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Coral Reefs

Internal Structure and Holocene Evolution of One Tree Reef, Southern Great Barrier Reef

J. F. Marshall and P. J. Davies

Bureau of Mineral Resources, Geology and Geophysics, P.O. Box 378, Canberra City ACT 2601, Australia

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Summary. Analysis of core from six drill holes and ten vibrocores from One Tree Reef has delineated five major biosedimentological facies: algal pavement, coral head facies, branching coral facies, reef flat rubble facies and sand facies. Holocene growth began around 8,000 years B.P. with a high energy coral head facies on windward margins and a lower energy branching coral facies on patch reefs and on leeward margins. Vertical accumulation rates for these two principal facies are not greatly different; the coral head facies grew at 1.8–7.3 m/1,000 years and the branching coral facies at 0.6–8.3 m/1,000 years. Growth was initially much slower than the rate of sea level rise, a situation which changed only after sea level stabilized around 6,200 years B.P. A facies evolution model with rigidly imposed time constraints divides growth into three phases, i.e. vertical growth to sea level, transitional adjustment of biofacies at sea level, and leeward progradative phases.

Introduction

The internal structure of Holocene reefs in the Great Barrier Reef has until recently been little understood, a fact which has not deterred most workers from speculating on their evolutionary development and even classifying them (e.g. Maxwell 1968; Davies et al. 1977; Flood and Orme 1977). Since 1978, an intensive drilling program in the southern Great Barrier Reef by the Bureau of Mineral Resources has shown that contrary to earlier beliefs, Holocene reefs are relatively thin (4–20 m), that growth is related to substrate and that growth may be divided into vertical and lateral phases (Davies and Marshall 1980). The objectives of the present paper are an analysis of the internal structure of One Tree Reef, together with an assessment of reef growth rates and their significance.

Methods

A portable hydraulic operated drilling rig, built specifically for continuous coring (54 mm diameter) of coral reefs, was used to drill six holes through the Holocene section of the reef. The depth of the holes varied between 8.5 and 23.0 m and three of the holes penetrated the entire Holocene sequence at depths of between 13–14 m. Recovery depended upon the type of framework and abundance of cavities and varied from 25%–95%. The drill system also converted to a vibrocorer, and ten cores of lagoonal sediments, up to 5 m long, were obtained.

Modern Reef Morphology and Zonation

The morphological variation of One Tree Reef (Fig. 1) has been described in detail previously (Davies et al. 1976). The following is a summary. One Tree Reef is 20 km from the shelf edge, 70 km from land, and is surrounded by water depths of approximately 60 m. The windward reef slope is generally steep with a near-vertical Pleistocene wall along the southern margin (Davies and Marshall 1979). Spurs and grooves are prominent along the eastern and southeastern margins. The leeward slope is gentle and supports abundant and luxurious coral growth. The reef top exhibits the classical reef zonation of coralline algal rim, coral flat, sand flat and lagoon. The coralline algal rims dominate around the southern and southeastern margins where they form indurated pavements 60 m wide, covered by a thin veneer of sediment-trapping algal turf. The coral flat is best developed on the southern side where it is 200 m wide and comprised of various species of *Acropora*, *Pocillopora*, *Seriatopora*, *Porites* and *Goniopora*, sculptured into prominent windrows. Along the eastern margin, the coral flat has been overwhelmed by extensive intertidal coral rubble. Subtidal sand sheets separate coral flats/rubble flats from the lagoon along the southern and eastern sides of the reef, and are actively prograding into the lagoon. Scattered *Acropora*/*Pocillopora*-dominated patches are developing on the sand sheets. The lagoon is 10 km^2 in area, deepens to 10 m at the western end and is partially filled with reticulate and linear patterns of lagoonal patch reefs. The leeward rim of One Tree Reef is 1 km wide at the northwestern corner and is comprised of alternating zones of coralline algal encrusted low branching corals and sand/gravel accumulations.

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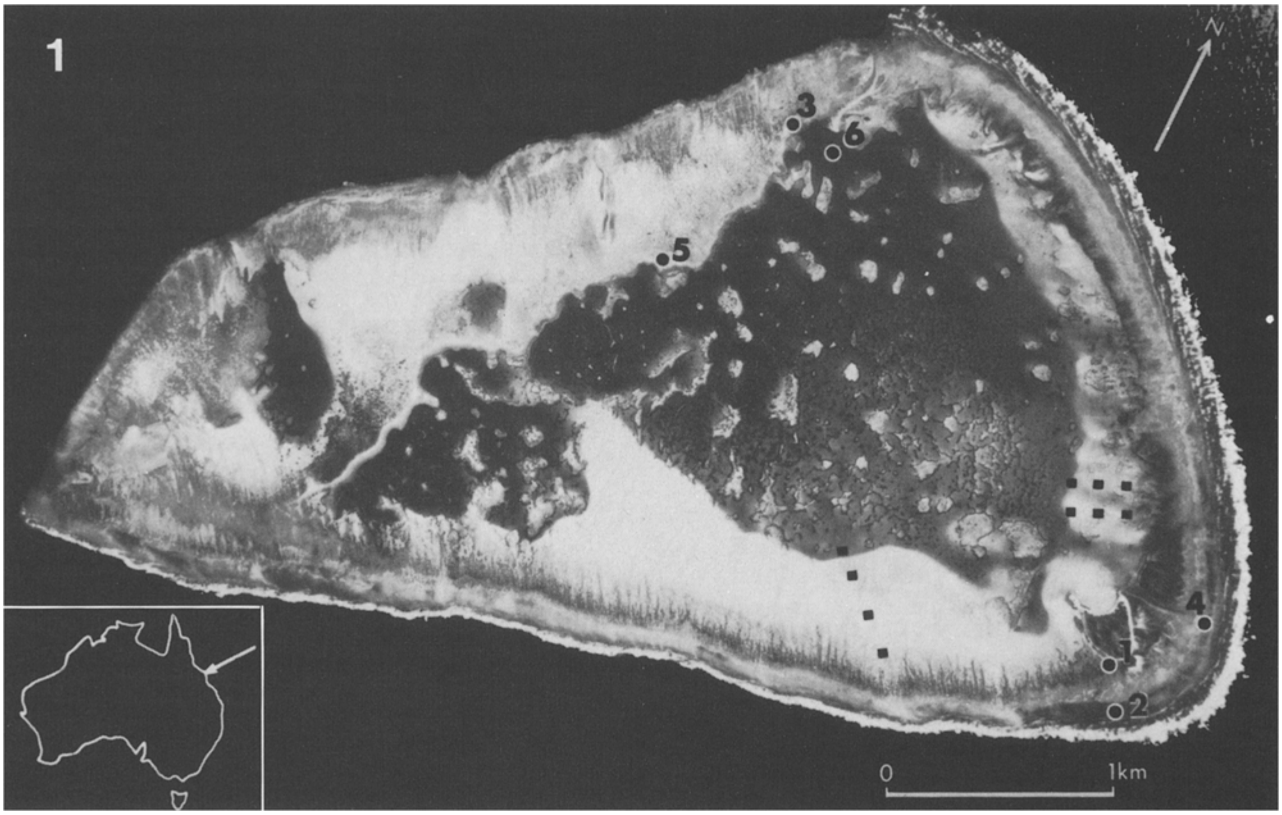

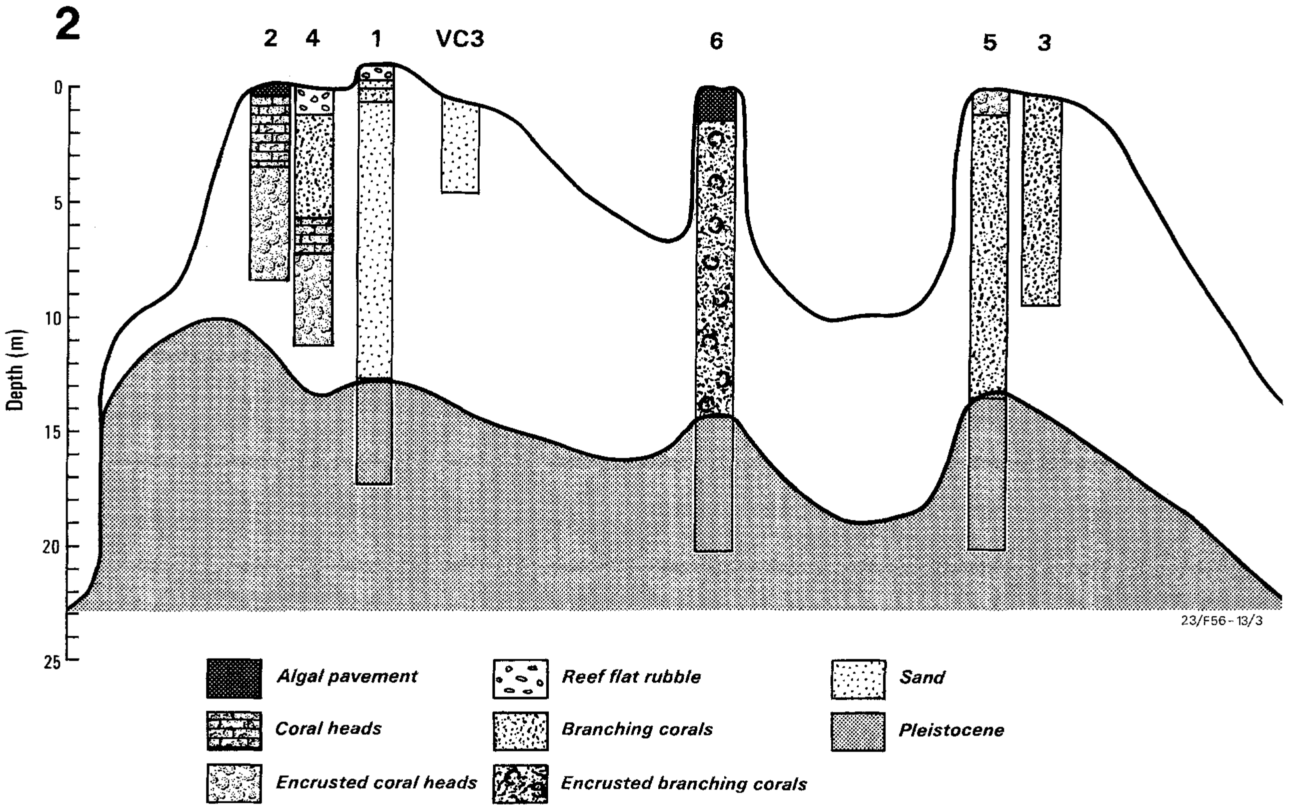

Fig. 1. Vertical aerial photograph of One Tree Reef showing the reef's large-scale physiographic features and the location of drill hole (*numbered circles*) and vibrocore (*dark squares*) sites. **Fig. 2.** Cross-section of One Tree Reef outlining the general depth and shape of the pre-Holocene surface and projected drill hole (*1–6*) and vibrocore (*VC3*) sites which show the distribution of the various facies

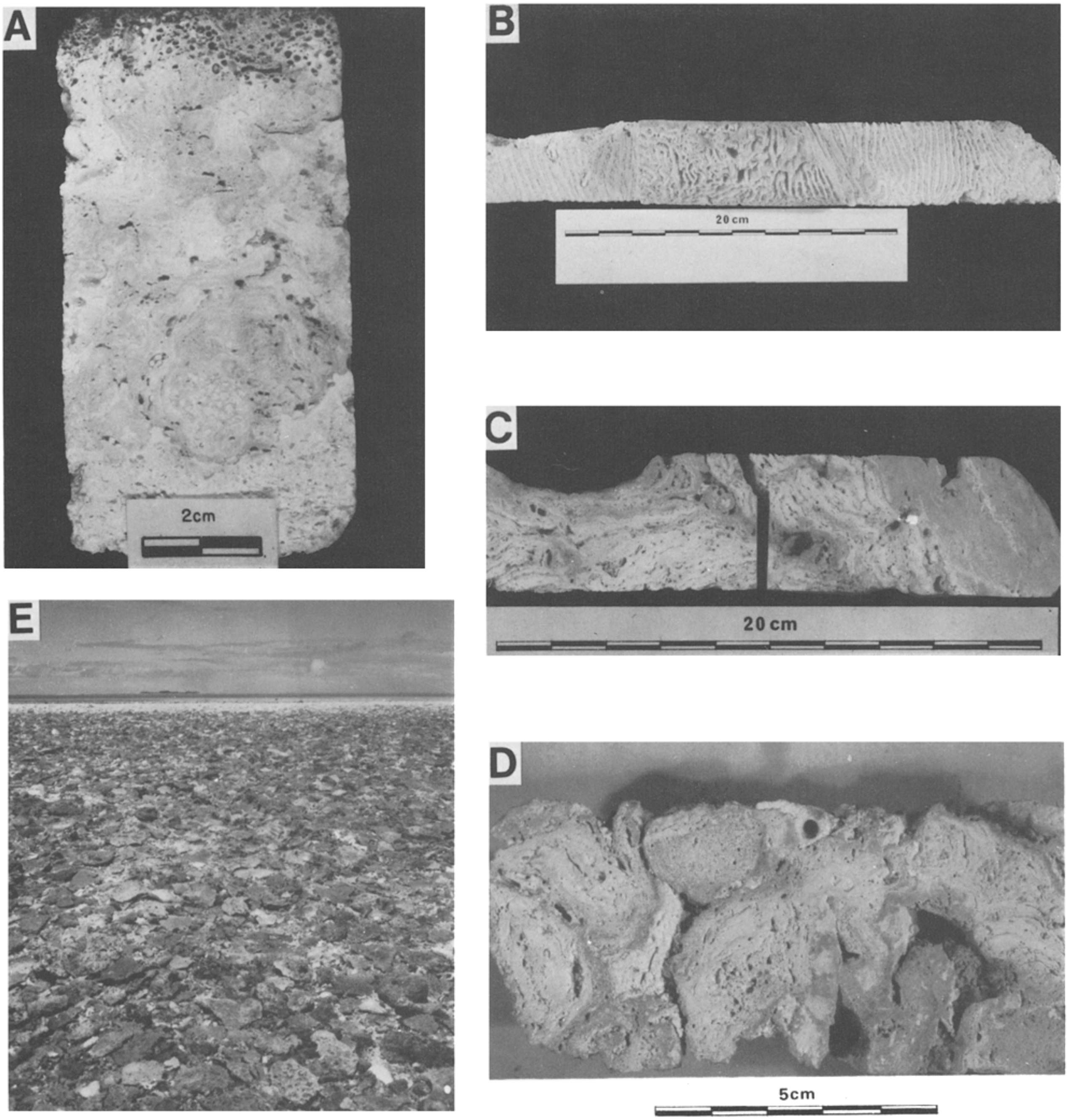

Fig. 3A–E. Photographs showing representative examples of the various facies. **A** Algal pavement facies: core showing extensive coralline algal encrusted corals from the top of hole 2. Note the extensive polychaete borings within the top centimetre. **B** Coral head facies: core of a large head of *Platygyra* from the unencrusted subfacies. **C** Coral head facies: thick coralline algal crust on coral from the encrusted subfacies. **D** Branching coral facies: core of coralline algal encrusted branching corals from the patch reef. **E** Rubble flat facies: surface of the rubble flat showing large plates of *Acropora*. Base of photograph is about 3 m wide

Internal Structure and Composition

Six holes were drilled at One Tree Reef, three on the windward margin, two on the leeward margin, and one on a patch reef at the leeward end of the lagoon (Fig. 1). Interpretation of each drill hole (Fig. 2) has allowed the delineation of five major biological/sedimentological facies. These are briefly described below.

Algal Pavement (Fig. 3A)

This forms the windward algal rim and the top of the patch reef (Holes 2 and 6, Figs. 1 and 2). It is 40 cm thick beneath the algal rim and 1.4 m thick beneath the patch reef.

The major components of the algal pavement are gravel sized fragments of branching corals and molluscs bound by various species of coralline algae and encrusting corals; accessory faunal components include vermetid gastropods, encrusting Foraminifera (*Homotrema* sp.) and bryozoans. Interskeletal cavities and borings are heavily infilled with partially or totally cemented sand and mud. Borings by sponges, bivalves and polychaetes are common. Laminar and stalagmitic lithified crusts dominate in the larger cavities and have effected marked porosity reductions.

Coral Head Facies (Fig. 3B and C)

This facies occurs beneath the windward margin (Holes 2 and 4, Figs. 1 and 2) and close to the surface beneath the leeward margin (Hole 5, Figs. 1 and 2). It may be subdivided into two parts, a coralline algal encrusted coral head subfacies below, and a non-encrusted coral head subfacies above, as seen in both windward margin holes (Holes 2 and 4, Figs. 1 and 2). The lower encrusted subfacies consists mainly of coral heads of *Porites*, *Goniopora*, *Favia* and massive *Acropora*, 5–25 cm high separated by coralline crusts 2–10 cm thick. Cavities between individual algal sheets contain encrusting Foraminifera, bryozoans, vermetids, serpulids and cemented lime mud. Borings by sponges, bivalves and polychaetes are extensive. The upper non-encrusted subfacies consists of heads of *Porites*, *Platygyra*, *Symphyllia* and massive *Acropora palifera*; the heads vary in height from 6 to 52 cm. Sponge borings dominate at the base of colonies whereas bivalve and polychaete borings occur throughout.

Branching Coral Facies (Fig. 3D)

This facies occurs beneath the windward margin, the leeward margin and the lagoonal patch reef (Holes 4, 5 and 6, Fig. 2). Beneath the windward margin it is 4.5 m thick and overlies the coral head facies. Much thicker sequences (13 m) comprise both the leeward edge and the lagoonal patch reef. Beneath the windward and leeward margins the branching coral facies is comprised of an open, cavernous framework of branching and platy species of *Acropora* with a few small *Porites* heads. The framework is extensively bored by sponges. Thin coralline algal crusts coating branches are often the principal framework support. Cavities up to 1 m high are common. In the patch reef this branching coral facies is composed of both *Acropora* and *Pocillopora* sps. bound into a rigid framework by coralline algal crusts 1–4 cm thick. Lithified crusts (Macintyre 1977; Land and Moore 1980) have effected marked porosity reduction within the framework cavities. Other cavities rarely exceed 20 cm in height. Multiple endolithic borings, repeated sediment infill and lithification have produced a heterogeneous rock which comprises much of the patch reef.

Reef Flat Rubble Facies (Fig. 3E)

Intertidal coral rubble is a prominent surface feature on the southeastern and eastern reef flats. Such material may be loose and imbricated or cemented and undergoing extensive bioerosion. Coral rubble occurs to a depth of 1.4 m in Hole 4 (Fig. 2) where it is mixed with a porous matrix of poorly cemented skeletal sand.

Sand Facies

An 11 m section of unconsolidated sands drilled in Hole 1 (Figs. 1 and 2) consists of three upward fining sequences (gravel to fine sand) separated by in situ corals. *Halimeda* dominates as a sediment constituent in the lower cycle, but *Calcarina* is ubiquitous. The sequence seen in Hole 1 is the lateral equivalent of the sand wedge from which vibrocores show identical rhythms to those seen in the borehole.

Rates of Vertical Accretion

The results of extensive and careful radiocarbon dating (62 dates) of borehole material from One Tree Reef are shown in Table 1 and Figs. 4A and B. The data allow the following major conclusions:

1) Holocene reef development at One Tree Reef began around 8,000 years B.P. confirming earlier predictions (Davies et al. 1976; Davies and Kinsey 1977; Davies and Marshall 1980).

2) The total variation in the rate of vertical reef accretion is 0.6–8.3 m/1,000 years.

3) The growth curves in Figs. 4A and B, suggest that vertical growth was largely uniform with inflections in the growth curves representing variations in growth rates, the time and depth of which vary from hole to hole. Such variations do not coincide with facies boundaries.

4) Accumulation rates for the two principal coral facies are similar. The coral head facies varies from 3.2–7.3 m/1,000 years in Hole 2 to 1.8–4.0 m/1,000 years in Hole 4. The latter range approximates better to accumulation rates published for Atlantic reefs (Adey 1975; Focke 1978). Overall variation in the branching coral facies is 0.6–8.3 m/1,000 years but throughout most of the sections rates of between 3.0–5.6 m/1,000 years predominate. Such rates are comparable to those described for *Acropora palmata* at Galeta, Panama (Macintyre and Glynn 1976) but are less than those described for *A. palmata* and *A. cervicornis* from St. Croix and Alacran (Adey 1975; Macintyre et al. 1977). Accumulation of the sand facies is much less (1.7 m/1,000 years) than that of the biologically in situ facies. However, Davies (1982) has shown that the main direction of sediment accretion is lateral, and confirms from quantitative sediment transport studies the vertical accumulation rates derived from radiocarbon dating.

No estimates have been derived for accumulation of either the algal pavement or the rubble flat facies because of their relative thinness and because of the dangers of dating material from such environments. While the reversed slope of the accumulation curve in the rubble facies shown in Hole 4 confirms a derived origin for the dated samples, a similar interpretation cannot be discounted for any material affected by a surf dominated environment.

Table 1. Radiocarbon dating results from cored corals at One Tree Reef

Drill-hole number	Core number	^{14}C Lab[a] code and number	Depth interval [m]	Mineralogy[b]	Conventional age [years B.P.]
1	1	NSW-316	0.20– 0.29	A	690± 80
1	2	NSW-317	0.29– 0.35	A	750± 80
1	11	NSW-311	1.02– 1.09	A	780± 80
1	15	NSW-309	1.19– 1.25	A	860± 80
1	16	NSW-310	1.25– 1.30	A	860± 80
1	21	NSW-313	1.58– 1.62	A	1210± 90
1	28B	NSW-318	5.10– 5.20	A	3760±140
1	35C	NSW-319	7.80– 8.30	A	5280±120
1	43D	NSW-314	13.50–13.70	A	> 30,500
2	3	NSW-289	0.39– 0.54	A	5290±120
2	4	NSW-293	0.54– 0.68	A	5330±120
2	5	NSW-301	0.68– 0.84	A	5380±150
2	7	NSW-290	0.94– 1.01	A	5330±120
2	8	NSW-302	1.01– 1.20	A/hmc	5310±120
2	10	NSW-291	1.50– 1.70	A	5400±120
2	11	NSW-298	1.70– 1.83	A	5310±120
2	12	NSW-294	1.83– 2.07	A	5460±120
2	15	NSW-299	2.27– 2.31	A/hmc	5310±120
2	20	NSW-300	2.79– 3.17	A/hmc	5760±130
2	20	NSW-295	2.79– 3.17	A	5780±130
2	22	NSW-296	3.24– 3.45	A	5680±130
2	31	NSW-292	5.79– 6.01	A/hmc	6820±130
2	36	NSW-297	8.20– 8.35	A	7440±140
3	2A	NSW-320	0.70– 1.20	A	950± 80
3	8B	NSW-312	7.56– 7.63	A	2140± 90
3	9C	NSW-308	8.67– 8.88	A	4180±110
3	9E	NSW-315	8.97– 9.26	A	4380±110
4	1B	GX-6950	0.05– 0.08	A	185±115
4	1D	GX-6951	0.51– 0.60	A	4155±135
4	1F	GX-6952	0.80– 0.98	A	4010±150
4	1G	GX-6953	0.98– 1.16	A	3910±135
4	2E	GX-6954	1.67– 1.83	A	3700±140
4	3C	GX-6955	3.20– 3.25	A	4020±150
4	4B	GX-6956	4.28– 4.34	A	4265±140
4	5D	GX-6957	5.33– 5.40	A	4455±145
4	6E	GX-6958	6.57– 6.65	A/hmc	4885±160
4	7B	GX-6959	8.38– 8.58	A	5535±150
4	8B	GX-6960	9.40– 9.53	A	5560±175
4	8F	GX-6961	10.27–10.47	A	6415±165
4	9B	GX-6962	10.80–11.03	A	6460±185
5	1A	GX-6963	0.00– 0.10	A/hmc	4350±140
5	2C	GX-6964	0.80– 0.95	A/hmc	4185±150
5	3B	GX-6965	1.65– 1.78	A	4640±140
5	4A	GX-6966	3.06– 3.22	A/hmc	4650±160
5	6B	GX-6967	5.70– 5.86	A	6105±160
5	6E	GX-6968	6.22– 6.41	A/hmc	5715±175
5	7A	GX-6969	7.15– 7.30	A	4845±145
5	8B	GX-6970	8.05– 8.25	A	5915±170
5	8E	GX-6971	9.00– 9.50	A/hmc	6390±185
5	9B	GX-6972	10.33–10.70	A	6980±180
5	9E	GX-6973	11.70–11.80	A	7045±195
5	10B	GX-6974	13.05–13.15	A	6925±215
6	2	WK-253	0.65– 0.90	A	5390±180
6	3B	WK-254	1.70– 1.80	A	5880±100
6	5D	WK-255	3.52– 3.78	A	5950±200
6	6B	WK-256	4.97– 5.18	A/hmc	6910±140
6	7B	WK-257	6.75– 7.02	A	6390±180
6	8B	WK-258	7.80– 8.00	A/hmc	6700±210
6	9C	WK-259	9.35– 9.55	A/hmc	7250±140
6	10C	WK-260	10.40–10.58	A	7430±190
6	10G	WK-261	11.09–11.31	A	7800±270
6	11B	WK-262	12.00–12.40	A	7380±240

[a] NSW = University of New South Wales Radiocarbon Laboratory
GX = Geochron Radiocarbon Laboratory
WK = Waikato University Radiocarbon Laboratory

[b] A = Aragonite
hmc = High magnesium calcite (≦5%)

Discussion

We believe that our data raise three points of significance: (1) The relations between accumulation rate and sea level history; (2) the environmental significance of the recognized facies, and (3) a scheme of facies evolution for One Tree Reef within rigid time constraints. It is proposed to treat each point in turn.

1) For eastern Australia Thom and Chappell (1975) have established a relative Holocene sea level curve which exhibits two essential components, a decrease in the rate of sea level rise from 10 m/1,000 years to 6 m/1,000 years around 7,500 years B.P., and a final stabilization of sea level at about its present level 6,250 years B.P. The envelope of radiocarbon dates representing the Thom and Chappell sea level curve is superimposed on the growth rate curves shown in Fig. 4A, B. Comparisions of sea level and growth rate curves prior to stabilization of sea level, shows that the depth of water between sea level and reef top was increasing. This is well illustrated in Fig. 5 for growth curves 2, 5 and 6, i.e. water depth is increasing 2–3 times faster than reef growth. Clearly if this had continued in the southern Great Barrier Reef, the reefs would have drowned. However, coincident with sea level stabilization around 6,250 years B.P., Fig. 5 also indicates that reef growth was increasingly and rapidly able to catch up to sea level and this occurred from depths as great as 7.5 m. Significantly, the top of the patch reef was deeper than the windward margin at the time of sea level stabilization and yet was able to reach sea level first because of the faster accumulation rate exhibited by the branching coral facies compared with the head coral facies of the windward margin.

2) We have identified and distinguished three major biologic-sedimentologic facies in our drill core. Their windward to leeward distribution suggests that wave energy is an important factor in their development. The coral head facies forms a massive framework, occurs on windward margins and predominates in shallow water throughout the Holocene; we interpret this as a high energy

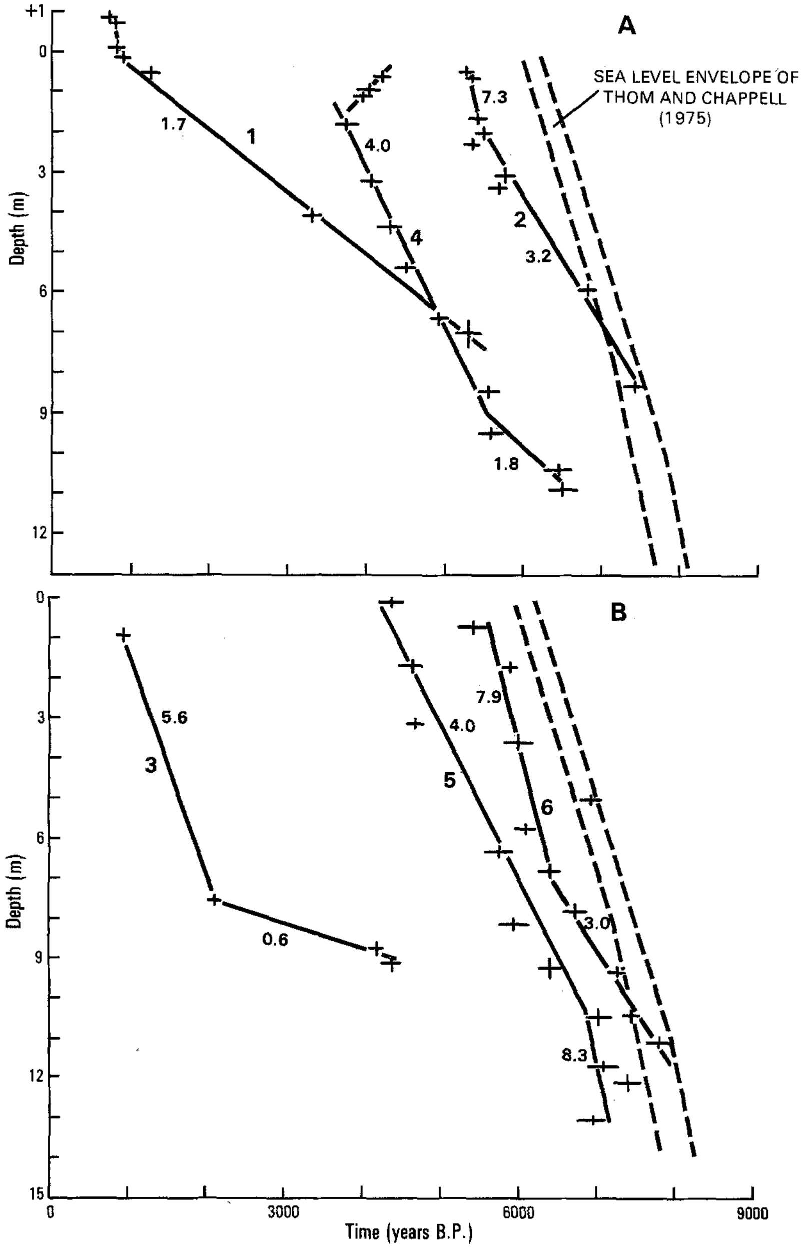

Fig. 4A, B. Rates of vertical reef accretion (in m/1,000 years) for **A** windward sites (holes 1, 2 and 4) and **B** leeward sites (holes 3, 5 and 6) showing their relationship with the sea level curve of Thom and Chappell (1975)

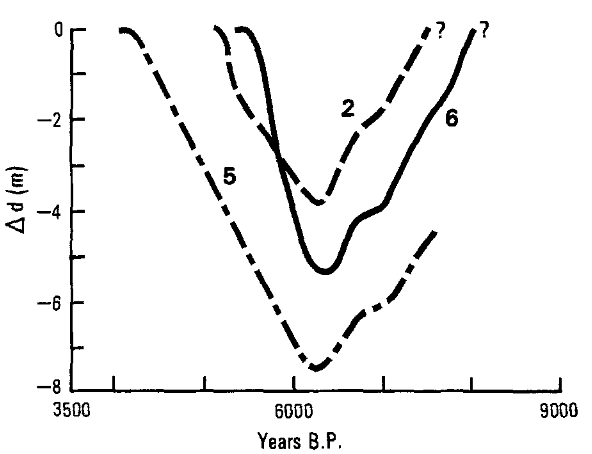

Fig. 5. Curves showing the differential height between reef top and sea level for holes 2, 5 and 6, both prior and subsequent to sea level stabilisation at about 6,200 years B.P.

facies. The algal pavement facies associated with, and topping the coral head facies, is the shallowest water and highest energy facies. The branching coral facies occurs predominantly in leeward or protected environments, and is interpreted as a low energy facies. Significantly, in hole 4, this facies did not develop until the windward rim had reached sea level and was offering maximum protection.

3) Stages in the facies evolution of One Tree Reef within rigid time constraints may be reconstructed using the data in this paper together with seismic, radiocarbon, tidal and sedimentologic data published previously for this reef (Harvey et al. 1979; Davies et al. 1976, 1977; Davies and Marshall 1980; Luddington 1979). Such diagrams are shown in Figs. 6A, B and C in which facies boundaries are interpolated and in which the following three time-growth periods are recognized.

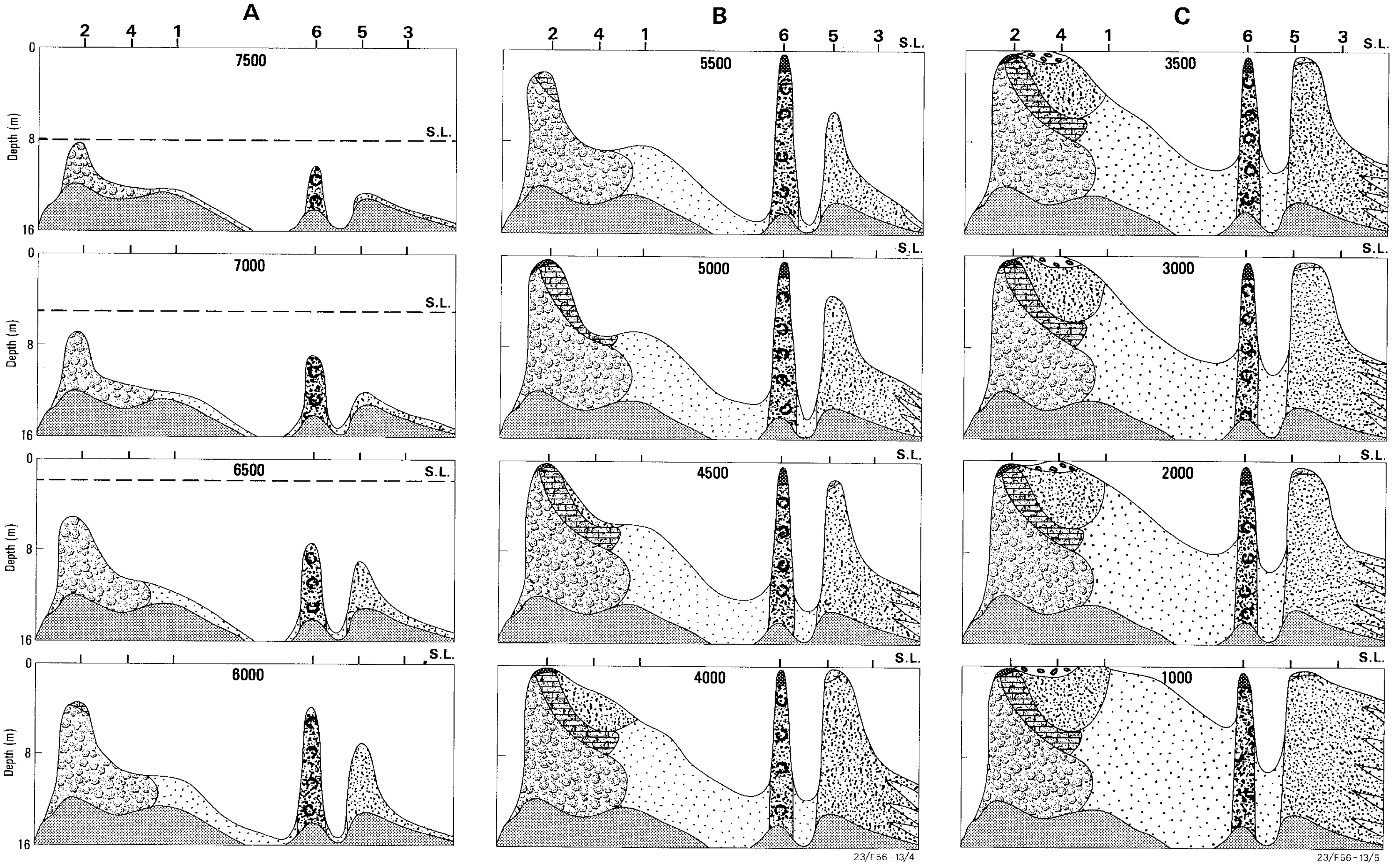

Fig. 6A–C. Diagramatic reconstruction of the Holocene evolution of One Tree Reef during three stages: **A** initial vertical growth phase; **B** transitional growth phase; **C** lateral growth phase. For key to symbols see Fig. 2

(i) 8,000 to 6,000 years B.P. – Initial Vertical Growth Phase (Fig. 6A)

Soon after transgression of the pre-Holocene subaerially eroded surface, reef growth initiated almost synchronously as head coral assemblages on windward margins and branching assemblages on substrates to leeward. Growth was dominantly vertical as sea level rise was faster than reef growth rate. The increasing protection offered to leeward environments resulting from the slow growth of the windward margin into shallow water may have precipitated the increased growth rate of the leeward patch reef around 6,400 years B.P. resulting in windward margins and patch reef achieving a similar level with respect to sea level by 6,000 years B.P. During this period the reef was entirely subtidal.

(ii) 6,000 to 4,000 years B.P. – Transitional Growth Phases (Fig. 6B)

After stabilization of sea level, the reef continued to accrete vertically. The patch reef and windward margin developed coralline algal cappings as they approached the intertidal zone (2.5 m tidal range currently at One Tree) and ultimately reached stabilized sea level around 5,000 years B.P. Between 5,000 and 4,000 years B.P. the dominantly branching corals of the windward reef flat developed (Hole 4) and parts of the leeward margin approached sea level, as evidenced by development of an encrusted coral head sub-facies (Hole 5). Lagoon sediment infill began around 5,000 years B.P.

(iii) 4,000 years B.P. to Present – Lateral Growth Phase (Fig. 6C)

The major phase of lateral expansion of the reef is evidenced by the progradative growth of the sand sheets and coral flats, and lateral expansion of the leeward margin in a manner similar to the windward margin. Lagoon infill was greatly enhanced by the development of linear and reticulate patch reef systems.

The growth scheme outlined above is the effective response of an ecosystem to basic physical and biologic parameters which have acted similarly not only throughout much of the Great Barrier Reef, but in many other coral reef provinces. Subsequent drilling in the central and northern Great Barrier Reef since 1979 has convinced us that the essential elements of the One Tree story is repeated time and again, i.e. growth is vertical and then progradative to leeward. We are encouraged by the recent recognition that the Holocene section of the Belize barrier reef has growth in a similar manner i.e. vertically and laterally backwards (Macintyre et al. 1982). If such principles of growth are generally established for known physical parameters, further interpretations and possible re-interpretations of both modern and ancient reefal sequences may prove useful and interesting.

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