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Coral variation in two deep drill cores: significance for the Pleistocene development of the Great Barrier Reef

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Abstract

Variations in lithology and coral assemblages in drill cores from outer- and inner-shelf reefs are used to characterize the Pleistocene development of the Great Barrier Reef. Based on petrographic, isotopic and seismic characteristics, the outer-shelf core from Ribbon Reef 5 is divided into three sections: (1) a main reef section from 0 to 96 m is composed of six reef units, (2) a rhodolith section from 96 to 158 m is interbedded with two thin reef units and (3) a basal section from 158 to 210 m is composed of non-reefal skeletal grainstones and packstones. Two distinct coral assemblages identified in this core represent a shallow, high-energy community and lower-energy community. These two assemblages are repeated throughout the main reef section, with some units recording transitions between assemblages, and others composed of only a single assemblage. These coral assemblage data also correlate with transitions recorded by coralline algae. Using similar criteria, the inner-shelf core from Boulder Reef is divided into two sections: (1) an upper carbonate-dominated section from 0 to 34 m is comprised of four reef units and (2) an underlying mud section from 34 to 86 m is composed of siliciclastics and two thin, coral-bearing units. The four reef units in the upper section are dominated by a single coral assemblage representing a community typical of low energy, turbid environments. Taken together, these data indicate that: (1) reef growth on the inner shelf initiated later than on the outer shelf, (2) true reef 'turn-on' in outer shelf areas, as represented by the main reef section in Ribbon Reef 5, was preceded by a transitional period of intermittent reef development and (3) the repeated occurrence of similar coral assemblages in both drill cores indicates that the Great Barrier Reef has been able to re-establish itself, repeatedly producing reefs of similar composition over the last 500 ky, despite major environmental fluctuations in sea level and perhaps temperature.

Keywords: Great Barrier Reef; Coral assemblages; Coralline algae; Paleoenvironment; Pleistocene reef development

1. Introduction

Over the last 30 years, significant progress has been made in understanding reef development in response to changes in Pleistocene climate and sea-level through extensive investigations of carbonate sequences on active margins such as Barbados, Huon Peninsula and the Ryukyus. Similarly, reef development on passive continental margins has been the focus of extensive study, especially during the 1970s and 1980s (e.g. Davies et al., 1988; Macintyre, 1988). These were the decades of intensive reef drilling, however in most cases, the primary aim of drilling

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on such margins was to understand the development of Holocene reefs.

Passive margin drilling has been largely concentrated in the Caribbean (Adey, Macintyre and co-workers) and the Great Barrier Reef (Davies, Hopley and co-workers). Such studies however were restricted to an examination of shallow variations in Holocene reef composition and geometries with respect to eustatic Holocene sea-level (Macintyre and Glynn, 1976; Macintyre, 1988; Marshall and Davies, 1982; Davies and Hopley, 1983; Davies et al., 1985). In both these regions, the deeper Pleistocene substrate was usually

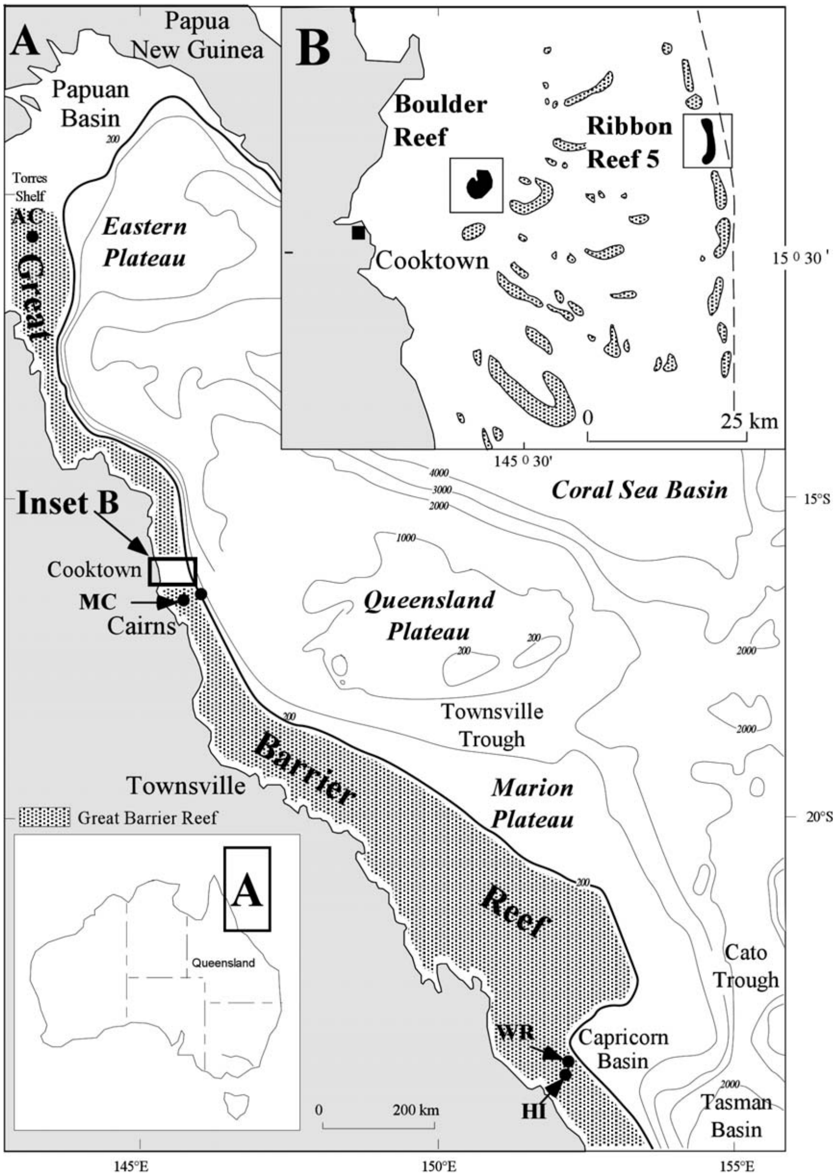

Fig. 1. (A) The position of the GBR relative to the bathymetry and main physiographic features of northeast Australia. Marked are the positions of four holes previously drilled at Anchor Cay (AC), Michaelmas Cay (MC),Wreck Reef (WR) and Heron Island (HI). (B) The shelf in the vicinity of Cooktown, and the positions of Ribbon Reef 5 and Boulder Reef.

not penetrated beyond a few metres because the equipment used was not appropriate for deep drilling.

Previously, the only deep drilling in the Great Barrier Reef was focused on Anchor Cay, Michaelmas Cay, Heron Island and Wreck Reef (Richards and Hill, 1942; Maxwell, 1962; Lloyd, 1968) (Fig. 1A). These studies described the basic stratigraphy, lithology and diagenetic features of pre-Holocene reef deposits. A reinterpretation of these data published by Davies et al. (1989) found that bore holes on Michaelmas Cay, Heron and Wreck had a remarkably similar stratigraphy, with 100–150-m-thick Plio–Pleistocene reef limestones overlying a thinner sequence of foraminiferal limestone and siliciclastics or mixed siliciclastics and carbonates. A major problem with these data and subsequent interpretations, however, was the poor recovery and lack of age control. As a consequence, little is still known about the Pleistocene development of the Great Barrier Reef.

To resolve these problems, two new holes were cored in the northern Great Barrier Reef by the International Consortium for Great Barrier Reef Drilling (2001), one from an inner shelf reef, Boulder Reef, and the other from an outer-shelf reef, Ribbon Reef 5 (Fig. 1A,B). This study described initial results on basic stratigraphy and lithology and confirmed for the first time that the Great Barrier Reef is a relatively young feature. A combination of Sr isotope, paleomagnetic and spin-resonance dating (ESR) indicated an age of 320–780 ky and $< 210 + 40$ ky for the onset of reef growth on the outer and inner shelf, respectively.

Here we present further data from Ribbon Reef 5 and Boulder Reef cores, and provide a detailed analysis of Pleistocene coral assemblages during the development of the Great Barrier Reef. Our objectives are to: (1) document the coral assemblages at the two sites, (2) reconstruct their paleoenvironmental setting, (3) compare these findings with the coralline algal data documented by Braga and Aguirre (1997), (4) define the paleoenvironmental variation through the Pleistocene and (5) discuss the implications of this faunal record for the initiation and growth of the Great Barrier Reef.

2. Location and methods

Ribbon Reef 5 and Boulder Reef are two reefs located in the northern Great Barrier Reef (Fig. 1A). Ribbon Reef 5 is a linear reef forming part of the outer barrier, located 49-km east of Cooktown on the shelf edge (Fig. 1B). It is 6 km long and 1 km wide, and is typical of the high-energy reefs forming the outer barrier of the Great Barrier Reef. Boulder Reef is a flat-topped platform reef about 5-km east of Cooktown on the inner shelf (Fig. 1B) and is 3.5 km long and 2.5 km wide. These reefs were chosen as the sites for deep drilling for several reasons: (1) they represent contrasting inner and outer shelf environments, (2) the Holocene reef at both sites has been studied previously (Davies and Hopley, 1983; Davies et al., 1985) and (3) they continue a transect started by the ODP program (Leg 133) and thus form a framework for understanding Pleistocene reef development. The deep drilling for this study was carried out in 1995 using a wire line Mobile drill rig, mounted on a jack-up platform. Both the Ribbon Reef 5 and Boulder Reef cores were situated on the leeward reef flat in ~ 2 m of water. At both sites, drilling continued until the reef section had been completely penetrated. The core at Ribbon Reef 5 was drilled to a depth of 210 m and at Boulder Reef to a depth of 86 m. Recoveries at Boulder Reef averaged 46% while Ribbon Reef 5 averaged 76%, although recoveries of 95% were common in the lower half of the section. Laboratory studies involved slabbing the cores and describing lithological variations and identifying corals. We followed standard stratigraphic procedure and, based on major lithogic and faunal changes, we defined major stratigraphic sections in each core. Based on all available relative age criteria such petrographic, seismic, log and isotopic data (Davies and Hopley, 1983; Davies et al., 1985; Andres, 1997; International Consortium for Great Barrier Reef Drilling, 2001), the coral-bearing sections were subdivided further into a series of reef units. These reef units are in turn characterized on the basis of sedimentary facies and coral and coralline algal composition. Taxonomic identification of corals is based on Veron and Pichon (1976, 1979, 1982), Veron and Wallace (1984), Veron (1986) and Veron et al. (1977). Due to the severe effects of diagenesis in some parts of the core and the difficulties inherent in identifying corals to species level in drill cores, it was necessary to place the corals into more broadly defined groups (Crame, 1980) based on closely related species and growth forms (Table 1). A combination of criteria was used to

Table 1
Coral species and groups identified in the Ribbon Reef 5 and Boulder Reef cores

Family ACROPORIDAE	Family MERULINIDAE
Acropora sp. group 1—*Acropora* sp., *Acropora humilis* group (i.e. *A. monticulosa*)*	*Hydnophora exesa*
Acropora sp. group 2—*A. robusta*, *A. danai*?, *A. palmerae*	Family MILLEPORIDAE
Acropora palifera	*Millepora exaesa*
Acropora sp. group 4—delicate branching forms (horrida group)	Family MUSSIDAE
Montipora sp. group 1—?	
Family AGARIIDAE	*Lobophyllia* sp. group 1—*L. corymbose Symphyllia* sp.
Pavona sp. group 1—*P. varians*, *venosa*, and *minuta*?*	Family OCULINIDAE
Pachyseris speciosa	*Galaxea fascicularis*
Pachyseris rugosa	*Galaxea astreata*?*
Family CARYOPHYLLIDAE	Family POCILLOPORIDAE
Euphyllia glabrescens	*Pocillopora* sp. group 1—*P. verrucosa**
	Pocillopora sp. group 2—*P. woodjonesi, P. eydouxi*
Family FAVIIDAE	*Seriatopora hystrix*?* *Stylophora pistillata**
Cyphastrea sp. group 1—*C. microphthalma**, *C. seralia Goniastrea* sp. group 1—*G. retiformis, G. edwardsi*	Family PORITIDAE
Echinopora sp. group 1—*E. pacificus*, *Echinopora lamellosa*?, *E. gemmacea*?, *E. hirsutissima*?*	*Goniopora* sp. * *Porites* sp. group 1—*P. lutea, P. lobata*
*Echinopora mammiformis**,	*P. australiensis**
Favia pallida	*Porites* sp. group 2—*P. lichen*?
Favites sp. group 1—*F. flexuosa*	*Porites* sp. group 3. *P. cf cylindrica**
Favites sp. group 2—*F. chinensis Leptoria phygia*	*Porites* sp. group 4—*P. murrayensis*?
Leptastrea sp. group 1—*L. purpurea*?, *L. transversa Montastrea* sp. group 1—*M. curta*	Family SIDERASTRIDAE
Montastrea sp. group 2—*M. valenciennesi Platygyra* sp. group 1—*P. daedalea*	*Coscinraea* sp.
Platygyra sp. group 2—*P. ryukyuensis*, *P. sinensis*?	Family TUBIPORA
P. verispora	*Tubipora musica*
Family FUNGIIDAE	
Fungia spp.	

Note the asterisk indicates the corals types found in Boulder Reef as well as in the Ribbon Reef 5 core.

distinguish in situ coral colonies from coral rubble larger than the core diameter; (1) lack severe surface abrasion and rounding; (2) upward orientation of well-preserved corallites; (3) upward orientation of acroporid and pocilloporid branches; and (4) coral colonies or branches capped by centimeter-thick coralline algal crusts.

3. Results

3.1. Coral assemblages and paleoenvironmental interpretation

Twenty coral genera and around fifty-five species were identified from the Ribbon Reef 5 and Boulder Reef cores (Table 1). Based on this coral composition and comparison with modern reef zonation and ecology in the Indo–Pacific (Done, 1982; Davies and Montaggioni, 1985; Pirazzoli and Montaggioni, 1988; Montaggioni and Faure, 1997; Cabioch et al., 1999), we identified three coral assemblages and their paleoenvironments (see also Table 2 for summary):

- Assemblage A is characterized by robust branching corals (*Acropora* sp. group 1—*humilis* group; *Acropora* sp. group 2—*robusta* group, *Acropora palifera*, *Stylophora pistillata* and *Pocillopora verrucosa*, *P. damicornis*) with associated massive faviids (*Goniastrea* sp. and *Platygyra* sp.) (Fig. 2). Similar robust branching *Acropora* communities have been observed on modern reef edges and upper reef slopes exposed to strong wave action and in water depths less than 10 m in the Great Barrier Reef (Done, 1982; Veron, 1986), and less than 6 m in Tahiti (Bard et al., 1996; Montaggioni et al.,

Table 2
Summary of the main characteristics, distribution and paleoenvironmental interpretation of the coral assemblages, sedimentary facies and coralline algal associations[a] observed in the Ribbon Reef 5 and Boulder Reef cores

Coral assemblages	Characteristics	Paleoenvironmental Interpretation	Distribution
Assemblage A	Robust branching *Acropora* sp. gp. 1—*humilis* group, *A.* sp. gp. 2—*robusta* group, *A. palifera*, *Stylophora pistillata* and *Pocillopor a verrucosa*, *P. damicornis*, with associated massive *Goniastrea* sp. and *Platygyra* sp.	Shallow (~ 0–10 m), high energy, characteristic of windward margins (i.e. outer reef flat to upper reef slope).	Restricted to Ribbon Reef 5, R1 (16–9.5 m), R2 (19–16 m), R3 (61–58, 51–25), R4 (79–72 m), R5 (94–85 m), R6 (96–94 m), R7 (122–117 m) and R8 (135–130 m)
Assemblage B1	Mainly *massive Porites* sp. gp. 1 (*P. cf lutea*, *P. cf solida*) and faviids (*Favia* sp., *Favites* sp.), with encrusting forms (*Porites* sp. gp. 2 and *Montipora* sp.)	Lower energy environments (e.g. leeward reef margin or perhaps deeper environments)	Restricted to Ribbon Reef, R1 (9.5–0 m), R2 (25–23 m), R3 (64–61 m), R4 (85–79, 72–64 m) and R6 (96–94 m)
Assemblage B2	Massive *Porites* sp. group 1 (*P. cf lutea*) and associated faviids (*Favia* sp., *Favites* sp.); similar to Assemblage B1 but lacks any significant encrusting coral forms	Similar to B1, lower energy environment but with increased turbidity (i.e. leeward reef flat from an inner shelf reef)	Restricted to Boulder Reef, occurring within R1, R2, R3 and R4.

Sedimentary Facies	Description	Distribution
Facies A	In-situ coral framework as defined by criteria discussed in the methods section	Both Ribbon Reef 5 and Boulder Reef
Facies B	Mixed packstone/grainstone material with associated Assemblage A coral fragments (i.e. branching *Acropora* spp., *Stylophora pistillata* and *Pocillopora* spp.)	Both Ribbon Reef 5 and Boulder Reef cores
Facies C	Packstone/grainstone material with mixed encrusting and massive coral fragments	Both Ribbon Reef 5 and Boulder Reef
Facies D	Packstone/grainstone material with very few visible coral fragments. Bioclastic fragments such as molluscs, foraminifera, coralline algae bivalves, gastropods, echinoderms and bryozoans dominate	Restricted to Ribbon Reef 5 within basal section (210–158 m)
Facies E	Grainstones dominated by *Halimeda* plates	Restricted to R2 (25–19 m) in Ribbon Reef 5
Facies F	Coralline algal dominated rhodoliths occurring as grainstones/packstones	Rhodolith section (158–96 m) in Ribbon Reef 5 and thin horizon in the Boulder Reef core (R2)
Facies G	Unlithified bioclastic carbonate sands composed of coral, molluscs, foraminifera, coralline algae and bryozoans fragments	Limited to Ribbon Reef 5
Facies H	Disaggregated coral rubble comprised mainly Assemblage A coral fragments	Both Ribbon Reef 5 and Boulder Reef cores
Facies I	Disaggregated coral rubble comprised mainly Assemblage B coral fragments	Both Ribbon Reef 5 and Boulder Reef cores
Facies J	Unlithified to partially lithified siliciclastic muds and clays with minor sands	Restricted to the lower half of Boulder Reef
Facies K	Disaggregated coral and grainstone fragments sitting within a matrix of unlithified to partially lithified siliciclastic muds and clays with minor sands	Restricted to the lower half of Boulder Reef

(*continued on next page*)

Table 2 (*continued*)

Coralline Algal Associations[a]	Characteristics	Palaeoenvironmental Interpretation	Distribution (data limited to Ribbon Reef 5)
Mastophoroid association (M)	Dominated by *Hydrolithon onkodes* and *Neogoniolithon fosliei*	Shallow water, (< 12–15 m), tropical reef environments	Dominates the main reef section (0–96 m), also occurs within R7 and R8
Lithophylloid association (L)	Mainly of *Lithophyllum* species	Shallow water, subtropical to warm temperate non-reefal mid-latitude regions	Basal (210–158 m) and rhodolith section (158–96 m), alternating with association B. Also occurs in four small intervals within the main reef section (0–96 m)
Melobesioid association (B)	Mainly of *Mesophyllum* and *Lithothamnion* species	Deep (>15 m), outer platform environments	Basal (210–158 m) and rhodolith section (158–96 m), alternating with association L

[a] Data after Braga and Aguirre, 1997.

1997), Mayotte (Camoin et al., 1997), Ryukyu Islands (Nakamori, 1986; Iryu et al., 1995; Webster et al., 1998) and New Guinea (Nakamori et al., 1995). Thus, the paleoenvironment of Assemblage A is interpreted as shallow (~ 0–10 m), high energy, characteristic of windward margins (i.e. outer reef flat to upper reef slope).

- Assemblage B1 is characterized by mainly massive *Porites* sp. group 1 (*Porites cf lutea*, *Porites cf solida*) and faviids (*Favia* sp., *Favites* sp.) with

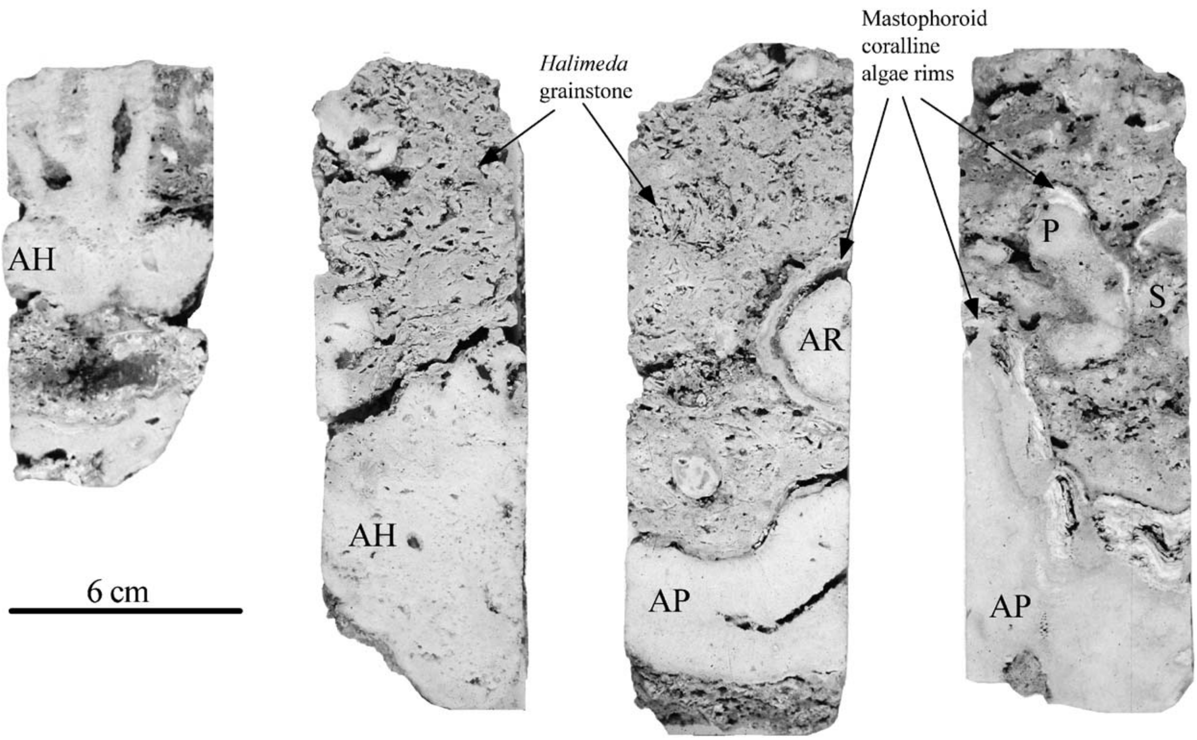

Fig. 2. Photographs showing the principal coral components of Assemblage A from the Ribbon Reef 5 core. Robust branching (AH) *Acropora* sp. group 1 (*humilis*) group. (AR) *Acropora* sp. group 2 (*robusta*) group. (AP) *Acropora palifera*. (*S*) *S. pistillata* and (P) *Pocillopora* sp. Note the extensive coralline algal rims encrusting much of the coral framework.

significant encrusting forms (*Porites* sp. group 2 and *Montipora* sp.) (Fig. 3). Although the modern environmental distribution of massive *Porites* communities is widespread (reef slope, reef flat to back reef), there is a tendency for these communities to dominate lower-energy (and perhaps deeper) reef environments (Done, 1982; Veron, 1986; Montaggioni et al., 1997). This suggests that Assemblage B1 occupied a lower-energy environment, especially when compared to Assemblage A.

- Assemblage B2 is again dominated by massive *Porites* sp. group 1 (*P. cf lutea*) and associated faviids (*Favia* sp., *Favites* sp.); although similar to Assemblage B1, this assemblage lacks any significant encrusting coral forms (Fig. 3). The paleoenvironment of Assemblage B2 is again interpreted as a lower-energy environment with perhaps increased turbidity (i.e. leeward reef flat from an inner shelf reef) as indicated by the lack of encrusting coral forms and the dominance of *Porites* sp. (Marshall and Orr, 1931; Manton, 1935; Wells, 1954; Scoffin and Stoddart, 1978; Martin et al., 1989).

3.2. Coralline algal associations and paleoenvironmental interpretation

The composition, distribution and paleoenvironmental significance of coralline algae in the Ribbon Reef 5 core have been reported by Braga and Aguirre (1997) (summarised in Table 2). They identified three main algal associations: (1) a mastophoroid association (M) dominated by mainly *Hydrolithon onkodes* and *Neogoniolithon fosliei* which are characteristic of shallow water (< 12–15 m), tropical reef environments. This association is common in modern Pacific reefs including the Great Barrier Reef (Borowitzka and Larkum, 1986; Adey, 1986; Montaggioni et al., 1997); (2) a lithophylloid association (L) composed primarily of *Lithophyllum* sp. and typical of shallow water set-

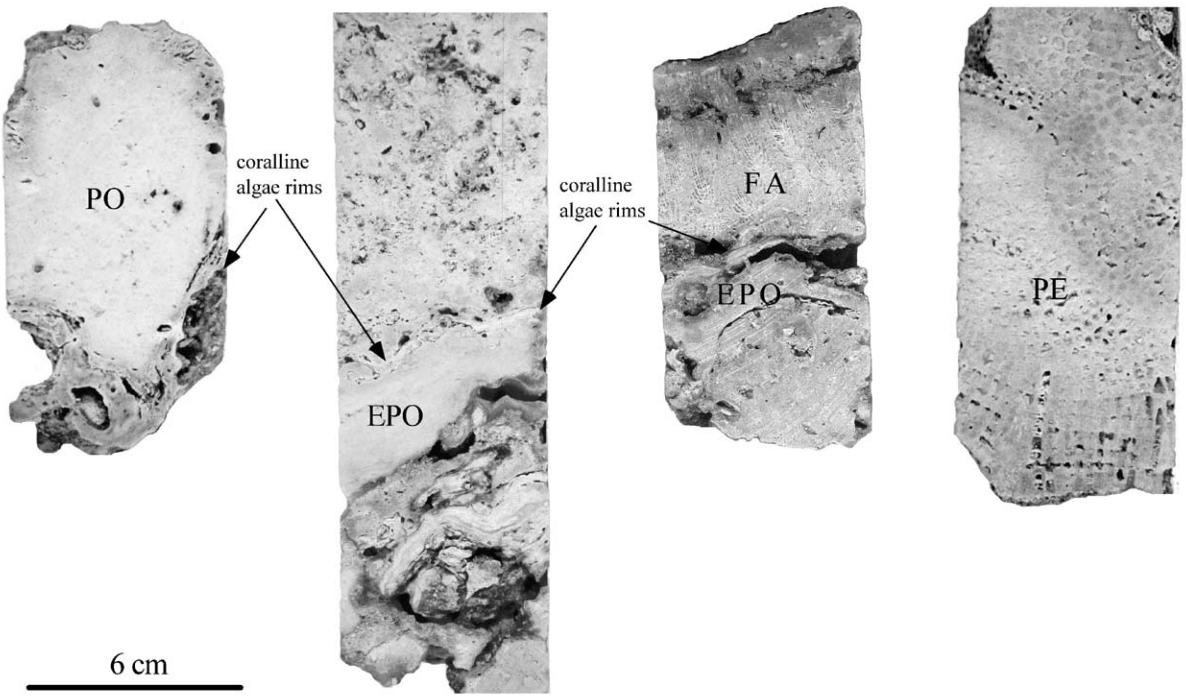

Fig. 3. Photographs showing the principal coral components of Assemblage B1 and B2 from the Ribbon Reef 5 and Boulder Reef cores. (PO) massive *Porites* sp. group 1 (*Porites cf lutea*), (EPO) encrusting *Porites* sp. group 2, and massive faviids such as (FA) *Favites* sp. and (PE) *P. verispora*). Note the extensive coralline algal rims encrusting much of the coral framework.

tings in present-day subtropical to warm temperate non-reefal mid-latitude regions (Adey, 1986); and (3) a melobesioid association (Me) made up mainly of *Mesophyllum* and *Lithothamnion* species characteristic of modern deep (>15 m) platform environments (Adey, 1986) such as the outer platform off southern Queensland immediately to the south of the Great Barrier Reef (Lund et al., 2000).

3.3. Ribbon Reef 5 stratigraphy and lithology

Preliminary examination by the International Consortium for Great Barrier Reef Drilling (2001) defined three distinct sections in the Ribbon Reef 5 core; (1) a main coral reef section (0–100 m), a rhodolith section (100–155 m) and a basal section composed of non-reefal skeletal grainstones and packstones (155–210 m). In this paper, we adhere to essentially the same boundaries, but based on subsequent examination of lithologic and faunal variation near these boundaries, we suggest a minor revision; 0–96 m for the main reef section, 96–158 m for the rhodolith section and 158–210 m for the basal section (Fig. 6).

3.3.1. Section 1 (0–96 m)

This main reef section is composed predominantly of in situ coral framework facies which we have subdivided into six different reef units based on relative age criteria such as petrographic, seismic, log and isotopic data (Davies and Hopley, 1983; Davies et al., 1985; Andres, 1997; International Consortium for Great Barrier Reef Drilling, 2001). These stratigraphic boundaries as well as major variations in sedimentary facies, coral assemblages and coralline algal associations (after Braga and Aguirre, 1997) within each reef unit are described below (also in Table 2 and Fig. 4).

3.3.1.1. R1 (0–16 m). Previously published radiocarbon and seismic data (Davies and Hopley, 1983; Davies et al., 1985) combined with the presence of spherular and acicular aragonitic cements (International Consortium for Great Barrier Reef Drilling, 2001) confirm the Holocene age of this unit and indicate growth initiated ~ 8 ky. The unit is dominated by in situ coral framework (Facies A) and is comprised of Assemblage A corals below 9.5 m and Assemblage B1 corals above this depth. The top (9.5–0 m) of R1 is characterized by in situ massive *Porites* sp. group 1 and associated encrusting *Porites* sp. group 2 corals. The entire unit is dominated by the mastophoroid coralline algal association (M). The base of this unit (16 m) is characterized by a prominent surface-bearing pale-brown sediment containing areas of calcitized plant cells and vugs lined with blocky calcite cements (International Consortium for Great Barrier Reef Drilling, 2001). This combined with the radiometric data (Davies and Hopley, 1983; Davies et al., 1985) and a significant negative shift in δO^{18} values (Andres, 1997) indicates that the base of R1 is at 16 m (R1/R2 boundary) and that it probably represents a subaerial exposure horizon formed at the Holocene/Pleistocene boundary.

3.3.1.2. R2 (16–25 m). R2 represents the uppermost Pleistocene reef unit. The lower 6-m section (25–19 m) of R2 is composed of a *Halimeda*-rich grainstone facies (Facies E) within which little in situ coral framework is recorded. The few corals that are present in this lower section of R2 are composed of mostly Assemblage B1 coral types, characterized by massive (*Porites* sp.) and encrusting corals (*Millepora exaesa*), with minor branching Assemblage A corals (e.g. *Acropora* sp. group 3—*monticulosa*). The top of R2 (19–16 m) records a change to in situ coral framework (Facies A) mainly Assemblage A coral types (*S. pistillata, A. cf palifera and Acropora* sp. group 2—*robusta* group) and an associated change from *Halimeda*-rich grainstones to coral-rich grainstones/packstones with associated branching coral fragments (Facies B). The coralline algal data record a clear change at ~ 22 m from lithophylloid (L) to mastophoroid (M) associations vertically. The International Consortium for Great Barrier Reef Drilling (2001) defined a diffuse subaerial exposure horizon at 28 m associated with cavities filled with a pale brown laminated sediment wrapped around tubules that contain yellowish blocky calcite resembling calcitized plant cells. At 25 m, a significant shift in the natural gamma log and a negative shift in δO^{18} are also recorded (Andres, 1997). On this basis, combined with a sharp lithologic and coralline algal change (Figs. 4 and 6), we define the contact between R2 and R3 at ~ 25 m.

3.3.1.3. R3 (25–64 m). R3 is the thickest reef unit observed within the Ribbon 5 core. The unit shows

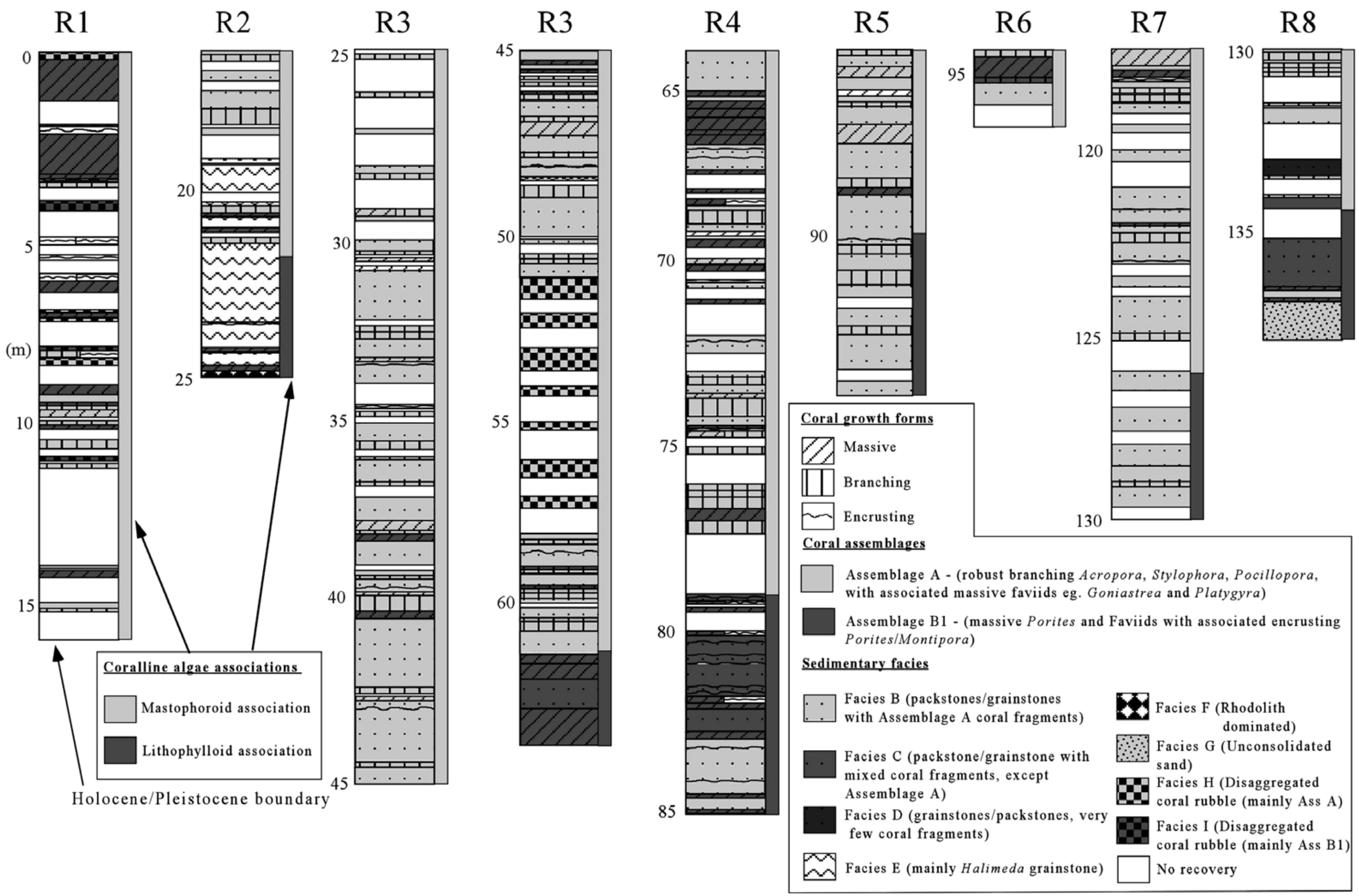

Fig. 4. Individual reef units at Ribbon Reef 5 showing the distribution of coral assemblages, coralline algal associations (data after Braga and Aguirre, 1997) and major sedimentary facies.

significant vertical variations in coral assemblages and sedimentary facies. The lower 3 m of R3 (64–61 m) consists largely of coral framework dominated by Assemblage B1 corals (e.g. *Porites* sp. group 1, *Montipora* sp., *Platygyra daedalea*, *Porites* sp. group 2). This changes between 61 and 58 m into dominantly Assemblage A corals (*Pocillopora* sp. group 1, *A. cf palifera* and *Acropora* sp. group 1 (*humilis* group). This change is also coincident with a transition from lithophylloid (L) to mastophoroid (M) coralline algal associations. Next is a 7-m interval of detrital rubble composed of coral and grainstones, derived mostly from broken *Acropora*, *Pocillopora* and *Stylophora* colonies (Facies B) and which are interpreted as the re-worked remains of Assemblage A corals. From 51 to 44 m, Assemblage A corals (*Acropora* sp. group 1 (*humilis* group), *A. palifera*, *Pocillopora* sp. group 1 with minor *Porites* spp.) again dominate coral framework. Overlying this framework is another 3-m interval of grainstones and branching coral fragments (Facies B) with associated in situ Assemblages A corals (e.g. *A. palifera*, *S. pistillata*, *Leptoria phygia*). The remaining 16 m of R3 (i.e. 41–25 m) is dominated by coral framework, composed mainly of Assemblage A corals. The base of this unit (64 m) is characterized by a significant negative shift in the δO^{18} record (Andres, 1997), a marked change in the color of the core from pink to brown and a corresponding shift from mastophoroid (M) to lithophylloid (L) coralline algae associations.

3.3.1.4. R4 (64–85 m). This 21-m reef unit is characterized by a predominance of coral framework (Facies A), which shows distinct coral-assemblage variations. The lower part (85–79 m) is composed primarily of Assemblage B1 corals (*Montipora* sp. group 1, *Porites* sp. group 2, *Cyphastrea* sp. group 1, *Galaxea* sp., *Porites* sp. group 1). The volume of coral framework (Facies A) is not very high given the abundance of encrusting coral types (e.g. *Montipora* sp., and *Porites* sp. group 2), detrital grainstone/packstones and coral fragments (Facies B and C). A faunal change occurs at 79 m with Assemblage A (*A. cf palifera*, *A.* sp. group 2, *robusta* group), with minor faviids (*Cyphastrea* sp. group. 1, *L. phygia* and *Favia pallida*) replacing Assemblage B1 (79–72 m). Coincident with this faunal change is a significant increase in the volume of coral framework and a change from lithophylloid (L) to mastophoroid (M) coralline algal associations. A second faunal change occurs at 72 m with Assemblage B1 (*Porites* sp. group 1, *Montipora* sp., *Porites* sp. group 2, and *Montastrea* sp.) dominating the in situ coral types from 72 to 64 m. Large massive *Porites* sp. group 1 colonies are abundant in this interval, hence the high volume of coral framework. R4 therefore shows two sequential changes in coral fauna. The base of this unit (85 m) is characterized by a significant negative shift in the δO^{18} record (Andres, 1997). This is matched by a clear shift in both the corals (Assemblage A to B1) and coralline algal mastophoroids (M) to lithophylloids (L).

3.3.1.5. R5 (85–94 m). R5 shows very little coral variation and is mainly composed of Assemblage A coral types (e.g. *Acropora* sp. group 1 (*humilis* group), *Acropora* sp. group 2 (*robusta* group), *A. cf palifera* and *Goniastrea* sp. group 1). The volume of in situ coral framework (Facies A) throughout R5 is relatively high with a number of large massive *Goniastrea* sp. group 1 colonies. At 90 m, there is a change from lithophylloid (L) to mastophoroid (M) coralline algal associations. The base of this unit (94 m) is characterized by a small negative shift in the δO^{18} record (Andres, 1997) with a corresponding clear shift from a mastophoroid (M) to a lithophylloid (L) coralline algae association.

3.3.1.6. R6 (94–96 m). R6 is only 2 m thick and represents the first reef unit in the main reef section (0–96 m). The in situ corals making up R6 are comprised of examples of both Assemblage A and B1 coral types e.g. tabulate *Acropora* sp. group 1 (*humilis* group), with associated massive *Plesiastrea verispora* and short stubby branching *Porites* sp. group 3. Grainstone/packstones with associated branching coral fragments (Facies B) complete this reef unit. The entire unit is dominated by the mastophoroid coralline algal association (M). The base of the unit (96 m) is characterized by a major shift in sedimentary facies and thus represents the major section boundary between the main reef section (0–96 m) and rhodolith section (96–158 m).

3.3.2. Section 2 (96–158 m)

The middle section of the Ribbon 5 core consists of a rhodolith sequence dominated by four rhodolith-bearing grainstone horizons separated by coralline algae-dominated grainstones/packstones (Facies F) and two in situ coral framework-bearing reef units (Fig. 4).

3.3.2.1. R7 (117–130 m). This 13-m-thick unit is composed of basal grainstones with branching coral fragments (Facies B) (130–122 m) overlain by a 5-m interval (122–117 m) dominated by in situ coral framework (Facies A) comprised of Assemblage A corals (*A. cf palifera*, *A.* sp. group 1—*humilis* group, and *Goniastrea* sp. group 1—*edwardsi*). At ~ 127 m, there is a change from lithophylloid (L) to mastophoroid (M) coralline algal associations. The base of the unit (130 m) is characterized by a significant negative shift in the δO^{18} record (Andres, 1997) and a sharp irregular surface identified by the International Consortium for Great Barrier Reef Drilling (2001). This is also matched by a clear shift in coralline algae associations (mastophoroids to a lithophylloids).

3.3.2.2. R8 (130–138 m). R8 represents the oldest coral unit in the Ribbon 5 core. The lower part of the unit (138–135 m) is composed of interbedded grainstones/packstones with coral fragments (Facies B and C) and unconsolidated sediments with few in situ corals (Facies G). The upper part (135–130 m) is composed of a coral framework (Facies A) and is characterized by Assemblage A coral types (*S. pistillata*, *Acropora* sp. group 1—*humilis* group, and *Pocillopora* sp. group 1—*damicornis*). This interval coincides with a change from lithophylloid to mastophoroid coralline algae associations. The base of R8 is identified on the basis of a major change in sedimentary facies, from various reef-derived facies (Facies B, C and D) to the underlying rhodolith facies (Facies F). This corresponds with a clear shift from mastophoroid to lithophylloid coralline algae associations.

3.3.3. Section 3 (~ 158–210 m)

This basal section is characterized by bioclastic grainstones and packstones composed primarily of foraminifera, red coralline algal, *Halimeda*, bryozoans, bivalves, gastropods and echinoderms (Facies D).

3.4. Boulder Reef stratigraphy and lithology

On the basis of major lithological and faunal changes, the Boulder Reef core is divided into two distinct sections as shown in Fig. 7: (1) an upper carbonate dominated section (0–34 m) and (2) an underlying mud section (34–86 m) composed of siliciclastics and two thin, coral-bearing units (International Consortium for Great Barrier Reef Drilling, 2001). The major variations in sedimentary facies, coral assemblages and coralline algal associations within each reef unit are described below (also in Table 2 and Fig. 5).

3.4.1. Section 1 (0–34 m)

This upper carbonate-dominated section is divided into four reef units on the basis of previously published radiocarbon data, increasing diagenetic alteration (Davies and Hopley, 1983; Davies et al., 1985; International Consortium for Great Barrier Reef Drilling, 2001) and intervening siliciclastic mud layers.

3.4.1.1. R1 (0–11 m). Previously published radiocarbon ages place the Holocene/Pleistocene boundary at 16 m with the Holocene section at Boulder Reef initiating at ~ 8 ky (Davies and Hopley, 1983; Davies et al., 1985). This is consistent with the present study, where the Holocene/Pleistocene boundary is placed at 11 m. Due to the lack of recovery and the abundance of broken coral rubble, the volume of in situ framework is very low in R1. The few in situ corals present are composed of Assemblage B2 corals i.e. mainly massive *Porites* sp. group 1 in addition to minor *Acropora* sp. group 1 (*humilis* group). Due to the lack of recovery, it is not possible to discern any clear vertical faunal pattern. The coral rubble (Facies H) is comprised of predominately branching coral fragments (i.e. *Acropora*, *Pocillopora* and *Stylophora* sp.).

3.4.1.2. R2 (11–20 m). R2 contains the highest percentage of coral framework (Facies A) in the Boulder core. Assemblage B2 dominates the coral types and is composed of massive *Porites* spp. and faviids (*Goniastrea* sp. group 1, *Montastrea* sp. group 1 and *Favia* sp. group 2—*favus*). Interbedded with the coral framework are thin (< 1 m) layers of grainstones/packstones and coral fragments (Facies B and C), rhodoliths (Facies F) and mixed disaggregated coral rubble (Facies H and I). The base of this unit is identified by a zone of very low recovery with few corals and significant coral rubble and grainstones/packstones.

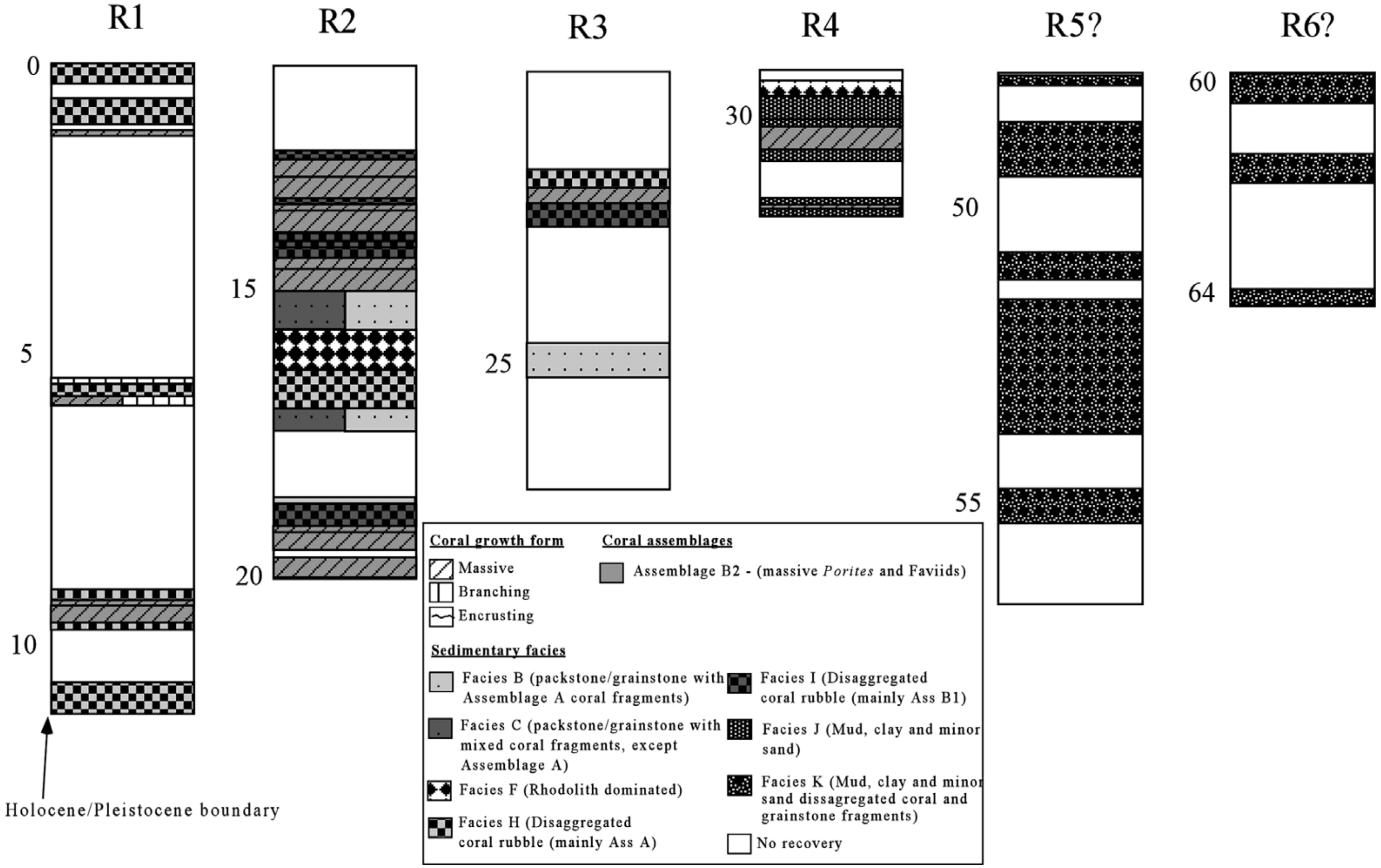

Fig. 5. Individual reef units at Boulder Reef showing the distribution of coral assemblages and major sedimentary facies.

3.4.1.3. R3 (20–27 m). R3 is characterized by poor core recovery. As a result, in situ corals are few and are represented by a single *Porites* sp. group 1 colony with associated mixed coral rubble (Facies G and H) and grainstones/packstones (Facies B). A 1 m thick siliciclastic mud layer separates the R3 and R4.

3.4.1.4. R4 (28–34 m). R4 is composed of Assemblage B2 corals set within a clay/mud matrix (Facies J). Coral fragments (*Pocillopora* sp. group 1, *Acropora* sp., *Cyphastrea* sp.) are also present. R4 represents the oldest reef unit containing coral framework. The base of this unit marks the boundary between the carbonate-dominated section and the lower siliciclastic section.

3.4.2. Section 2 (34–86 m)

The lower section of the Boulder core consists of unlithified and partially lithified siliciclastic muds, clays and minor sands. Two thin coral-bearing horizons occur within this section and are separated by 4 m of siliciclastic muds.

3.4.2.1. R5 (47–56 m) and R6 (60–64 m). R5 and R6 occur as thin coral-bearing horizons within this mud section and lack coral framework. These two units are dominated by muds and clays with associated mixed coral rubble and grainstones (Facies K).

4. Discussion

4.1. Coral assemblage variation within reef units

Coral variations within reef units at Ribbon Reef 5 occur as (1) vertical faunal transitions from Assemblage A to B1, (2) reverse transitions from B1 to A and (3) no transitions with a reef unit being dominated by a single assemblage. These patterns are interpreted below with reference to modern examples, and their possible implications for reef development.

The transition from one coral assemblage to another within some individual reef units may represent the response of reef growth to a range of environmental factors (e.g. sea-level, accommodation space, wave energy and sediment input). The Holocene reef (R1) at Ribbon Reef 5 is characterized by the transition from Assemblage A to B1 towards the top of the core. Based on the interpretation of coral faunas, this vertical change is thought to represent a shift from shallow, high-energy to low-energy (Done, 1982; Davies and Montaggioni, 1985; Montaggioni et al., 1997; Camoin et al., 1997), and could be produced as a consequence of either (1) lateral and/or (2) vertical accretion of the reef. For example, observing Walther's Law, a vertical assemblage change from A to B could be produced by reef progradation. Alternatively, vertical reef accretion and ecological succession could also explain this pattern. After the initial flooding of the Pleistocene basement at ~ 8 ky, the high-energy assemblage A dominated the reef (Davies et al., 1985, 1988). But as the windward part of the reef reached sea-level at ~ 6 ky, it produced low-energy conditions in the leeward zone and enabled Assemblage B1 to developed as the reef caught up to sea-level at ~ 2 ky. The leeward position of the Ribbon 5 hole (500 m from the windward margin) and the paleowater depth data presented by Davies et al. (1985, 1988) support this interpretation at least for R1. An identical faunal change is identified at the top of R4 (72–64 m) and could have formed as a result of both alternatives.

In the Ribbon Reef 5 core, the opposite transition from Assemblage B1 to Assemblage A is recorded in R3 and the lower part of R4. Based on the interpretation of coral assemblages, this probably reflects a shift from a lower-energy to a shallow, high-energy environment, characteristic of windward margins. Walther's Law and the lateral accretion of the reef could again provide the simplest interpretation of this pattern. Alternatively, this faunal change may reflect ecological succession as the reef grew vertically to sea-level. In this scenario, reef accretion may have taken place further windward, or alternatively, the windward part of the reef was not acting as a barrier.

The other pattern to emerge is that some reef units show little coral variation and are composed of a single, uniform assemblage (e.g. R5, R7 and R8). This suggests that these units developed under constant environmental conditions. Recent data from drilling in Tahiti also recorded evidence of long-term reef communities developing in response to constant environmental conditions (Montaggioni et al., 1997). Dominated by a single robust branching *Acropora* sp. (*danai* and *robusta* group) assemblage, the reef in Tahiti produced a 70-m-thick sequence over a 12-ky period. Montaggioni et al. (1997) suggested this sequence formed through mainly continuous, shallow (~ 0–6 m) keep-up growth. Recent results from Mayotte record a similar style of reef development, with a uniform sequence of robust branching *Acropora robusta/danai* corals produced over 9 ky (Camoin et al., 1997). Although representing a different reef environment compared with Ribbon Reef 5 (inner shelf reef, lower energy, turbid), the reef units (R1–R4) identified in the Boulder Reef core are similarly dominated by coral assemblage B2 throughout.

Another significant finding from the Ribbon Reef 5 data is the repeated occurrence of both Assemblage A and B1 down the core in different reef units (Fig. 6). We interpret this to mean that the same coral assemblages were present throughout the construction of the Great Barrier Reef on the outer shelf. Despite experiencing numerous cycles of major environmental perturbation, such as sea-level changes (up to 120 m rise and fall, Chappell et al., 1996) and possible sea-surface temperature fluctuations (up to 6 °C, Guiderson et al., 1994; Beck et al., 1992), the reef has been able to re-establish itself and produce similar coral assemblages. This suggests a robust ecosystem in the long term (~ 400 ky) and probably one influenced by repeated, but similar environmental changes. Although at a different taxanomic level, results from the Pleistocene raised-reefs in Barbados and the Huon Peninsula support these conclusions (Jackson, 1992; Pandolfi, 1995). The Barbados and Huon data indicate that the taxonomic composition of coral communities between terraces has remained constant over long periods of time, 250 and 95 ky, respectively.

4.2. Comparison of coral assemblages with coralline algal data

In the Ribbon 5 core, the coral assemblage data record good correlation with the coralline algal association data reported by Braga and Aguirre (1997). A correlation is observed between the major sections and also within the reef units. For example, the basal grainstone/packstone section (210–158 m) alternates between deep water, outer-platform environments (Me association) and shallower, cooler, non-reef settings (L association). This is consistent with the coral record, because there is no coral framework in this lower section. Isolated coral communities may have existed, as evidenced by the detrital coral fragments within some sediments, but there were no true coral-framework reefs.

The first appearance of shallow, high-energy, coral assemblage A occurs within the rhodolith-dominated section (e.g. R7 and R8 from 158 to 96 m). Coincident with the development of this coral framework is the earliest occurrence of the mastophoroid coral algal association (M), which is also characteristic of shallow water, tropical environments.

The main reef section (96–0 m) is dominated by the mastophoroid (M) association with minor lithophylloids (L). Correlated with this is the dominance of the assemblage A corals in this section. Furthermore, four out of the six reefs units in this main reef section (R5, R4, R3 and R2) record an upward transition from the lithophylloid to the mastophoroid association. This algal change is also seen in R7 and R8, in the underlying rhodolith-dominated section. Significantly, within R2, R3 and R4, the variation in coral assemblages correlates with the coralline algal variation. For example, in these reefs, the change from the lithophylloid to the mastophoroid association is matched by the transition from the lower-energy coral assemblage B1, to the shallow, higher-energy assemblage A.

4.3. Paleoenvironmental variation

4.3.1. Reef ‘turn on’

In the outer shelf, the first appearance of true shallow, high energy, reef growth occurs within the rhodolith-dominated section (R7 and R8 from 158 to 96 m). Apart from these reef units, the section is characterized by successive deep and shallow, cool, non-reefal settings (i.e. sub-tropical mid-to outer shelf environments). Thus the rhodolith section marks a transitional period between non-reefal, perhaps temperate conditions characterized by the basal grainstone/packstones (below 158 m) and true tropical reef ‘turn on’, defined later by the main reef section (96–0 m). During deposition in this transitional period, environmental factors (i.e. sea-surface temperature and/or the frequency/amplitude of sea-level change) may have been such that minor reef growth did occur (i.e. R7 and R8) but was not sustainable.

In the inner shelf, reef ‘turn on’ is characterized by the upper carbonate-dominated section (34 m, R4, Figs. 5 and 7). These data indicate that turbid, lower-

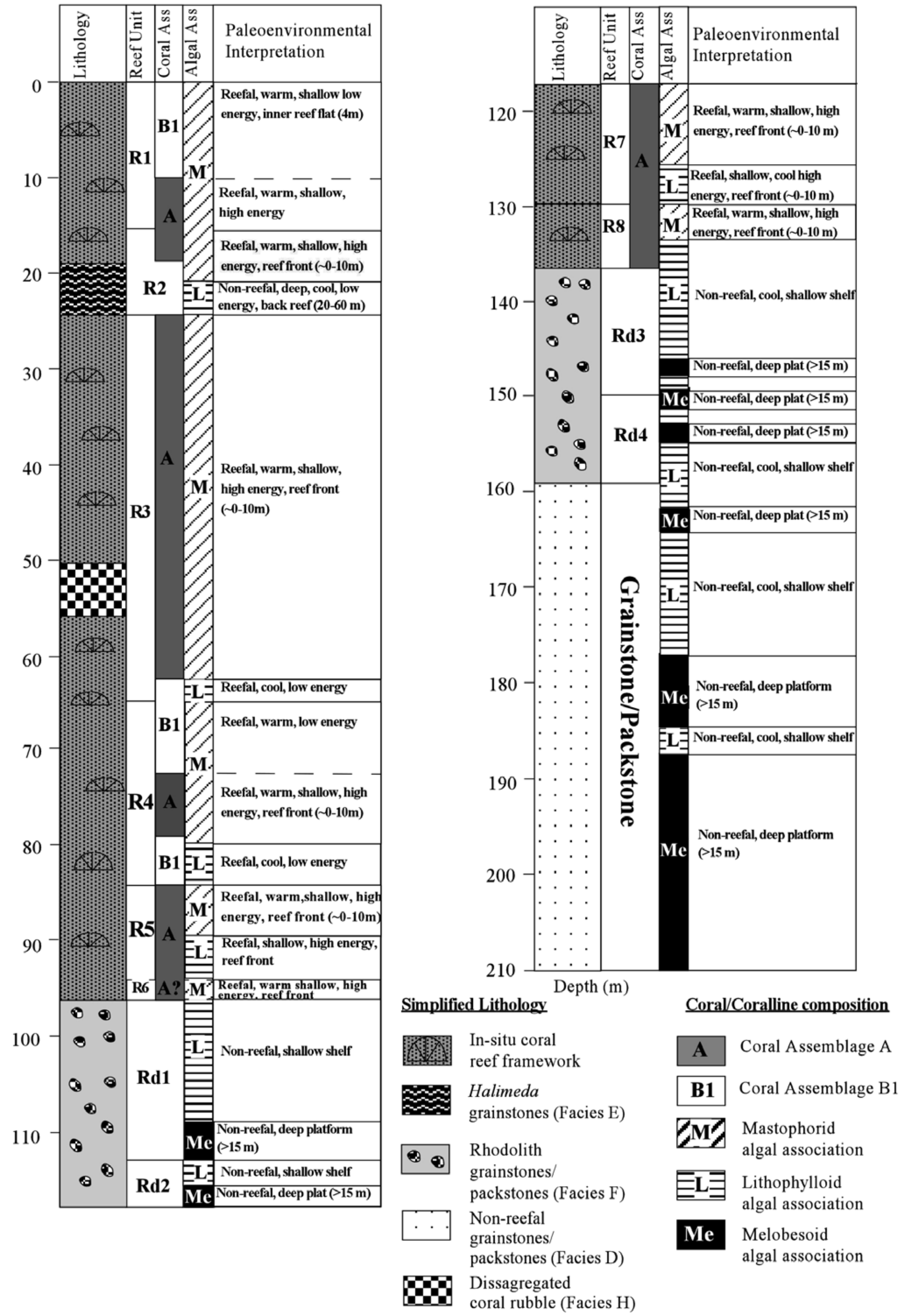

Fig. 6. Log summarising the lithologic and biologic variation in the Ribbon Reef 5 core. The paleoenvironmental interpretation is based on the composition and distribution of corals and coralline algae (data after Braga and Aguirre, 1997) and sedimentary characteristics.

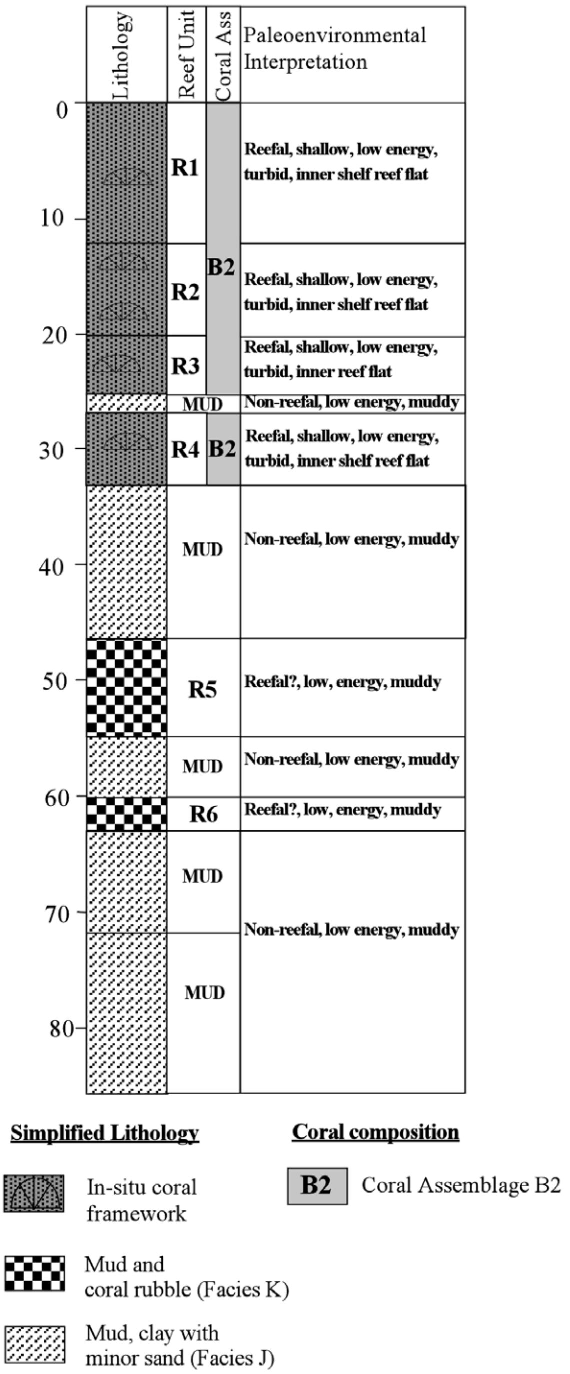

Fig. 7. Log summarising the major lithologic and coral assemblage variation in the Boulder Reef cores. The paleoenvironmental interpretation is based on the coral composition and sedimentary characteristics.

energy conditions prevailed during the deposition of these reef units. The basal section (86–34 m) of the Boulder core defines a series of low energy, siliciclastic mud and clay environments. The coral-bearing units (R6 and R5) in this section lack true framework and were probably low-diversity coral communities reworked to form a rubble.

4.3.2. *Reef growth*

All available data indicate at least six distinct reef units comprising the main reef section at Ribbon Reef 5 (R1–R6). These reefs may define six separate growth phases perhaps formed during as many sea-level cycles. The faunal data indicate that, for the most part, tropical, shallow water, high-energy conditions prevailed. However, within some individual reef units, significant paleoenvironmental variations are recorded. For example, a synchronous shift in both coral assemblages and coralline algal associations occurs in R4, R3 and R2. We suggest this defines the biological response of each reef growth phase to environmental perturbations such as sea-surface temperature (L to M coralline algal associations), sea-level or accommodation space and energy (Assemblage B1 to A). One possible scenario to explain the dual and synchronous change of corals and coralline algae is that as sea-level rise re-flooded the platform during the first part of a transgression, early reef growth was characterized by relatively cool, lower-energy conditions. Subsequently, as sea-level rise stabilised and highstand conditions prevailed, there was a corresponding shift to shallow, high-energy tropical reef building conditions.

Data from Boulder Reef on the inner shelf indicate that there were marked faunal and lithological differences in reef growth between the inner and outer shelf. This may reflect the contrasting Pleistocene development of the Great Barrier Reef in an outer shelf, as opposed to a more turbid, lower energy inner shelf environment. For example, Woolfe and Larcombe (1999) recently stressed the importance of terrigenous sedimentation in controlling coral framework types and species compositions, particularly in inner shelf or turbid-zone reefs in the Great Barrier Reef. Therefore, it is likely that low energy and turbidity were important factors controlling the coral composition at Boulder Reef.

4.4. The age of the Ribbon Reef 5 and Boulder Reef cores

The dates published by International Consortium for Great Barrier Reef Drilling (2001) constrain the age of the total drilled section at Ribbon Reef 5 (Fig. 6) to 320 to less than 780 ky. Sedimentation and facies distribution data published in Davies and Peerdeman (1997) and sedimentologic studies by Tsuji et al. (1995) and Marshall et al. (1997) help to refine this further. On the basis of the sedimentologic studies, the vertical change in Ribbon 5 from the main reef section (0–96 m) to the rhodolith section (96–158 m) and the basal non-reefal grainstones–packstones section (158–210 m) define boundaries duplicated in the modern surface of offshore eastern Australia. This clearly represents a southward change from tropical to subtropical to temperate conditions with an identical change recognized in the northern hemisphere off southern Japan (Tsuji et al., 1994). The Ribbon Reef 5 core is interpreted similarly. It is therefore important to know when these changes occurred. In the absence of firm isotopic dates, an analysis of all other available data, including fossil data from the nearby ODP cores (Davies and Peerdeman, 1997), magnetostratigraphic data (International Consortium for Great Barrier Reef Drilling, 2001; Barton et al., 1993) and the sedimentation rates data (Davies and Peerdeman, 1997), indicates a possible age of 365–452 ky for the main reef–rhodolith section boundary, and 520–606 ky for the rhodolith–grainstone–packstone section boundary. We cannot as yet firmly substantiate these ages but propose them as a best estimate to stimulate discussion. For example, recent SST data from the western equatorial Pacific confirm that Stage 11 (~ 410 ky) was the warmest interglacial of the last 450 ky (Lea et al., in press). Perhaps the turn on of the main reef section was associated with onset of this major palaeoclimatic event.

An ESR date of 210 ± 40 ky from the base of Boulder Reef at 86 m (International Consortium for Great Barrier Reef Drilling, 2001) implies that reef growth on the inner shelf started later than on the outer shelf. The inner-shelf reef commenced growth on a muddy substrate, whereas outer-shelf growth initiated on a presumably well-lithified rhodolith limestone. The much higher turbidity and lower energy experienced in the inner shelf, combined with the contrasting basement substrates, might explain not only the very different stratigraphy and coral composition but also the delay of reef development on the inner shelf.

5. Summary and conclusions

Based on a detailed examination of the stratigraphic, lithologic and coral-assemblage variation in both Ribbon Reef 5 and Boulder Reef (northern Great Barrier Reef), and comparison with a previously published coralline algal record, we draw the following conclusions:

(1) In Ribbon Reef 5, six reefs units (R1–R6) comprise the main reef section (0–96 m). Two further thin reef units (R7–R8) occur within the rhodolith section (96–158 m).

(2) Two distinct coral assemblages and their paleoenvironmental settings were identified in the Ribbon Reef 5 core. Assemblage A (shallow, high energy) and Assemblage B1 (lower energy) are repeated several times throughout the main reef section (R1–R6). Sometimes, individual reef units record assemblage variations (i.e. R4 Assemblage B1 to A), while others are composed of a single coral assemblage (i.e. R5).

(3) Within Ribbon Reef 5, the coral assemblage data do show a correlation with the coralline algal record reported by Braga and Aguirre (1997). In R2, R3 and R4, the vertical change from the lithophylloid (shallow, cool) to the mastophoroid (shallow, tropical reef) association is matched by the transition from a lower energy coral assemblage (Assemblage B1) to a shallow, higher energy one (Assemblage A). This dual and synchronous faunal shift is interpreted as an SST and sea-level related transition, affected by the shift from transgression to highstand during major sea-level fluctuations influencing the main reef section.

(4) The upper section (0–34 m) of the Boulder Reef core is characterized by a carbonate-dominated section composed of four reef units (R1–R4). Underlying this is a siliciclastic mud-dominated section (34–86 m) and two further thin coral horizons (R5–R6).

(5) The four reef units at Boulder Reef show little coral variation and are composed of a single coral assemblage (Assemblage B2, low energy and turbid).
(6) The repeated occurrence of similar coral assemblages in both drill cores suggests that the Great Barrier Reef has been able to re-establish itself and produce reefs of similar composition again and again over hundreds of thousands of years, despite major environmental fluctuations (i.e. sea-level and temperature changes).
(7) Reef growth on the outer shelf experienced a transitional period as defined by the rhodolith section (158–96 m, R7–R8). However, we consider that true tropical reef turn on occurred later (~ 452–365 ky) as indicated by the development of main reef section (0–96 m).
(8) The inner shelf may have initiated reef growth later than on the outer shelf. The higher turbidity and lower energy experienced in the inner shelf, combined with the contrasting basement substrates, might explain the delay in reef initiation and also the very different stratigraphy and coral composition observed in the inner and outer shelf reefs.

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References

Adey, W.H., 1986. Coralline algae as indicators of sea-level. In: van de Plassche, O. (Ed.), Sea-Level Research: A Manual for the Collection and Evaluation of Data. Free University of Amsterdam, Amsterdam, pp. 229–279.

Andres, M.S., 1997. Evolution of the Great Barrier Reef: a chemostratigraphic approach. Diploma Thesis. University of Zurich, Switzerland, p. 85.

Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G., Rougerie, F., 1996. Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. Nature 382, 241–244.

Barton, S., Lackie, M., Lackie, F.M., 1993. Environmental control of magnetic properties of upper-slope sediments near the Great Barrier Reef: results from Leg 133, Site 820. In: Mckenzie, J.A., Davies, P.J., Palmer-Julson, A., et al. (Eds.), Proc. of the Ocean Drilling Scientific Results, pp. 773–778.

Beck, J.W., Edwards, E., Ito, E., Taylor, F., Recy, J., Rougerie, F., Joannot, P., Henin, C., 1992. Sea-surface temperature from coral skeletal strontium–calcium ratios. Science 257, 644–647.

Borowitzka, M.A., Larkum, A.W.D., 1986. Reef Algae. Oceanus 29, 49–54.

Braga, J.C., Aguirre, J., 1997. The environmental significance of coralline red algae in Ribbon 5 drill hole (Great Barrier Reef, NE Australia). The Tenth Edgeworth David Symposium "Funafuti to Mururoa: A Century of Reflections on Carbonate Reservoirs". Department of Geology and Geophysics, University of Sydney, Australia, pp. 39–40.

Cabioch, G., Montaggioni, L.F., Faure, G., Ribaud-Laurenti, A., 1999. Reef coralgal assemblages as recorders of paleobathymetry and sea level changes in the Indo–Pacific province. Quat. Sci. Rev. 18, 1681–1695.

Camoin, G.F., Colonna, M., Montaggioni, L.F., Casanova, J., Faure, G., Thomassin, B.A., 1997. Holocene sea level changes and reef development in southwestern Indian Ocean. Coral Reefs 16, 247–259.

Chappell, J., Omura, A., Esat, T., McCulloch, M., Pandofi, J., Ota, Y., Pillans, B., 1996. Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. Earth Planet. Sci. Lett. 141, 227–236.

Crame, J.A., 1980. Succession and diversity in the Pleistocene coral reefs of the Kenya Coast. Paleontology 23, 1–37.

Davies, P.J., Hopley, D., 1983. Growth fabrics and growth rates of Holocene reefs in the Great Barrier Reef. BMR, J. Aust. Geol. Geophys. 8, 237–251.

Davies, P.J., Montaggioni, L., 1985. Reef growth and sea level change: the environmental signature. Proc. Fifth Int. Coral Reef Symposium, Tahiti, 477–515.

Davies, P.J., Peerdeman, F.M., 1997. The origin of the Great Barrier Reef—the impact of Leg 133 drilling. In: Camoin, G.F., Davies, P.J. (Eds.), Reefs and Carbonate Platforms in the Pacific and Indian Oceans. IAS Spec. Pub., vol. 25. Blackwell, Oxford, pp. 23–38.

Davies, P.J., Marshall, J.F., Hopley, D., 1985. Relationships between reef growth and sea level in the Great Barrier Reef. Proc. Fifth Int. Coral Reef Congress, Tahiti, pp. 95–103.

Davies, P.J., Symonds, P.A., Feary, D.A., Pigram, C.J., 1988. Facies models in exploration—the carbonate platforms of north-east Australia. APEA J. 28, 123–143.

Davies, P.J., Symonds, P.A., Feary, D.A., Pigram, C.J., 1989. The evolution of the carbonate platforms of Northeast Australia, controls on carbonate platform and basin development. Soc. Econ. Paleontol. Mineral., 233–258.

Done, T.J., 1982. Patterns in the distribution of coral communities across the central Great Barrier Reef. Coral Reefs 1, 9–14.

Guiderson, T.P., Fairbanks, R.G., Rubenstone, J.L., 1994. Tropical temperature variation since 20,000 years ago: modulating inter-hemisphere climate change. Science 263, 663–665.

International Consortium for Great Barrier Reef Drilling, Alexander, I., Andres, M.S., Braithwaite, C.J.R., Braga, J.C., Davies, P.J., Elderfield, H., Gilmour, M.A., Kay, R.L., Kroon, D., McKenzie, J.A., Montaggioni, L.F., Skinner, A., Thompson, R., Vasconcelos, C., Webster, J.M., Wilson, P.A., 2001. New constraints on the origin of the Australian Great Barrier Reef: results from an international project of deep coring. Geology 29, 483–486.

Iryu, Y., Nakamori, T., Matsuda, S., Abe, O., 1995. Distribution of marine organisms and its geological significance in the modern reef complex of the Ryukyu Islands. Sediment. Geol. 99, 243–258.

Jackson, J.B.C., 1992. Pleistocene perspectives on coral reef community structure. Am. Zool. 32, 719–731.

Lea, D.W., Pak, D.K., Spero, H.J. (in press). Sea surface temperatures in the Western Equatorial Pacific during marine isotope Stage 11. AGU monograph 46.

Lloyd, A.R., 1968. Foraminifera from H.B.R. Wreck Island No. 1 Well, and Heron Island Bore, Queensland. Their taxonomy and stratigraphic significance. 1—Lituolacea and Miliolacea. BMR J. Aust. Geol. Geophys. 92, 69–114.

Lund, M.J., Davies, P.J., Braga, J.C., 2000. Coralline algal nodules off Fraser Island, eastern Australia. Facies 42, 25–34.

Macintyre, I.G., 1988. Modern coral reefs of western Atlantic: new geologic perspectives. Am. Assoc. Pet. Geol. Bull. 72, 1360–1369.

Macintyre, I.G., Glynn, P.W., 1976. Evolution of modern Carribean fringing reef, Galata Point, Panama. AAPG Bull. 60, 1054–1072.

Manton, S.M., 1935. Ecological surveys of coral reefs. Scientific Reports of the Great Barrier Reef Expedition. 57, 278–289.

Marshall, J., Davies, P.J., 1982. Internal structure and Holocene evolution of One Tree Reef, Southern Great Barrier Reef. Coral Reefs 1, 21–28.

Marshall, S.M., Orr, A.P., 1931. Sedimentation on the Low Isles and its relation to coral growth. Scientific Reports of the Great Barrier Reef Expedition 1, 93–133.

Marshall, J.F., Tsuji, Y., Matsuda, H., Davies, P.J., Iryus, Y., Honda, N., Satoh, Y., 1997. Quaternary and tertiary subtropical carbonate platform development on the continental margin of southern Queensland, Australia. In: Camoin, G.F., Davies, P.J. (Eds.), Reefs and Carbonate Platforms in the Pacific and Indian Oceans. IAS Spec. Pub., vol. 25. Blackwell, Oxford, pp. 163–195.

Martin, J.M., Bragga, J.C., Rivas, P., 1989. Coral successions in Upper Tortonian reefs in SE Spain. Lethaia 22, 271–286.

Maxwell, W.G.H., 1962. Lithification of carbonate sediments in the Heron Islands Reef, Great Barrier Reef. J. Geol. Soc. Aust. 8, 217–238.

Montaggioni, L.F., Faure, G., 1997. Response of reef coral communities to sea-level rise; a Holocene model from Mauritius (western Indian Ocean). Sedimentology 44, 1053–1070.

Montaggioni, L.F., Cabioch, G., Camoin, G.F., Bard, E., Faure, G., Dejardin, P., Recy, J., 1997. Continuous record of reef growth over the past 14 k.y. on the mid-Pacific island of Tahiti. Geology 25, 555–559.

Nakamori, T., 1986. Community structure of recent and Pleistocene hermatypic corals in the Ryukyu Islands, Japan. Tohoku University Science Reports, 2nd Series. Geology, vol. 56, pp. 71–133.

Nakamori, T., Campbell, C.R., Wallensky, E., 1995. Living hermatypic coral assemblages at Huon Peninsula, Papua New Guinea. J. Geogr. (Japan) 104, 743–757.

Pandolfi, J.M., 1995. Limited membership in Pleistocene reef coral assemblages from the Huon Peninsula, Papua New Guinea: constancy during global change. Paleobiology 22, 152–176.

Pirazzoli, P.A., Montaggioni, L.F., 1988. The 7000 yr sea-level curve in French Polynesia: geodynamic implications for mid-plate volcanic islands. Proc. 6th International Coral Reef Symposium, Townsville, Australia, vol. 3, pp. 467–472.

Richards, V., Hill, D., 1942. Great Barrier Reef Bores, 1926 and 1937. Descriptions, analyses and interpretations. Rep. Great Barrier Reef Comm. 5, 1–122.

Scoffin, T.P., Stoddart, D.R., 1978. The nature and significance of microatolls. Philos. Trans. R. Soc. Lond., B 284, 99–122.

Tsuji, Y.J., Honda, N., Matsuda, H., 1994. Sedimentology of subtropical to temperate carbonates off eastern Australia. Earth Monthly 16, 407–411.

Tsuji, Y., Marshall, J., Honda, N., Davies, P.J., Matsuda, H., 1995. Facies relationships of subtropical and warm temperate carbonate environments, southern Queensland continental shelf, Australia. AGSO Report. 85 pp.

Veron, J.E.N., 1986. Corals of Australia and the Indo–Pacific. Angus and Robertson, North Ryde, NSW. 644 pp.

Veron, J.E.N., Pichon, M., 1976. Scleractinia of Eastern Australia. Part I Families Thamnasteriidae, Astrocoeniidae, Pocilloporidae, 1. Australian Institute of Marine Science, Qld. 86 pp.

Veron, J.E.N., Pichon, M., 1979. Scleractinia of Eastern Australia. Part III Families Agariciidae, Siderastreidae, Fungiidae, Oculinidae, Merlinidae, Mussidae, Pectiniidae, Caryophylliidae, Dendrophylliidae. Australian Institute of Marine Science Monograph Series, vol. 4. Australian Institute of Marine Science, Qld. 422 pp.

Veron, J.E.N., Pichon, M., 1982. Scleractinia of Eastern Australia. Part IV Family Poritidae. Australian Institute of Marine Science Monograph Series, vol. 5. Australian Institute of Marine Science, Qld. 159 pp.

Veron, J.E.N., Wallace, C., 1984. Scleractinia of Eastern Australia. Part V Families Acroporidae. Australian Institute of Marine Science Monograph Series, vol. 6. Australian Institute of Marine Science, Qld. 484 pp.

Veron, J.E.N., Pichon, M., Wijsman-Best, M., 1977. Scleractinia of Eastern Australia. Part II Families Faviidae, Trachyphyllidae.

Australian Institute of Marine Science Monograph Series, vol. 3. Australian Institute of Marine Science, Qld. 233 pp.

Webster, J.M., Davies, P.J., Konishi, K., 1998. Model of fringing reef development in response to progressive sea level fall over the last 7000 years—(Kikai-jima, Ryukyu Islands, Japan). Coral Reefs 17, 289–308.

Wells, J.W., 1954. Recent corals of the Marshal Islands. U. S. Geol. Surv. Prof. Pap. 200-I, 385–486.

Wolfe, K., Larcombe, P., 1999. Terrigenous sedimentation and coral reef growth: a conceptual framework. Mar. Geol. 155, 331–345.