Pavana mutica</td>
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<tr>
<td>Family ASTROCOENIIDAE</td>
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<td>Stylocoeniella guentheri</td>
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<tr>
<td>Family FAVIIDAE</td>
<td><em>Family FAVIIDAE</em></td>
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<tr>
<td>Cyphastrea sp.</td>
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<tr>
<td>Cyphastrea microphthalmal</td>
<td><em>Family FAVIIDAE</em></td>
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<tr>
<td>Cyphastrea seruikai</td>
<td><em>Family FAVIIDAE</em></td>
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<tr>
<td>Echinopora sp.</td>
<td><em>Family FAVIIDAE</em></td>
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<tr>
<td>Echinopora gemmacea</td>
<td><em>Family FAVIIDAE</em></td>
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<tr>
<td>Echinopora hirsutissima</td>
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<tr>
<td>Favia sp.</td>
<td><em>Family FAVIIDAE</em></td>
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<td>Favia laxa</td>
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<tr>
<td>Favia stelligera</td>
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<tr>
<td>Favites basta</td>
<td><em>Family FAVIIDAE</em></td>
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<tr>
<td>Favites chinensis</td>
<td><em>Family FAVIIDAE</em></td>
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<tr>
<td>Favites haliota</td>
<td><em>Family FAVIIDAE</em></td>
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<tr>
<td>Favites pentagona</td>
<td><em>Family FAVIIDAE</em></td>
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<tr>
<td>Goniatrea sp.</td>
<td><em>Family FAVIIDAE</em></td>
<td></td>
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<tr>
<td>Leptastrea sp.</td>
<td><em>Family FAVIIDAE</em></td>
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</tbody>
</table>

*Geniculate coralline algae, superscript numbers indicate which platform the species were recovered from e.g. 1239 m, 2625 m, 3823 m, 41113 m, 41216 m, 41612 m, 41947 m, 42121 m, 42393 m.
2.4. Site selection and sampling

Extensive bathymetric (SeaBeam) and side-scan sonar (DSL-120) data, processed while at sea, allowed us to select suitable dive targets at the platform tops. A separate paper based on this data detailing the structure and morphology of the platforms will be presented elsewhere. We recovered 333 samples totaling 1200 kg of limestone during 18 days of continuous Jason ROV operations. To record the paleoenvironmental signature prior to and during drowning, sampling focused on the elevated platform rim, the shallowest part of the platform. This also had the effect of minimizing any error if samples were not in situ, presumably any transported and re-cemented samples would not have traveled far from the top of the platform. Wherever possible we attempted to sample in-situ limestones by breaking them off with the manipulator arm or the edge of the ROV’s sampling platform.

2.5. Sample preparation and fossil identification

Laboratory studies involved cutting, ultrasonically cleaning and microscopic identification of the samples to identify the corals and other organisms (e.g. coralline algae, foraminifera). Coral identification was based on Veron and Pichon (1976, 1979, 1982), Veron and Wallace (1984); Wallace (1991); Veron (1986) and Veron et al. (1977). Petrographic analysis of 125 thin sections was used to determine the texture, composition and relative abundance of the associated platform components such as coralline algae, planktonic, benthic and encrusting foraminifera, Halimeda, gastropods, bivalves, echiinodermes, non-skeletal and terrigenous grains. Given their importance as indicators of paleoenvironments, special attention was given to the taxonomic identification of coralline algae (Ringeltaube and Harvey, 2000; Verheij and Erfemeijer, 1993; Woelkerling and Campbell, 1992; Woelkerling et al., 1993; Womersley, 1996) and large benthic foraminifera (Hallock and Glen, 1986; Hohenegger, 1995; Hohenegger et al., 1999, 2000). A combination of criteria was used to distinguish in-situ limestone samples from allochthonous rubble: (1) whether the sample was broken off or collected loose, (2) the presence of dark Mn–Fe crusts on the exposed outer limestone surface indicating an original orientation, (3) lack of severe surface abrasion and rounding of coral colonies, (4) orientation of well preserved corallites, (5) orientation of acroporid and pocilloporid branches, (6) coral colonies or branches capped by thick (few cm) coralline algal crusts, and (7) presence of macroscopic and microscopic sediment geopetals in cavities and mollusc chambers and valves.

3. Results

3.1. Sedimentary facies, coralgal composition and paleoenvironmental interpretations

Detailed examination of the hand specimens and thin sections revealed five main sedimentary facies: coral reef, coralline algal–foraminiferal nodule, coralline algal–foraminiferal crust, Halimeda, and planktonic limestones. Characterized by their sedimentary textures and composition (e.g. coralgal assemblages, benthic foraminifera, other microfacies), these facies and their likely paleoenvironmental settings are discussed below and summarized in Tables 1 and 2.

3.1.1. Coral reef limestone

This limestone is dominated by autochthonous hermatypic coral material forming in-situ coral frameworks defined as bafflestones (Fig. 3A), framestones (Fig. 3D) or bindstones (Fig. 4A). Associated components contributing to the framework or matrix material include non-geniculate coralline algae, large benthic foraminifera (e.g. Calcarina sp.), molluscs, echinoderms, the green algae Halimeda, and peloids. This facies also contains obvious allochthonous coral reef materials, including loose hermatypic corals, grainstones, rudstones and floatstones.

In-situ hermatypic corals are common to abundant in reef environments down to 50 m in the Indo-Pacific (Veron, 1986; Iryu et al., 1995; Done, 1982); therefore this facies was presumably deposited in depths < 50 m. The paleoenvironmental setting of this facies can be determined
### Sedimentary Facies Table

<table>
<thead>
<tr>
<th>Sedimentary Facies</th>
<th>Definition</th>
<th>Sedimentological Features</th>
<th>Dominant Components</th>
<th>Associated Components</th>
<th>Paleoenvironmental Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coral Reef Limestone</strong></td>
<td>Limestone dominated by hermatypic corals</td>
<td>In-situ coral framework (bindstones to framestones), and loose coral reef debris (grainstones, rudstones and floatstones)</td>
<td>Hermatypic corals*</td>
<td>Coralline algae** (mastophoroid), large benthic forams (e.g. <em>Calcarina</em>), molluscs, echinoderms, <em>Halimeda</em> and peloids</td>
<td>Reef flat to upper reef slope (&lt; 20 m)</td>
</tr>
<tr>
<td><strong>Coralline Algal-Foraminiferal Nodule Limestone</strong></td>
<td>Dominated by nodule composite non-geniculate coralline algae and encrusting foraminifera</td>
<td>Rudstones to floatstones, cores of nodule mainly composed of coral fragments</td>
<td>Non-geniculate coralline algae** (Melobesiod) and acervulinids</td>
<td>Large benthic forams (<em>Amphistegina radiata</em>, <em>A. lessonii</em>, <em>Heterostegina depressa</em>), coral fragments and molluscs</td>
<td>Deep fore-reef slope (~ 20 - 60 m)</td>
</tr>
<tr>
<td><strong>Halimeda Limestone</strong></td>
<td>Dominated by <em>Halimeda</em> segments</td>
<td>Packstones to wackestones, extensive mud</td>
<td>Halimeda</td>
<td>Large benthic forams (<em>Amphistegina radiata</em>, <em>A. lessonii</em>, <em>Operculina</em>, <em>Heterostegina depressa</em>), coral fragments and molluscs</td>
<td>Deep fore-reef slope (~ 20 - 60 m)</td>
</tr>
<tr>
<td><strong>Coralline Algal-Foraminiferal Crust Limestone</strong></td>
<td>Dominated by overlapping crusts of non-geniculate coralline algae and encrusting foraminifera</td>
<td>Bindstone, forms a well developed crustose framework</td>
<td>Non-geniculate coralline algae** (Melobesiod) and acervulinids</td>
<td>Minor encrusting corals (e.g. <em>Montipora</em>, <em>Porites</em>), Bryozoa, large benthic forams (<em>Nummulites</em>, <em>Amphistegina</em>, <em>Cycloclypeus carteri</em>, <em>H. operculomoides</em>)</td>
<td>Deeper fore-reef slope (build up) (~ 60 - 90 m)</td>
</tr>
<tr>
<td><strong>Planktonic Foraminiferal Limestone</strong></td>
<td>Dominated by planktonic foraminifera</td>
<td>Mudstones to wackestones, commonly stained with Fe-Mn oxides and minor mud sized terrigenous (quartz and rock fragments)</td>
<td>Planktonic forams, <em>i.e. Globoideidae</em>, delicate molluscs, small benthic forams (e.g. <em>Textularia</em>)</td>
<td>Large benthic forams (<em>Amphistegina radiata</em> and <em>A. lessoni</em>, <em>Cycloclypeus carteri</em> and <em>Heterostegina depressa</em>)</td>
<td>Outer shelf (20-120 m)</td>
</tr>
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### Coral Assemblages Table

<table>
<thead>
<tr>
<th>Assemblage A</th>
<th>Dominated by robust branches or ridges of <em>Acropora palifera</em>, <em>A. humilis</em> group, and tabulate <em>A. hyacinthus</em> group (e.g. <em>cytherea</em>, <em>spicifera</em>), with associated encrusting <em>Montipora</em> sp. (e.g. <em>M. tuberculosa</em>, <em>M. informis</em>), and submassive to massive <em>Porites</em> sp. (e.g. <em>P. horizontata</em>, <em>P. lobata</em>) and minor encrusting <em>Siderastrea savignyana</em>, <em>Psammocora supercilios</em> and <em>faviids</em> (e.g. <em>Favia laxa</em>, <em>Montastrea multipunctata</em>).</th>
<th>Coral reef limestone</th>
<th>Reef, shallow (&lt; 5 m), high energy, characteristic of windward margins, outer reef flat to upper reef slope</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assemblage B</strong></td>
<td>Dominated by encrusting <em>Montipora</em> sp. (e.g. <em>M. monasteriata</em>, <em>M. corbettiensis</em>, M. <em>cf. aquatuberculata</em>), and <em>Porites</em> sp. (e.g. <em>P. horizontata</em>) with associated <em>faviids</em> (<em>Montastrea salebraea</em>, <em>M. curta</em>, <em>Cyphastrea</em> sp., <em>Favia laxa</em>, and <em>Echinopora hirsutissima</em> or <em>E. gemmacea</em>), and <em>agariciids</em> (<em>Siderastridea savignyana</em>, <em>Pseudodiseraster tayamii</em> and <em>Psammocora</em> sp.).</td>
<td>Coral reef limestone</td>
<td>Reef, shallow (&lt; 10 m), low-moderate energy, upper reef slope</td>
</tr>
</tbody>
</table>

### Non-Geniculate Coralline Algal Assemblages Table

<table>
<thead>
<tr>
<th>Assemblage M</th>
<th>Dominated by well developed crusts of <em>Neogoniolithon fastei</em> and <em>Hydrolithon onkodes</em> and with associated <em>Lithophyllum</em> gr. <em>pustulatum</em>.</th>
<th>Coral reef limestone, interior crusts on some of the coralline-foraminiferal nodular limestone</th>
<th>Shallow (&lt; 10 - 15 m) reef environments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Melobesiod Assemblage (B)</strong></td>
<td>Dominated by thin crusts of <em>Mesophyllum</em> sp., with associated <em>Lithothamnion</em> sp., <em>Lithophyllum</em> sp., <em>Sporolithon</em> sp., and <em>Peysseuella</em> sp.</td>
<td>Coral reef-algal-foraminiferal crust limestone, coralline algal-foraminiferal nodular limestone</td>
<td>Non-reefal, deep water (~ 10-90 m)</td>
</tr>
</tbody>
</table>
more precisely from analysis of the coralgal growth forms and species composition.

We identified 32 coral genera and 73 species within the coral reef limestone (Table 1). Based on the coral composition and comparison with modern reef zonation and ecology in Papua New Guinea and other areas from the Indo-Pacific, we identified two main coral assemblages and their paleoenvironmental settings within coral reef limestone prior to drowning (Table 2).

Assemblage A is dominated by robust branches or ridges of Acropora palifera (Fig. 3A,B), the Acropora humilis group (Fig. 3C), Acropora grandis and the tabulate Acropora hyacinthus group with associated encrusting Montipora sp. (M. turgida, M. informis), submassive to massive Porites sp. (P. horizontalata, P. lobata) (Fig. 3D) and minor encrusting colonies of Siderastrea sa-
flat/upper reef slope environment, best developed on windward margins exposed to strong wave activity.

Assemblage B is dominated by encrusting *Montipora* (*M. monasteriata*, *M. corbettensis*, *M. aequituberculata*), and *Porites* sp. (*P. horizontala*) with associated faviids (*Montastrea salebrosa*, *M. curta*, *Cyphastrea* sp., *Favia laxa*, *Echinopora hirsutissima* or *E. gemmacea*) and agariciids (*Siderrastrea savignyana*, *Psammosiderastrea tayamata*, *Psammocora* sp.) (Fig. 4A–D). While the species assemblage is still indicative of shallow, perhaps upper-reef slope environments, this community probably developed in lower to moderate energy reef conditions, indicative of more sheltered margins, particularly when compared with assemblage A (Done, 1982; Veron, 1986; Montaggioni et al., 1997; Pandolfi and Minchin, 1995).

Significant nongeniculate coralline algal crusts are associated with the abundant coral framework within this facies (Fig. 4A). These crusts are dominated by mastophoroids such as *Neogoniolithon fosli* and *Hydrolithon onkodes* and associated *Lithophyllum* gr. *pustulatum*, and commonly occur as 2–5-mm crusts sandwiched between encrusting corals in assemblage B (Fig. 5A–C), and around branching corals. This same assemblage is common in shallow modern Indo-Pacific reefs (<15 m) from the Great Barrier Reef (Borowitzka and Larkum, 1986; Adey, 1986), Tahiti, New Caledonia, Ryukyus (Montaggioni et al., 1997; Cabioch et al., 1999; Iryu et al., 1995), and Papua New Guinea (Matsuda et al., 1994). Thus, this mastophoroid assemblage (M) is characteristic of shallow (∼<10–15 m) tropical reef environments.

Summarizing, the coralgal composition indicates that the coral reef limestone was deposited...
in a shallow reef flat to upper reef slope environment, in probably 0–10 m of water, but certainly less than 20 m.

### 3.1.2. Coralline algal–foraminiferal nodule limestone

This limestone is characterized by coral and minor mud fragments (up to 5 cm) encrusted by thin (0.2–4 mm) overlapping layers of non-geniculate coralline algae and encrusting acervulinid foraminifera (*Gypsina* or *Acervulina?* sp.). Commonly, the coral fragments forming the nodule nuclei are extensively micritized, bored and infilled with peloidal micrite and minor bioclasts such as large benthic foraminifera (*Amphistegina* sp.) and molluscs. Texturally, this limestone ranges from rudstones to floatstones (Fig. 6A,B), with abundant large benthic foraminifera, and minor contributions of *Halimeda* and mud making up the matrix.

The non-geniculate coralline algae forming the nodule crusts are dominated by a melobesiod assemblage (B), composed of thin crusts of *Mesophyllum* sp., with associated *Lithothamnion* sp., *Lithoporella* sp., *Sporolithon* sp., *Peyssonnelia* sp. and common acervulinids (Fig. 6B–D). Similar coralline assemblages exist on modern deepwater (*Ady, 1986*) platforms in the southern Great Barrier Reef and around Hawaii ranging from ~10 to 90 m, but these are commonly observed below 60 m (*Ady, 1979; Ady et al., 1982; Lund et al., 2000*). In the Gulf of Mexico, *Minnery et al. (1985*) described analogous foraminifera–algal nodules currently forming at 50–75 m, while *Reid and Macintyre (1988*) recorded a similar facies forming at 30–60 m in the eastern Caribbean. Furthermore, on Florida’s outer shelf similar encrusting foraminifera/coralline nodules have been observed at 35–56 m in quiet water conditions (*Prager and Ginsburg, 1989*).
Large benthic foraminifera characterized by *Amphistegina radiata*, *A. lessonii*, and *Heterostegina depressa* commonly comprise the bioclasts making up the matrix in this facies. Recent work on the distribution and ecology of large benthic foraminifera in the Indo-Pacific (Indonesia: Renema and Troelstra, 2001; Ryukyu Islands: Hohenegger, 1995; Hohenegger et al., 1999, 2000) suggest that this assemblage usually lives on deep fore-reef slopes or shallow shelves between ~20–50 m. While the coralline assemblages alone might suggest deep water conditions...
Fig. 7. (A) Coralline algal foraminiferal crust limestone characterized by alternating thin crusts of (B) non-geniculate algae dominated by the melobesioid assemblage (1), encrusting foraminifera (2), and micrite (3). (C) Associated with this facies are large benthic foraminifera such as *Cycloclypeus carpenteri* (1), encrusted here by a thin layer of *Mesophyllum* sp. (2). (D–G) Photomicrographs showing thin crusts of (D) *Mesophyllum* sp. (1), acervulinids (2), (E) *Lithoporella* sp., (F) *Lithothamnion* sp., and (G) *Peyssonnelia* sp. (1).
(perhaps below 60 m), their characteristic nodule morphology and large benthic foraminiferal composition indicate that this nodule limestone was deposited in a deep, fore-reef slope (∼20–60 m) setting.

3.1.3. Halimeda limestone

This limestone is characterized by abundant Halimeda segments (up to 1 cm), associated with large benthic foraminifera (A. radiate, A. lessonii, *Operculina* and *H. depressa*), molluscs and coral fragments floating within a matrix commonly composed of peloidal micrite (Fig. 6E,F). Texturally, this facies ranges from packstones to wackestones, and commonly grades into and is found at bathymetric levels similar to those of the coralline–foraminiferal nodule limestone.

Recent studies have shown that *Halimeda* can accumulate as significant deposits in shallow lagoons and on deeper shelves, e.g. the *Halimeda* banks in the Great Barrier Reef, east Java Sea and Nicaraguan Rise (Marshall and Davies, 1988; Roberts et al., 1988; Hine et al., 1988).

Coralline algal dominated nodules are also found on the tops of these banks in the east Java Sea and the Nicaraguan Rise (Hine et al., 1988; Phipps and Roberts, 1988). Because of its co-occurrence with the nodule limestone and the similar composition of benthic foraminifera, we conclude that the *Halimeda* limestone was deposited in a similar deep fore-reef slope (∼20–60 m) environment.

3.1.4. Coralline algal–foraminiferal crust limestone

This limestone is characterized by well developed coralline algal–foraminiferal bindstones (Fig. 7A). Morphologically, they form overlapping non-geniculate coralline crusts of thin encrusting thalli and minor warty plants growing one over the other (Fig. 7B). Sandwiched between these layers are encrusting acervulinid foraminifers and layers of micrite and minor encrusting corals (*Montipora* sp. and *Porites* sp.), bryozoans, large benthic foraminifera (*Palaeonummulites* sp., *Amphistegina* sp., *Cyclolyypeus carpenteri* and *Heterostegina operculinoides*) (Fig. 7C).

---

Fig. 8. (A) Photomicrograph of the planktonic foraminifera limestone composed of abundant planktonic foraminifera (1), delicate molluscs (2), smaller benthic foraminifera and minor terrigenous grains (e.g. quartz and rock fragments) (3). (B) Photomicrograph of associated large benthic foraminifera such as *Cyclolyypeus carpenteri* (1), and *Amphistegina radiata* (2). (C) Photomicrograph showing planktonic limestone filling a boring which cross cuts an encrusting acervulinid foraminifera (1).
Similar to the nodule limestone, the corallines as characterized by a melobesioid assemblage (B) composed primarily of *Mesophyllum* sp. and associated *Lithothamnion* sp., *Lithoporella* sp., *Sporolithon* sp., and *Peyssonnelia* sp. (Fig. 7D–G). The thin encrusting to warty morphology of the algae suggests a low to moderate energy and probably deeper environment for accretion (Bosence, 1983, 1985; Womersley, 1996). Almost identical algal frameworks form modern buildups in deeper fore-reef settings in the Great Barrier Reef in the Capricorns (60–90 m) (Lund, 1994) and off Fraser Island (90–110 m) (Marshall et al., 1998), off New Caledonia (60–80 m) (Rio et al., 1991, and the Gulf of Mexico (70–90 m) (Minnery et al., 1985). In these settings, the deep water, tropical–subtropical buildups form low-lying, meter-scale high, hummocky structures. Based on the similarities in structure, morphology and species composition, we suggest the coralline–foraminiferal crust limestone facies developed in a deeper fore-reef slope environment (~60–90 m).

3.1.5. Planktonic limestone

This facies is dominated by planktonic foraminifera (e.g. *Globoquadrina*), with delicate molluscs, small benthic foraminifera (*Textularia* sp.) and some large benthic foraminifera (*Amphistegina radiata*, *A. lessonii*, *Cycloclypeus carinerti*, and *Heterostegina depressed*) (Fig. 8A–C). Texturally, this facies occurs as mudstones to wackestones, and is commonly stained by Fe–Mn oxides with minor mud-sized terrigenous grains (e.g. quartz and rock fragments) (Fig. 8A,C).

This facies most commonly fills cavities created by bioerosion or as centimeter-scale caps on the top surfaces of other facies. Cross cutting (Fig. 8C) and superposition relationships clearly indicate that deposition occurred after the development of the other facies. In some cases, bioerosion (by clionid sponges and bivalves) and infilling by micrite and planktonic limestone is so intense that the original depositional texture of the rock can be completely obscured. This and the other facies are often capped by well developed Mn and Fe crusts, that range from thin (1 mm) to centimeter-scale bulbous crusts coating and commonly replacing much of the original depositional texture.

Although it is difficult to precisely define the paleobathymetry of this style of pelagic/hemipela-
<table>
<thead>
<tr>
<th>Platform depth</th>
<th>Platform morphology</th>
<th>Sample No.</th>
<th>Sample range</th>
<th>Sedimentary facies</th>
<th>Coral assemblages</th>
<th>Coralline algal assemblages</th>
<th>Paleoenvironmental settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>239 m</td>
<td>Single platform</td>
<td>16</td>
<td>239–300 m</td>
<td>Coraline algal-foraminiferal crust limestone</td>
<td>NA</td>
<td>Melobesioid (B)</td>
<td>Deeper fore-reef slope (build up) (~60–90 m)</td>
</tr>
<tr>
<td>625 m</td>
<td>Composite (1) platform with (2) multiple pinnacles</td>
<td>31</td>
<td>(1) 625–698 m</td>
<td>(1) Coraline algal-foraminiferal crust limestone</td>
<td>(1) NA</td>
<td>(1) Melobesioid (B)</td>
<td>(1) Deeper fore-reef slope (build up) (~60–90 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) 726 m</td>
<td>(2) Coral reef limestone</td>
<td>(2) Assemblage B?</td>
<td>(2) Mastophoroid (M)</td>
<td>(2) Reef, shallow (~ &lt; 10 m), low-moderate energy, upper reef slope</td>
</tr>
<tr>
<td>823 m</td>
<td>Composite platform showing two terrace levels</td>
<td>58</td>
<td>(1) 823–837 m</td>
<td>(1) Coral reef limestone</td>
<td>(1) Assemblage B</td>
<td>(1) Mastophoroid (M)</td>
<td>(1) Reef, shallow (~ &lt; 10 m), low-moderate energy, upper reef slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) 837–840 m</td>
<td>(2) Coraline algal-foraminiferal crust limestone</td>
<td>(2) NA</td>
<td>(2) Melobesioid (B)</td>
<td>(2) Deeper fore-reef slope (build up) (~60–90 m)</td>
</tr>
<tr>
<td>1113 m</td>
<td>Composite platform, with two terrace levels and multiple pinnacles</td>
<td>45</td>
<td>(1) 1130–1145 m</td>
<td>(1) Coral reef limestone</td>
<td>(1) Assemblage B</td>
<td>(1) Mastophoroid (M)</td>
<td>(1) Reef, shallow (~ &lt; 10 m), low-moderate energy, upper reef slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) 1137 m</td>
<td>(2) Coraline algal-foraminiferal nodule limestone</td>
<td>(2) NA</td>
<td>(2) Melobesioid (B)</td>
<td>(2) Deep fore-reef slope (~20–60 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) 1145–1174 m</td>
<td>(3) Coral reef limestone</td>
<td>(3) Assemblage B</td>
<td>(3) Mastophoroid (M)</td>
<td>(3) Reef, shallow (~ &lt; 10 m), low-moderate energy, upper reef slope</td>
</tr>
<tr>
<td>1216 m</td>
<td>Single platform with pinnacles</td>
<td>54</td>
<td>(1) 1216–1217 m</td>
<td>(1) Coraline algal-foraminiferal nodule limestone</td>
<td>(1) NA</td>
<td>(1) Melobesioid (B)</td>
<td>(1) Deep fore-reef slope (~20–60 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) 1218–1223 m</td>
<td>(2) <em>Halimeda</em> limestone</td>
<td>(2) NA</td>
<td>(2) NA</td>
<td>(2) Deep fore-reef slope (~20–60 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) 1264–1305 m</td>
<td>(3) Coral reef limestone</td>
<td>(3) Assemblage B</td>
<td>(2) Mastophoroid (M)</td>
<td>(3) Reef, shallow (~ &lt; 10 m), low-moderate energy, upper reef slope</td>
</tr>
<tr>
<td>1612 m</td>
<td>Single platform with pinnacles</td>
<td>47</td>
<td>(1) 1612–1682 m</td>
<td>(1) Coral reef limestone</td>
<td>(1) Assemblage B</td>
<td>(1) Mastophoroid (M)</td>
<td>(1) Reef, shallow (~ &lt; 10 m), low-moderate energy, upper reef slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2) 1623–1650 m</td>
<td>(2) Coraline algal-foraminiferal nodule limestone</td>
<td>(2) NA</td>
<td>(2) Melobesioid (B)</td>
<td>(2) Deep fore-reef slope (~20–60 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3) 1649–1682 m</td>
<td>(3) <em>Halimeda</em> limestone</td>
<td>(3) NA</td>
<td>(3) NA</td>
<td>(3) Deep fore-reef slope (~20–60 m)</td>
</tr>
<tr>
<td>1947 m</td>
<td>Composite platform, with two terrace levels</td>
<td>46</td>
<td>1947–1995 m</td>
<td>Coral reef limestone</td>
<td>Assemblage A</td>
<td>Mastophoroid (M)</td>
<td>Reef, shallow, (~ &lt; 5 m), high energy, outer reef flat to upper reef slope</td>
</tr>
</tbody>
</table>
The texture and compositions suggest deposition in non-reefal, deep open shelf settings (V ≤ 60 m). These five facies and their paleoenvironmental settings are summarized in Table 3. This table represents an idealized facies model fitting all the observed facies into a realistic paleoenvironmental scheme. It is from this framework that we describe and interpret the facies distribution and paleoenvironmental significance for each of the drowned carbonate platforms in the Huon Gulf, Papua New Guinea.

<table>
<thead>
<tr>
<th>Platform depth</th>
<th>Platform morphology</th>
<th>Sample No.</th>
<th>Sample range</th>
<th>Sedimentary facies</th>
<th>Coral assemblages</th>
<th>Coralline algal assemblages</th>
<th>Paleoenvironmental settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2121 m</td>
<td>Composite platform with two terrace levels and multiple pinnacles</td>
<td>39</td>
<td>2054–2076 m (pinnacle)</td>
<td>Coral reef limestone</td>
<td>Assemblage A</td>
<td>Mastophoroid (M)</td>
<td>Reef, shallow (&lt; 5 m), high energy, outer reef flat to upper reef slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2054–2076 m (pinnacle)</td>
<td>Coralline algal–foraminiferal nodule limestone</td>
<td>NA</td>
<td>Melobesioid (B)</td>
<td>Deep fore-reef slope (&lt; 20–60 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2124–2121 m (E platform)</td>
<td>Coral reef limestone</td>
<td>Assemblage A</td>
<td>Mastophoroid (M)</td>
<td>Reef, shallow (&lt; 5 m), high energy, characteristic of windward margins, outer reef flat to upper reef slope</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2121 m (platform)</td>
<td>Coralline algal–foraminiferal nodule limestone</td>
<td>NA</td>
<td>Melobesioid (B)</td>
<td>Deep fore-reef slope (&lt; 20–60 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2136–2173 m (W platform)</td>
<td>Coral reef limestone</td>
<td>Assemblage B</td>
<td>Mastophoroid (M)</td>
<td>Reef, shallow (&lt; 5 m), low–moderate energy, upper reef slope</td>
</tr>
<tr>
<td>2393 m</td>
<td>Pinnacle with two terrace levels</td>
<td>8</td>
<td>2393–2463 m</td>
<td>Coral reef limestone</td>
<td>Assemblage A</td>
<td>Mastophoroid (M)</td>
<td>Reef, shallow (&lt; 5 m), high energy, outer reef flat to upper reef slope</td>
</tr>
</tbody>
</table>

3.2. Platform composition, facies distribution and paleoenvironmental significance for each of the drowned platforms.
fore-reef slope environment (\(\sim 60-90\) m). Coral reef limestone facies composed of assemblage B corals (fragments of *Galaxea*, Mussidae, *Porites* sp. and *Leptoria phrygia*) and encrusted by a mastophoroid coralline crusts were recovered loose from the base of the pinnacle. Side scan images show well developed debris fields adjacent to and on the flanks of the steep pinnacles (Webster et al., 2002), indicating that the pinnacles represent a different phase of platform growth characterized by coral reef growing in shallow (\(\sim < 10\) m), low to moderate energy, upper reef slope settings.

### 3.2.1.3. The 823-m platform

Coral reef limestones are common near the top (823–840 m) of this platform. Assemblage B corals (encrusting *Montipora monasteriata*, *Porites lichen*, *Favites pentagona*, *Cyphastrea microphthalma*, tabulate *Acropora* sp.) and crusts of mastophoroid corallines (M) indicate that the top of this platform developed loose from the base of the pinnacle. Side scan images show well developed debris fields adjacent to and on the flanks of the steep pinnacles (Webster et al., 2002), indicating that the pinnacles represent a different phase of platform growth characterized by coral reef growing in shallow (\(\sim < 10\) m), low to moderate energy, upper reef slope settings. At almost the same bathymetric level, numerous samples of coralline–foraminiferal crust limestone (\(\sim 60-90\) m) were found, indicating platform deepening during a later phase of platform growth.

### 3.2.2. Middle platforms

#### 3.2.2.1. The 1113-m platform

This platform is dominated by coral reef limestone. Between 1135 and 1145 m in-situ assemblage B corals (encrusting *Montipora monasteriata*, *M. tuberculosa*, *Porites* sp. and minor *Pavona explanulata*, *Favites halicora*, *Stylocoeniella guentheri*, branching *Stylophora subseriata*, *Coscinaraea columna*; and tabulate *Acropora hyacinthus*) and mastophoroid coralline crusts dominate. This corallal assemblage indicates the top of the platform grew in shallow (\(\sim < 10\) m), low–moderate energy, upper reef slope conditions. Some coralline algal–foraminiferal nodule limestones were also recorded from the top of the platform (1137 m). Close examination of the nodules revealed an important sequence of non-geniculate coralline algal crusts (Fig. 6C). Typically, the inner crusts directly overlying the coral nuclei (Fig. 6C, 1) are composed of the shallow water, mastophoroid assemblage (*Neogoniolithon* sp.) (Fig. 6C, 2) while the outer layers are composed of the deep fore-reef slope (\(\sim 20–60\) m) melobesioids (*Sporolithon* sp., *Lithothamnion* sp., *Mesophyllum* sp., and *Lithophyllum gr. pustulatum*) (Fig. 6C, 3). This sequence implies either: (1) transport of shallow coral reef material to a deeper depositional site, or (2) deepening in place. From 1145 to 1174 m, allochthonous corals of the same taxonomic composition as the top of the platform were found.

#### 3.2.2.2. The 1217-m platform

The top of the platform, between 1216 and 1223 m, is composed of mixed *Halimeda* and coralline–foraminiferal nodule limestones. The composition of coralline algae (melobesioid assemblage) and benthic foraminifera indicates that they developed in a deep fore-reef slope (\(\sim 20–60\) m) environment. From 1264 to 1305 m, the platform is dominated by coral reef limestones composed of assemblage B corals (encrusting *Montipora monasteriata*, *M. corbettensis*, M. cf. *aequituberculata*, and encrusting *P. lichen* and submassive/massive *P. horizontalata*, *P. lobata*) with associated encrusting or foliaceous *Pavona varians*, *Pachyseris speciosa*, *Favia stelligera*?, *Favites pentagona*, and *Favites bes- tae*?), and well developed mastophoroid coralline crusts. This corallal assemblage indicates shallow (\(\sim < 10\) m), low–moderate energy, upper reef slope conditions. The occurrence of deep (\(\sim 20–60\) m), fore-reef slope environment facies bathymetrically above the coral limestone is consistent with platform deepening.

#### 3.2.2.3. The 1612-m platform

Coral reef limestone is common between 1612 and 1682 m and is characterized by assemblage B corals (encrusting *Montipora undata*? M. *cf. monastriata*, massive/encrusting *Porites* sp., submassive/encrusting *Montastrea salebrosa*?, *M. curta*?, *Cyphastrea*, *Favia laxa*, and *Echinopora hirsutissima*, *E. gemmacea* and *Siderastrea savignyana*, *Pseudosiderastrea tayamai*?, *Psammocora* sp.) and abundant mastophoroid coralline crusts (\(\sim < 10\) m). Mixed *Halimeda* and coralline algal–foraminiferal nodule limestones were also collected at similar bathymetric depths. Like the 1113-m platform, the inner crusts of these nodules are composed of the
shallow water, mastophoroid assemblage (Hydro-
lithon onkodes, Spongites sp.) while the outer
layers are composed of the deep fore-reef slope
(\(~\sim 20-60\) m) melobesioid assemblage and associ-
ated acervulinids. Again, this indicates either: (1)
the transport of shallow coral reef material to a
deeper depositional site, or (2) deepening in place.
The co-occurrence of the deep, fore-reef slope
(\(~\sim 20-60\) m) facies with shallow coral limestones
indicates platform deepening.

3.2.3. Deep water platforms

3.2.3.1. The 1947-m platform. This platform is
tightly dominated by coral reef limestone consist-
ing of assemblage A corals (e.g. robust branching
and ridge-like Acropora palifera, submassive/encrusted Montipora tuberculosa, with associated
massive and submassive Porites horizontalata,
Siderastrea savignyanana, Favia laxa?, Montastrea
multipunctata) and mastophoroid coralline crusts.
This coralgal community is typical of very shallow
(\(~\sim 5\) m), upper reef slope/reef crest environments
and is characteristic of windward margins. Nakamori et al. (1994a, 1995a, 1995b) observed a simi-
lar assemblage in the modern and uplifted Holoc-
cene and Pleistocene reefs of the Huon Peninsula
and considered this community to be indicative of
high energy, shallow (3-5 m), middle reef slope
environments.

3.2.3.2. The 2121-m platform. Sampling focused
on the platform and a single pinnacle above the
platform. The pinnacle (2054-2076 m) has both
coral reef limestones (assemblage A corals and
mastophoroid coralline algae assemblages) and
coralline algal-foraminiferal nodule limestones at
similar bathymetric levels. Therefore, the pinnacle
records the likely transition from shallow (\(~\sim 5\)

m), upper reef slope/reef crest to deep fore-reef
slope (\(~\sim 20-60\) m) environs.

Both the western and eastern parts of the plat-
form are dominated by coral reef limestone. How-
ever, analysis of the coral assemblages reveals im-
portant differences. The west platform (2136-2173
m) is composed of assemblage B corals (e.g. en-
crusting Montipora informis, Psammocora superfi-
cialis, Stylocoeniella guentheri, massive Porites
sp.) indicating a shallow (\(~\sim 0-10\) m), low-moder-
ate energy, upper reef slope environment. Side
scan imagery from the western part of the plat-
form suggests that it was probably sheltered lo-
cally by the seaward portion of the platform
(Webster et al., 2002). In contrast, the eastern
platform (2121-2124 m) is dominated by coral
assemblage A (robust branching/digitate Acropora
humilis group, tabulate Acropora hyacinthus
group, encrusting Montipora sp., massive Pavona
clavus? and Porites sp.) with associated mastoph-
oroind coralline crusts. This coralgal assemblage
suggests a shallow (\(~\sim < 3\) m), high energy envi-
ronment, characteristic of windward margins (e.g.
outer reef flat to upper reef slope) such as those
described by Nakamori et al. (1994b, 1995b).
Coralline algal-foraminiferal nodule limestones
were also recovered from the top of the eastern
platform (2121-2124 m). Examination of these
samples revealed a clear deepening sequence
(Fig. 10A-D). For example, coralline algal-fora-
miniferal nodule limestones with the concentric
layers of melobesioid coralline crusts (e.g. Mesos-
phyllum sp.) and acervulinids (Fig. 10B) grade
vertically into a 1-2-cm-thick mudstone composed
of peloids, larger benthic foraminifera (Amphiste-
gina sp.), mollusc and bryozoan fragments (Fig.
10C). The top of this sequence is marked by a
sharp boundary between peloidal mud and a thin
(1-cm) cap of planktonic foraminifera lime-
stone composed of Fe-Mn stained planktonic fora-
minifera, delicate mollusc and terrigenous
grains (Fig. 10D). The occurrence of the deep,
fore-reef slope (\(~\sim 20-60\) m) nodule facies on top
of the shallow coral limestones indicates platform
deepening and possible drowning. Furthermore,
the sharp boundary (Fig. 10D, 1) at the top of
the nodule limestone combined with the very dif-
frent nature of the sediments indicates a hiatus
between the deposition of the coralline algal-
foraminiferal nodule and the planktonic lime-
stone.

3.2.3.3. The 2393-m pinnacle. The few samples
collected from this deep pinnacle are composed of
coral reef limestone and are dominated by as-
semblage A corals (e.g. robust branching Acrop-
ora palifera, Acropora grandis, and massive Por-
ites sp.). This coralgal community is typical of shallow (<5 m), upper reef slope/reef crest environments, characteristic of windward margins, exposed to strong wave activity.

4. Discussion

The sedimentary and coralgal data indicate that the platforms record three main stages of development: (1) initiation and growth, characterized by shallow coral reef development as the platforms grew close to sea-level during sea-level lowstands, (2) incipient drowning marked by a shift to coralline algal–foraminiferal nodule, crust and Halimeda limestones as platforms began to drown during rapid eustatic sea-level rises and continued subsidence, and (3) the complete drowning of the platforms characterized by platform “turn off”, followed by increased bioerosion, Fe–Mn precipitation, and pelagic/hemipelagic sedimentation as the platforms finally drop below the photic zone. We discuss these stages of platform development and drowning, and their implications for climate change and tectonic subsidence in the Huon Gulf over the last ~450 ka.
4.1. Initiation and growth of the platforms

4.1.1. Platform initiation and growth

The development of carbonate platforms in foreland basins is controlled by the growth potential of the carbonate system (influenced by nutrients, salinity, temperature, sediment input, energy, etc.), accommodation space and relative sea-level fluctuations, which in turn are a function of tectonic subsidence and superimposed eustatic sea-level changes (Galewsky et al., 1996; Drobek, 1995). While we have no direct data detailing the initiation of the platform development in the Huon Gulf, numerical modeling by Wallace (2002) suggests that the platforms probably initiated growth as eustatic sea level stabilized sometime during the highstand phase of each major sea-level cycle. Depending on the relationship between the subsequent eustatic sea-level fall and rise during small interstadial events, subsidence rates and platform growth rates, the platforms may have experienced repeated short intervals of reef growth, subaerial exposure and platform drowning. This would have the effect of producing complex, stacked platform sequences with significant facies variations separated by drowning and subaerial exposure horizons. A separate paper modeling the internal structure and composition of each platform will be presented elsewhere. Ultimately, the only way to test these models is to collect high-resolution seismic data and then drill the platforms. Regardless of their internal configuration, by the time eustatic sea level fall stabilized during the major lowstands a thick sequence of carbonates had accumulated (100–200 m), the top of which is dominated by coral reef limestone.

4.1.2. Lowstand coral reef development and paleoenvironmental implications

This period of platform development is characterized by lowstand coral reef development. Over 73 species (Table 1) were recovered from these lowstand reefs, more than half of that reported from their highstand counterparts uplifted on the Huon Peninsula (Pandolﬁ, 1995). The Huon Gulf total, although lower, represents a diverse coral fauna given the extremely limited and random sampling strategy possible using an ROV. The coralgal assemblages (A and B) constrain fairly precisely the paleobathymetry of the coral reef dominated stage (Table 2). Based on comparison with modern reefs in Papua New Guinea and the Indo-Pacific, we conclude that the top of the platforms grew within 20 m of relative sea level. In fact, the data suggest that the shallow (823 m), middle platforms (1113, 1216, 1612 m) probably grew within 10 m of sea level, while the deeper platforms (1947, 2121, 2397 m) were within 5 m.

Accepting the ecological limitations of our data, we suggest that despite experiencing major environmental perturbations (e.g. rapid relative sea-level rise, drowning, subaerial exposure, seasurface temperature fluctuations) over the last 450 ka, reef growth in the Huon Gulf has been able to re-establish itself time and time again, producing thick (100–200 m) platforms, the tops of which are dominated by shallow coral assemblages similar to modern Indo-Pacific reefs. This ability of coral reefs to grow and re-establish themselves despite seemingly catastrophic events has been observed in the successive Pleistocene uplifted reefs from the Huon Peninsula, Barbados (Jackson, 1992; Pandolﬁ, 1995; Nakamori et al., 1994a) and more recently in a series of stacked reefs below the Great Barrier Reef (Webster and Davies, 2003).

The second major conclusion to emerge from this study is the clear difference in coral assemblages between the shallow, middle and deep platforms. The shallow and middle platforms are characterized by assemblage B corals (shallow, low to moderate energy conditions) while the deep platforms are dominated by assemblage A corals (shallow, very high energy conditions). Although little is known about modern fringing reefs along the Morobe coastline, the present oceanographic conditions are not consistent with a very high energy, windward margin (von der Borch, 1972; McAlpine et al., 1983). A likely modern analogue for this style of high energy reef growth occurs on the north coast of Papua New Guinea at Madang and the Huon Peninsula. For example, the exposed outer reefs of the Madang Lagoon and the reefs fringing the Huon Peninsula are composed of very similar coral assemblages to the assemblage A corals we recov-
ered from the deep platforms in the Huon Gulf (Pandolfi and Minchin, 1995; Nakamori et al., 1994b). Forming the eastern extension of modern reefs on the Morobe coastline, the more exposed Trobriand platform in the Solomon Sea (Fig. 1A) is another possible analogue for modern high energy reef growth. This platform forms a broad shallow (<100 m) area rimmed by carbonate reefs; it is relatively stable recording only minor subsidence (von der Borch, 1972).

Summarizing, the fossil coral data suggest that paleoenvironmental conditions have changed substantially in the Huon Gulf over the past ~450 ka, with a shift from high energy conditions, characteristic of windward reef margins to lower more moderate energy reef conditions ~350–300 ka. How can we explain this apparent oceanographic change? We propose two different possible mechanisms: (1) closure of the Huon Gulf due to the rotation and uplift of the Huon Peninsula, and/or (2) variation in more regional factors such as the position of the Intertropical Convergence Zone.

Fig. 11. (A). Position of the Papua New Guinea paleo-shoreline, trench and reef growth at 450 ka (green line) relative to their modern positions (gray lines). (B–F) These data in 100-ka time slices along with likely wind and wave vectors from the NW, NE and SE. These figures were constructed by rotating the South Bismarck plate (upper plate) relative to the Australian plate (lower plate) which is held fixed here about a well known pole of rotation between the two plates (After Wallace, 2002). For each figure the position of the modern coastline is shown as a light gray line.
4.1.3. Tectonic closure of the Huon Gulf

Recent tectonic reconstructions of the last 450 ka of vertical and lateral plate motions in the Huon Gulf (Wallace, 2002) provide some clues to explaining the change in coral assemblage patterns. Fig. 11A shows the likely position of the Huon Gulf shoreline 450 ka accounting for the rotation and uplift of the Huon Peninsula as the South Bismarck plate collides with and overrides the Australian plate (Abbott et al., 1994; Wallace, 2002). We speculate that oceanographic conditions in the Gulf were considerably different at this time as a result of this past shoreline configuration. Further, continued tectonic reorganization over the last 450 ka has acted to close or narrow the Huon Gulf, causing a significant shift in oceanographic conditions. This process is illustrated in a series of expanded diagrams showing the likely position of the present and paleo-coastlines, trench, reef and likely wind/wave vectors influencing reef development at 450-ka, 350-ka, 250-ka, 150-ka, and 0-ka time steps (Fig. 11B–F).

4.1.3.1. 450–350 ka. The situation of the Huon Gulf area in this period is illustrated in Fig. 11B,C. Its shoreline configuration was considerably different 450 ka ago. Our best estimates suggest that the SE coastline of the Huon Peninsula was 40–50 km farther NW than its current position. Furthermore, given the average published uplift rates (∼ 2 m/ky; Chappell et al., 1996; Abbott et al., 1994), the Huon Peninsula was ∼ 1 km lower in elevation. The different shoreline and lower elevation would have opened the Huon Gulf to substantially more wind and wave energy, from the N, NE and NW during the monsoon season. In this more open oceanographic setting, coral reefs in the Huon Gulf would have experienced the higher energy conditions, characteristic of windward margins (assemblage A) that appear to be recorded in the deeper pinnacles and platforms (2397 and 2121 m). Plate motion continued over the next 100 ka without much modification of oceanographic conditions, so that the 1947-m platform is also characterized by high energy reef growth.

4.1.3.2. 250, 150 and 0 ka. The situation of the Huon Gulf area at these time steps is illustrated in Fig. 11D–F. By 250 ka, the continued uplift and rotation of the Huon Peninsula had narrowed the Huon Gulf considerably. This caused a major shift in oceanographic conditions towards the more sheltered (from NW, N and NE directions), lower energy settings characterized by the assemblage B corals which dominate the middle and shallow platforms (1650, 1212, 1113, and 823 m). The period between 350 and 300 ka may represent an important oceanographic threshold in the Huon Gulf, because it is from this time that assemblage B corals (lower energy) have dominated the tops of the platforms. Since the Huon coastline approached its current configuration, the Gulf has experienced only low to moderate energy conditions, particularly when compared with the more exposed conditions of the Madang, northern Huon Peninsula, and Trobriand platform reefs.

4.1.4. Regional changes in climat/oceanography over the last ~450 ka

We favor tectonic closure because it is a more direct mechanism for changing oceanographic conditions in the Huon Gulf. However, we cannot completely rule out the influence of more regional variations in climate, such as shifts in the ITCZ or changes in the intensity and magnitude of lowstands. The ITCZ is a major feature affecting atmospheric circulation in the Pacific Ocean. It represents the near-equatorial region where air masses from the Northern and Southern hemispheres meet. Studies in the equatorial Pacific by Rea (1994) recorded variations in the accumulation rate and grain size of aeolian dust. Over Cenozoic time scales, these variations are thought to reflect changing climate regimes (i.e. trade winds) associated with shifts in the latitudinal position of the ITCZ. Recent results from the eastern equatorial Pacific indicate that over smaller time scales the position of the ITCZ shifts a few degrees further south during the glacials and retreats north during the interglacials (Rea, pers. commun.). Although the ITCZ is less distinct in the western Pacific, we speculate that variations in how far it shifts south during the glacial periods might influ-
ence winds and/or the distribution and frequency of storms in the Huon Gulf. While there is no direct evidence of this happening in the western Pacific, there are strong indications of a major change in the climate regime of the equatorial Pacific \( \sim 300 \text{ ka} \) (i.e. mid-Brunhes climate event) (Chuey et al., 1987; Pisias and Rea, 1988; Rea, 1994). Several paleoclimate proxies (e.g. eolian grain size) indicate increased amplitude variations from 850–300 ka, characterized by increased wind intensities when compared with period 300–0 ka (Pisias and Rea, 1988).

Long-term oxygen isotopic records from the western equatorial Pacific (Ontong Java) indicate that the intensity and magnitude of the lowstands has varied over the last 450 ka (Lea et al., in press). Recent Mg/Ca paleothermometry from the same location indicates that the SST values for marine isotope stages (MIS) 12 and 10 are significantly lower than those for MIS 8, 6, 4, and 2 (Lea et al., in press). These data provide additional evidence of a major shift in climate mode \( \sim 300–350 \text{ ky} \). In this case the Mg/Ca data indicate more intense lowstands before \( \sim 300–350 \text{ ka} \) (Lea et al., in press). It is possible that any change in lowstand conditions (e.g. SST) could have had a corresponding impact on regional climate/oceanographic conditions. Given that the tops of platforms probably grew mainly during lowstands, reef growth could have been influenced by climate variations between the different lowstand oceanographic conditions before and after \( \sim 350 \text{ ka} \) in the Huon Gulf.

Effects of such regional mechanisms would probably be enhanced by the tectonically more open Huon Gulf of the past, and it is entirely possible that these three main factors (tectonics, position of the ITCZ and the lowstand climate conditions) acted in concert to influence coral reef growth in the Gulf over the last 450 ka.

4.2. Incipient platform drowning

4.2.1. Sedimentary and coralgal signatures of platform drowning

The sedimentary and coralgal data from the tops of the platforms provide compelling evidence of incipient platform drowning in response to rapid eustatic sea-level rise and subsidence. Platform growth switches from a coral reef dominated stage (0–20 m) to a deeper fore-reef stage (20–90 m) characterized by coralline algal–foraminiferal nodule, crust and Halimeda limestones. Examining the data (Table 3), two main facies patterns emerge: (1) the coral reef limestones on deep and middle platforms are capped by a thin veneer of coralline algal–foraminiferal nodule and Halimeda limestones, and (2) the shallow platforms are capped with significant buildups of coralline algal–foraminiferal crust limestone. Based on the slow vertical accretion rates of crustose coralline algae frameworks (\( \sim 0.04 \text{ mm/yr} \); Reid and Macintyre, 1988; Bosence, 1983; Lund, 1994), it is very unlikely that the entire platform structure (i.e. 100–200 m) thickness was built entirely of this facies. We suggest that the coralline algal–foraminiferal crust limestone to be a well developed buildup over the drowned coral reef limestone and perhaps over a thin veneer of coralline algal–foraminiferal nodule and Halimeda limestones.

Based on the facies composition and distribution, we identified two incipient drowning scenarios perhaps controlled by the rate of relative sea-level rise. Furthermore, we speculate that the difference in subsidence rates between the deep and shallow parts of the margin may influence the incipient drowning signatures.

4.2.2. Incipient drowning – rapid relative sea-level rise

An average subsidence rate of 5.7 m/ky has been estimated for the 1947-m platform (Galewsky et al., 1996). After taking the flexural history of the margin into account, Wallace (2002) estimated that instantaneous subsidence rate, the rate experienced by the platform during the growth and incipient platform drowning, to be \( \sim 4 \text{ m/ky} \). For the deeper and middle platforms we speculate that rapid eustatic sea-level rise combined with rapid subsidence acted to quickly drown the shallow coral reef limestone. The resulting uneven and perhaps partially un lithified reef surface was probably re-worked. In this deep, fore-reef setting (20–60 m), a thin and patchy cover of coralline algal–foraminiferal nodule and Halimeda limestones developed (Fig. 6). The presence of
thin shallow water, mastophoroid coralline crusts around coral fragments, which are in turn overlain by crusts of deep water melobesioid corallines, may be direct evidence for such rapid drowning.

4.2.3. Incipient drowning – slow relative sea-level rise

For the shallowest platforms we speculate that the slower subsidence rates experienced by this part of the margin might play a role in the dominance of the coralline algal–foraminiferal limestone on the tops of these platforms. The 239-m platform has been dated at 60.3 ka ± 0.5 when, according to recent reconstructions, eustatic sea-level was ~51 m below the present day level (Lambeck and Chappell, 2001). On base of this evidence combined with new paleobathymetric constraints on platform depth (60–90 m) we estimate an average subsidence rate of between 1.6–2.1 m/ky for this platform. The instantaneous rate accounting for flexural subsidence is probably similar given the shorter time frame (e.g. ~60 ka as opposed to 348 ka for the 1947-m platform) (Wallace, 2002). In this scenario, after initial drowning of the coral reef, the platform surface remained within this deep to deeper, fore-reef setting (20–90 m) longer than the middle and deep platforms, assuming eustatic sea-level rise and the growth potential of the platforms were similar. As a result, significant deep water coralline algal–foraminiferal buildups had time to develop (Fig. 7). Similar coralline algal–foraminiferal crust facies are observed on the 150-m reef around Hawaii, and developed after the drowning of the coral reef during the last deglaciation (Webster et al., 2004).

4.3. Complete platform drowning

With continued eustatic sea-level rise and subsidence, the platform surface finally sinks below the photic zone of intensive carbonate production. Beneath this depth (>90–120 m) bioerosion, Fe–Mn precipitation and pelagic/hemipelagic sedimentary processes dominate.

4.3.1. Bioerosion

Multiple phases of sponge, worm and mollusc boring were present in many samples. Although the cross cutting relationships are complex, we recognize two stages: (1) pre-platform drowning bioerosion, and (2) incipient and post drowning bioerosion. The coral reef limestone contains clear evidence of syndepositional boring. For example, complete specimens of the boring bivalves Lithophaga? sp. (Fig. 4C) can still be seen within their cavities, and likely formed in shallow reef environments (Perry, 1998). Furthermore, numerous borings in this stage of bioerosion are filled with micrite and associated coral and mollusc fragments but lack planktonic foraminifera. With the development of the deeper non-reefal facies (coralline algal–foraminiferal nodule, crust and Halimeda limestone) boring is extensive, with multiple cross cutting infills (Fig. 8C). After the platforms drowned completely bioerosion continues and perhaps dominates. Planktonic limestone commonly fills the borings, in some cases with associated large benthic foraminifera (Cycloclypeus carpenteri). The bathymetric range of C. carpenteri in the Pacific is 60–120 m (Iryu et al., 1995; Hohenegger et al., 2000), constraining at least some of these infills to those depths. However, most of these infills are composed of planktonic foraminifera, smaller benthic foraminifera and delicate molluscs, all of which probably continued to accumulate as the platforms subsided to their current depths. Unlithified olive green pelagic muds routinely fill cavities in samples from all platform depths, providing evidence of continued pelagic sedimentation.

4.3.2. Iron–manganese coatings

Thick Fe–Mn crusts (few cm) are common on the outer surfaces and on surfaces buried within cavities of many limestone samples from the Huon Gulf. The timing, chemistry, growth rate and depth at which these crusts develop depend on a range of factors (e.g. exposure time, ocean chemistry) (Hein et al., 2000). James and Ginsburg (1979) observed that Fe–Mn crusts on limestones recovered from the fore-reef slope off the Belize barrier reef system occurred below 40 m. Further, they considered that Mn coatings were more common in the deeper reaches of the margin, below ~150 m. Camoin et al., 1998 recov-
ered similar crusts (phosphate–Mn) from drowned atolls in the NW Pacific. They considered these crusts probably formed as the guyot dropped below the photic zone (>100 m). Therefore, it is likely that the Fe–Mn crusts covering the submerged platforms in the Huon Gulf began to precipitate from around 100 m, after the complete drowning of the platform.

Eventually the platform surface is also colonized by diverse living or recently dead deep (≥120 m) water communities of ahermatypic corals (*Madrepora arbuscula*), bryozoans, sponges, echinoderms, molluscs and anemones. In summary, the combined affects of significant bioerosion, infilling and Fe-Mn precipitation probably intensifies following the lowering of the platforms below the photic zone (∼100–120 m). These processes continue as the platforms reach their current bathymetric levels, sometimes so intense that the original depositional texture of the carbonate material is completely destroyed.

4.4. Model of platform development and drowning

Summarizing all available data we now propose a general model of platform development and drowning. The model illustrates the development and drowning of a single platform, during an idealized 100-ky eustatic sea-level cycle and the likely sedimentary and coralgal responses (Fig. 12).

4.4.1. Stage 1 – Initiation and growth of the platform

The platform initiates growth sometime during the highstand and continues through to lowstand. Depending on rates of eustatic sea-level change, subsidence and platform growth, the platform potentially experiences short intervals of subaerial exposure and platform drowning. This has the affect of producing a complex, stacked platform sequence with significant facies variations and subaerial exposure horizons (dashed green line on Fig. 12). Eventually, eustatic sea-level fall stabilized during the lowstand period, having produced a thick sequence of carbonates, the top of which is dominated by shallow water coral reef limestone.

4.4.2. Stage 2 – Incipient platform drowning

Rapid eustatic sea-level rise during the first part of the transgression drowns the coral reef stage of platform growth. Depending on the rate of relative sea-level rise (eustatic sea-level rise and subsidence) two different signatures of platform deepening and incipient drowning develop (Fig. 12, 2a,b). In the deep fore-reef slope environment (20–60 m), coralline algal–foraminiferal nodule and *Halimeda* limestones develop as patchy veneer on top of the drowned coral reef surface on the middle and deep platforms. The shallower platforms experience slower rates of relative sea-level rise (e.g. subsidence rate is less than half the rate in the deeper platforms), and under these conditions significant coralline algal–foraminiferal crust limestones develop (∼60–90 m) (Fig. 8).

4.4.3. Stage 3 – Complete platform

Subsidence and transgression continue, finally lowering the platform surface below the photic zone (90–120 m). All significant platform production turns off and the platform drowns completely. Now erosional and diagenetic processes dominate with multiple phases of boring/infilling and minor planktonic foraminiferal limestone deposited in the infills and as thin caps. Significant Fe–Mn crusts develop along with a diverse living or recently dead deep (>120 m) water communities (e.g. ahermatypic corals, worms, bryozoans, sponges, echinoderms and molluscs). Subsidence continues until the platforms reach their current depth.

5. Summary and conclusions

The drowned platforms in the Huon Gulf record a detailed history of carbonate platform growth, drowning and backstepping in response to the combined affects of rapid subsidence and eustatic sea-level change. Based on a detailed examination of sedimentary, coralgal and paleoenvironmental data we draw the following conclusions:

(1) The drowned platforms record five main sedimentary facies: coral reef, coralline algal–foraminiferal nodule, coralline algal–foraminiferal
**Fig. 12. Summary model showing development and drowning of an idealized platform in the Huon Gulf. Eustatic sea-level curve represents an idealized 100-ka sea-level cycle with the platform growth period shown as a green line. The red circle is the possible timing of each stage of platform drowning. See Fig. 9 for explanation of sedimentary facies symbols.**

<table>
<thead>
<tr>
<th>Platform development stage</th>
<th>Idealized eustatic sea-level</th>
<th>Sedimentary and coralal response</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Initiation and growth, coral reef dominated</td>
<td><img src="image" alt="Diagram" /></td>
<td>* Coral reef limestone dominates, shallow (0-10 m), reef flat to upper reef slope conditions prevail.</td>
</tr>
</tbody>
</table>
| (2a) Incipient drowning - rapid | ![Diagram](image) | * Combination of transgression and subsidence and rapidly drowns the coral reef.  
* Coralline algal-foraminiferal nodule limestone with minor Halimeda limestone develops in this deep (20-60 m) fore-reef slope environment.  
* Bioerosion common with minor infilling of borings with planktonic foraminiferal limestone. |
| (2b) Incipient drowning - slow | ![Diagram](image) | * Coral reef or nodule limestone also drowns but relative sea-level rise is slow enough (influenced by slower subsidence?) that a coralline algal-foraminiferal crust limestone is deposited. This algal buildup develops in a deeper (60-90 m) fore-reef slope environment.  
* Bioerosion common with minor infilling of borings with planktonic foraminiferal limestone. |
| (3) Complete drowning stage | ![Diagram](image) | * Platform drowns completely as transgression and subsidence continues and paleowater depths exceeds the photic zone (90-120 m).  
* Bioerosion dominates with multiple phases of boring and infilling preserved.  
* Planktonic foraminiferal limestone continues, with deposition occurring as infills and thin caps. In some cases terrigenous particles are present.  
* Thick Mn-Fe crusts develop along with living or recently dead deep (>120 m) water communities (e.g. ahermatypic corals, worms, bryozoans, sponges, echinoderms and molluscs). |
crust, *Halimeda*, and planktonic foraminiferal limestones. They represent a range of paleoenvironments from reef, deep fore-reef slope, deeper fore-reef slope and pelagic/hemipelagic settings.

(2) The tops of the platforms are characterized by coral reef limestones that formed during lowstands and grew within ~10 m of sea level.

(3) Despite major environmental perturbations (e.g. relative sea-level and temperature changes), the platforms and the shallow water coral reefs exposed at the top have been able to re-establish themselves time and time again over the last 450 ka.

(4) Variation in coral assemblages between the platforms indicates that the oceanographic conditions in the Huon Gulf have changed over the last 450 ka from very high energy conditions, characteristic of windward margins (assemblage A), to lower, more moderate energy conditions (assemblage B), indicative of more sheltered margins. This is due to tectonic closure of the Huon Gulf related to the rotation and uplift of the Huon Peninsula with possible amplification as a result of variations in more regional oceanographic/climate factors.

(5) The platforms record clear signatures of incipient platform drowning, caused by eustatic sea-level rises associated with deglaciation and continued subsidence. We identified two different incipient drowning scenarios, perhaps influenced by the differing subsidence rates across the margin. More rapid relative sea-level rise in the middle and deep platforms produced a thin veneer of coralline algal–foraminiferal nodule and *Halimeda* limestones over shallow coral reef material, while the slower rates of the shallowest platforms allowed thick buildups of coralline algal–foraminiferal crust limestone to develop.

(6) Finally, we identified three main stages of platform development: (1) initiation and growth characterized by shallow coral reef growth as the platforms grew close to sea level during the lowstands, (2) incipient drowning marked by a shift to coralline algal–foraminiferal nodule, crust and *Halimeda* limestones as the platforms began to drown during rapid eustatic sea-level rise and continued subsidence, and (3) the complete drowning of the platforms characterized by platform ‘turn off’, followed by increased bioerosion, Fe–Mn precipitation and pelagic/hemipelagic sedimentation as the platforms finally drop below the photic zone.

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