In: Purcell, P & R, eds:
The Sedimentary Basins of Western Australia 2: Proceedings. PESA Symposium Perth, 1998:
p 647-663

Late Tertiary–Quaternary Geological Evolution of the Houtman Abrolhos Carbonate Platforms, Northern Perth Basin.

Lindsay B. Collins[1], Zhong Rong Zhu[1] and Karl-Heinz Wyrwoll[2]

Abstract

The Houtman Abrolhos coral reefs are three shelf-edge carbonate platforms which together form the discontinuously rimmed Abrolhos Shelf. During the Tertiary to Quaternary there was a vertical transition from cool-water ramp sedimentation to reefal platform development near the shelf edge, producing a discontinuously rimmed shelf during the Quaternary. The facies transition owes its existence to regional patterns of oceanographic circulation, driven in the longer term by plate tectonic and palaeolatitude changes, whilst changes in the frequency of sea level oscillations controlled a transition from late Tertiary third order cycles, to fourth and fifth order cycles during the Quaternary. Seismic investigations and coring have confirmed the existence of 4–6 m thick, unconformity-bounded shelf sequences which are the lateral equivalents of reef buildups within the platforms during the Quaternary.

Reef limestones of Last Interglacial age are dense and calcretized, in marked contrast with the more porous Holocene lithofacies. Coral framestone facies of the Last Interglacial consist mainly of branching coral or head coral, with minor encrusting coralline algae and white lime mud. The exposed uppermost part of the Last Interglacial reefs of the central platforms normally consists of an upward-shallowing sequence, commonly 2–3 m thick and locally up to 6 m thick. In the 'large' islands of the Wallabi Group, aeolianites cap the sequence.

Late Quaternary platform evolution has been influenced by sea level oscillations and differing wave energy regimes. Each of the three island groups in the Abrolhos consists of a central platform of Last Interglacial reefs, about which windward and leeward Holocene reefs have developed asymmetrically. Most Holocene reef growth took place on the lee-side of an antecedent platform from an essentially flat surface, generating Holocene constructional topography characterised by 'blue-hole' terrain, which was previously interpreted as karst. The Holocene sea level record provided by dates from the 40 m thick leeward reef is the first such record from the western continental margin of Australia.

The Abrolhos carbonate platforms provide new insights into the evolution of carbonate ramps to rimmed shelves on passive margins, cool- to warm-water carbonate facies transitions, and the interaction of sea level change, antecedent topography and wave energy regimes in platform evolution and facies architecture. An understanding of these geological processes is also vital for sound environmental management.

Introduction

The southwestern continental margin of Australia is characterised by a narrow, open shelf with a latitudinal gradient along its length, from North West Cape at 22°S to Cape Leeuwin in the south at 34°S (Fig. 1). This segment of shelf lies within a region of overlapping biogeographic zones, which range from tropical in the north to warm temperate in the south (Wilson & Allen, 1987; Morgan & Wells, 1991). In addition, the poleward-flowing Leeuwin Current carries warm, low salinity water from northwest Australia to Cape Leeuwin, and then across the southern Australian margin (Cresswell & Golding, 1980; Church et al., 1989; Cresswell, 1991). This current disperses tropical representatives of many taxa to southwestern and

[1] School of Applied Geology, Curtin University of Technology, Perth, Australia, 6102.
[2] Department of Geography, University of Western Australia, Nedlands, Australia, 6009.

Acknowledgements: This research was funded by the Australian Research Council. We would also like to thank the following organisations and individuals for support and assistance: Fisheries Department of Western Australia (including Captains and crews of R.V. Flinders and RV. McLaughlan; and particularly Randall Owens) for logistic and marine support; seismic data acquisition: Department of Geology and Geophysics, University of Sydney (Prof. Peter Davies and Mr David Mitchell); drilling assistance: Department of Biogeography and Geomorphology, ANU, particularly Damien Kelleher; and Mosslake Drilling Pty Ltd. The following are thanked for biotic identifications: WA Museum and Mr G. Kendrick (molluscs), Ms L. Marsh (echinoderms; corals). Vessel support from Island Leader 2 and Ray Horvarth, and CSIRO and R.V. Franklin (Cruise 01/96) is gratefully acknowledged.

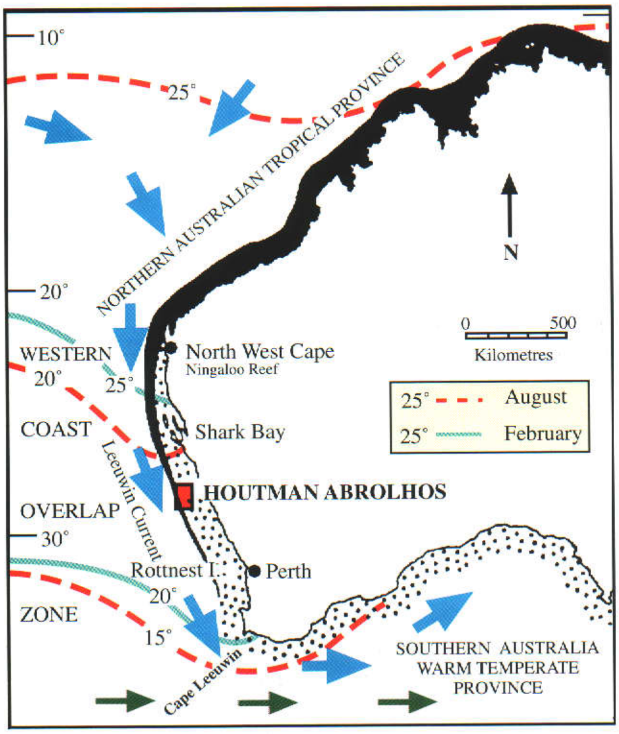

Figure 1: The western continental margin of Australia, showing regional oceanography, and biotic zones. Data after Morgan and Wells (1991) and Pearce (1991). Note position of the Leeuwin Current and seasonal movement of isotherms.

southern Australia.

This paper describes the sedimentology and carbonate platform evolution of the Abrolhos Shelf (that part of the northern Rottnest Shelf at latitudes 28-29.5°S with shelf-edge coral reefs; France, 1985), which lies within the biotic transition zone. The shelf is bounded by tropical carbonate sediments to the north (latitudes 22° to 26° S) and cool-water shelf sediments to the south (latitudes 32° to 34° S). This region includes the Houtman Abrolhos reefs (Fig. 2), three shelf-edge carbonate platforms regarded as the southernmost occurrence of coral reefs in the Indian Ocean (Hatcher, 1991; Veron, 1995).

The Houtman Abrolhos islands are small islands of Holocene and Pleistocene reef limestone which occur within a chain of coral reefs located 70 km from the Western Australian coast, in the eastern Indian Ocean. The exposed parts of the reef complex consist of over 100 small islands which occur in three groups (the Wallabi, Easter and Pelsaert groups; Fig. 2). The islands, generally of only a few metres of elevation, are mainly rocky, sparsely vegetated, and uninhabited except during the three month rock lobster fishing season.

Early descriptions of the geology and geomorphology were provided by Teichert (1947) and Fairbridge (1948), and more recently France (1985) studied the Holocene

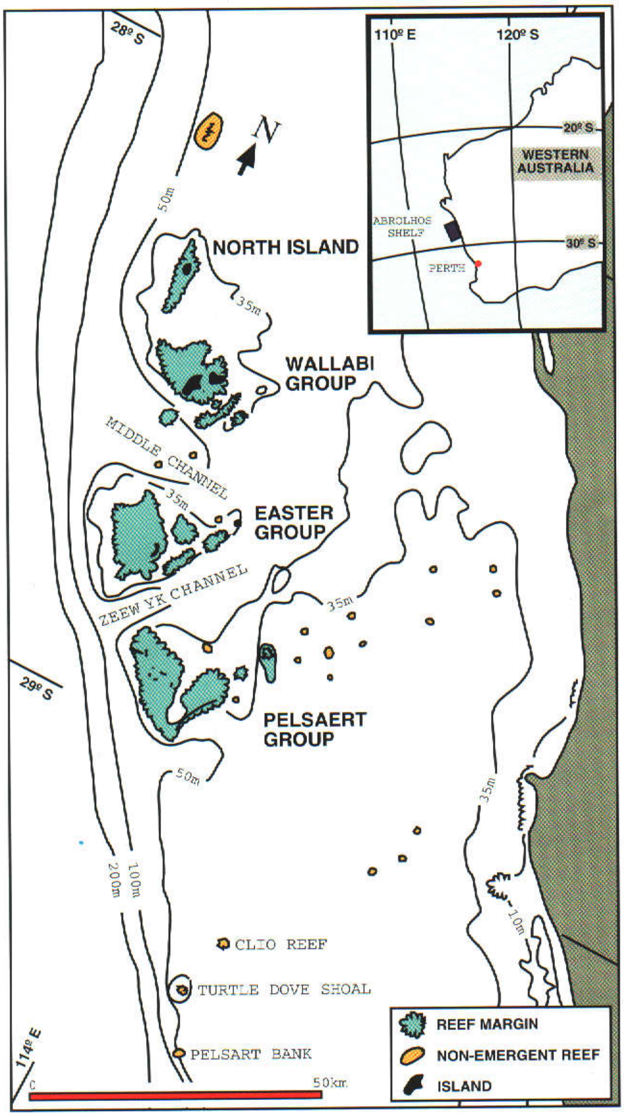

Figure 2: Location map of the Abrolhos Shelf (inset) and Houtman Abrolhos carbonate platforms.

geology of the Pelsaert Group. Current geological research by Curtin and UWA has been in progress since 1990 (Eisenhauer et al., 1993; Collins et al., 1993a, b; 1996; 1997a, b; Zhu et al., 1993). During the 1960s there was a significant amount of hydrocarbon exploration interest in the Abrolhos Sub-basin, and this led to the drilling of the Gun Island 1 well at the end of the decade. Subsequently a number of further wells were drilled, notably Batavia 1, Geelvink 1A and Houtman 1. More recently, a significant amount of marine seismic was completed over the sub-basin. The hydrocarbon potential has been discussed by Smith and Crowley (1987) and Quaife et al. (1994).

During the 1990s geological research has involved geological mapping of the islands, shallow seismic surveying, and drilling and dating of the reef complex.

The Abrolhos carbonate platforms provide data on the evolution of carbonate ramps to rimmed shelves on passive margins, cool- to warm-water carbonate facies transitions, and the interaction of sea level change, antecedent topography and wave energy regimes in platform evolution and facies architecture. Such data may assist in refining exploration strategies when working with ancient carbonate facies. In addition, when exploration is taking place near coral reef environments, an understanding of both geological and biological processes is necessary for sound environmental management of the reef systems.

Methods

The study is based on petrographic and mineralogic compositions of sediment samples (80 from the continental shelf and 70 from platform environments) and twelve sediment cores collected on several oceanographic cruises to the region (see Zhu et al., 1993; Collins et al., 1993a, b; 1996; 1997a, b). Eight drill cores were taken in reefs on the Abrolhos platforms, in the Easter and Wallabi platforms. A further two cores were taken to a depth of 60 m in the Easter Platform to test a model developed from a 100 line-km shallow (Boomer) seismic survey which was conducted over the Easter Platform and adjacent shelf. A detailed dating program, using U-series Thermal Ionisation Mass Spectrometry (TIMS) and alpha counting, and 14C Accelerated Mass Spectrometry (AMS) and conventional dating, was completed to determine Late Quaternary events (see Eisenhauer et al., 1993, Collins et al., 1993a, b, Zhu et al., 1993).

Regional Setting

The study area (Fig. 1) is in the Abrolhos Sub-basin, a part of the Perth Basin, which lies along a quiescent, rifted margin (Veevers, 1974; Smith & Crowley, 1987; Quaife et al., 1994). Well data indicate that the basin has been an area of carbonate sedimentation since the Late Cretaceous. During the Tertiary the sub-basin saw the development of a seaward-thickening carbonate wedge dominated by bryozoan-mollusc-echinoid calcarenites and calcilutites and lacking reef-building corals (Fig. 3). Our knowledge of the precise depth of the transition to reefal carbonates beneath the platforms is hampered by an interval of no recovery (between 70 and 130 m depth) in the Gun Island 1 well drilled through the Pelsaert Platform. The shallowest of the known Tertiary sediments are Late Eocene at a depth of 130 m, and these are non-reef calcarenites dominated by bryozoans, foraminifers and molluscs (Hawkins, 1969). A thin sheet of post-Eocene carbonates is present to 70 m, and the deepest coral below the top of the well is recognised from cuttings

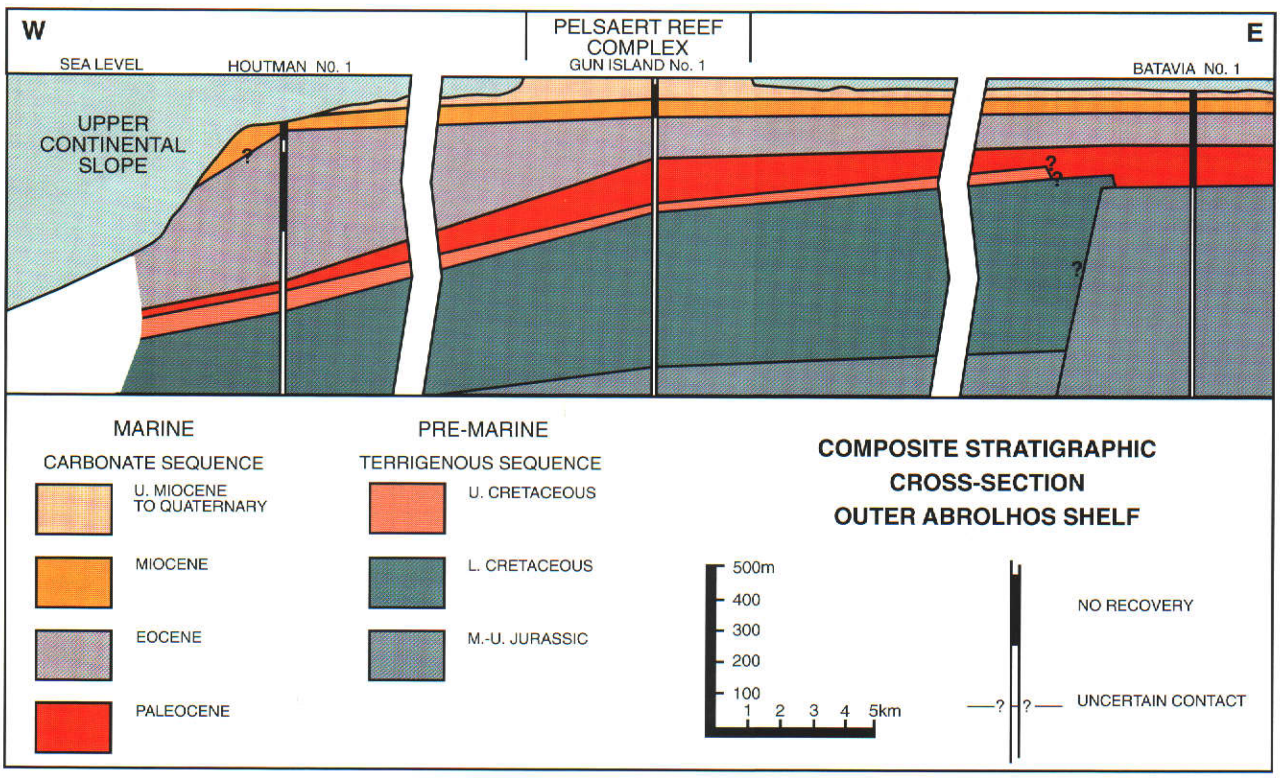

Figure 3: **Geological cross-section of the Abrolhos Shelf at the latitude (28.9°S) of the Pelsaert Platform. After France (1985) and Collins et al. (1997).**

at 67 m. These limited data suggest that the maximum possible thickness of reef complex in the platforms is 130 m, and the minimum may be 70 m.

Seismic and shallow core data obtained recently confirm that 40 m of Quaternary reef buildup has occurred, and details of platform structure will be discussed here. A vertical facies transition took place at the Abrolhos, from cool-water shelf carbonates in the Eocene and Miocene to warm-water platform carbonates in the Quaternary.

Geomorphology

Between latitudes 28° to 29.5°S the open, low-gradient shelf is interrupted by a 150 km long, discontinuous rim, whose seaward margin is 8-10 km east of the shelf/slope break (Fig. 2). The emergent rim consists of three platforms (Pelsaert, Easter and Wallabi platforms; the latter including North Island) separated by channels up to 40 m deep. Each platform rises abruptly some 40 m above a flat shelf, and is expressed as reef flats and low islands. Submerged banks lie to the north and south of the platforms, along the same trend.

The three platforms differ geomorphologically but a windward reef, leeward reef, and lagoon with a central platform is distinguishable in each case (Fig. 4). Both the central platforms and leeward reefs are expressed as small islands of various types, whereas windward reefs are wave-swept. The central platforms are Last Interglacial in age, whereas the windward and leeward reefs are

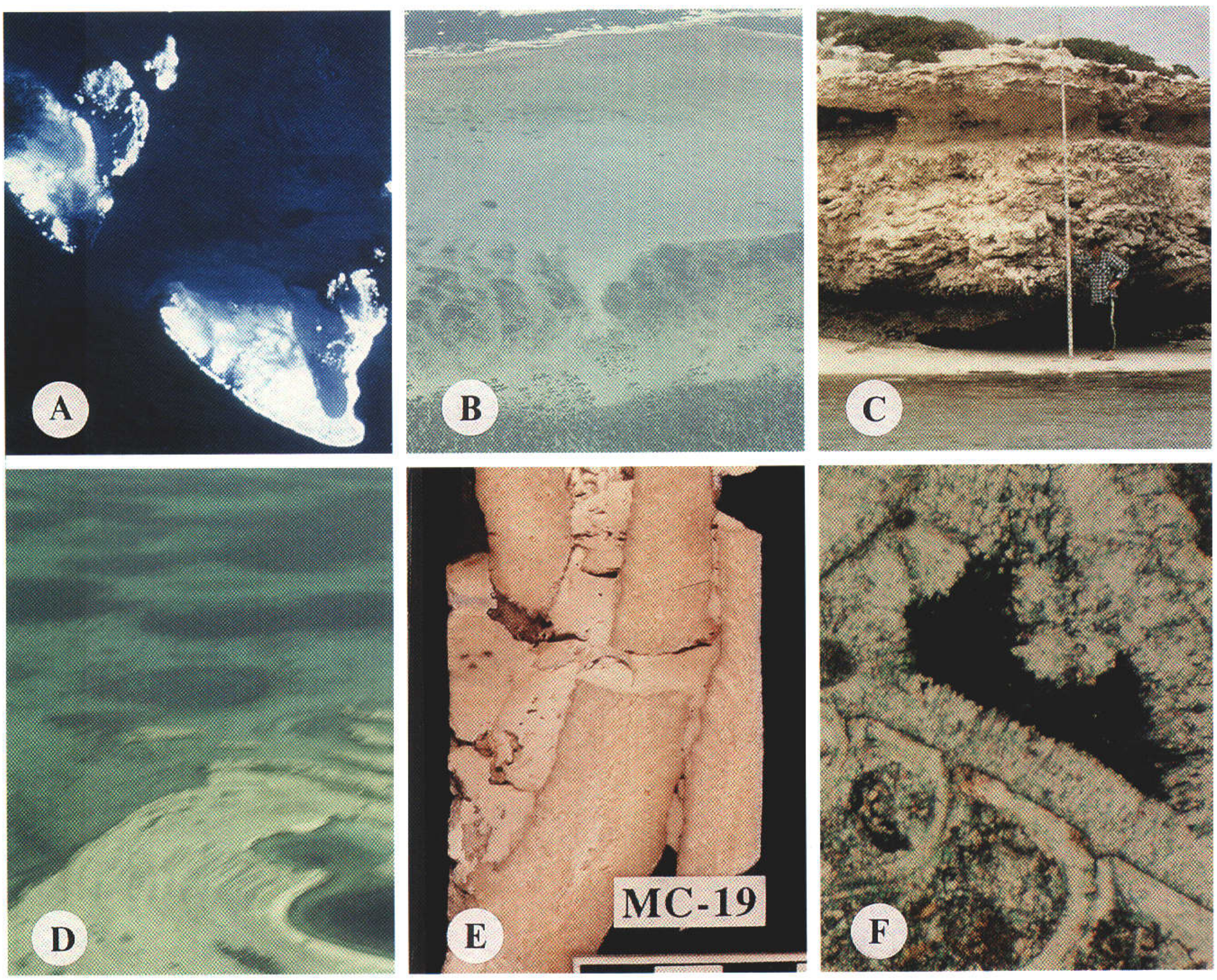

Figure 4: Morphological features of the Abrolhos platforms. A. Landsat view of Easter Platform (top) and Pelsaert Platform. Windward and leeward reefs and central platform are cleary visible in the Easter Platform (width 25 km). B. Aerial oblique view (looking west) of windward reef and sand sheet in lagoon, Easter Platform. C. Central Platform island, consisting of emergent Last Interglacial reef, Turtle Bay, Wallabi Platform. Vertical scale is 5 m. D. View of leeward Holocene island (Serventy Island; foreground) and associated 'blue-hole' terrain, Easter Platform, looking west. E. Core of Holocene reef facies, Easter Platform, Morley 1 core. F. Isopachous bladed Mg-calcite, an early marine cement in Holocene reef facies from Morley 1 core. Thin section, MCP7, crossed polars; width of field is 0.7 mm.

Holocene (Eisenhauer et al., 1993; Collins et al., 1993a, b; Zhu et al., 1993). The islands generally rise only 3-5 m above sea level. Extensive 'blue-hole' terrains and reticulate reefs occur at the eastern parts of the platforms, and Holocene sand sheets have developed in both the windward and leeward lagoons. Central platform islands are surfaced by dense, calcretized limestones, while subparallel ridges of coral rubble characterise leeward (eastern) islands.

Climate and Oceanography

The Abrolhos region has a Mediterranean climate, with hot, dry summers, cool, wet winters and a tidal range of <1 m. Dominant winds are from the southwest to southeast, but winter storms are from the west and northwest. Summer tropical cyclones pass through the area with an average frequency of once every three years (Steedman, 1977). Runoff from the continental hinterland to the east is low and seasonal.

Persistent swell waves with a mean height of 1.2 m (range commonly 1–3 m) and periods of 12–14 seconds impinge on the region throughout the year, approaching from the south and west 78% of the time (Steedman, 1977), forming a high energy, windward regime, and medium energy, leeward margins due to refracted swell and wind waves. Northern margins experience low wave energy, except during storm events.

The shelf is open and swell wave-dominated. Long period (12–14 s) waves from the southwest have wavelengths of up to 200 m, with implications of sorting of sands by oscillatory motion to water depths of 100 m. Using wave equations of Komar (1976) and the wave data of Steedman (1977), the entire shelf, to at least 100 m depth, is subject to wave-induced currents which are strong enough at some stage of the wave-climatic cycle to entrain sediment of coarse sand size, and gravel size material on the 50 m deep inner shelf plain (France, 1985).

Mean annual sea surface temperatures range from 26°C in summer to 18°C in winter (Wilson & Marsh, 1979). They fall below 20°C for up to 30% of the time (France, 1985) and may fall below 17–18°C for several days at a time in areas of restricted circulation on the platforms (Wilson & Marsh, 1979). Both shelf and platform waters have a similar temperature range.

The Leeuwin Current is an important influence on regional oceanography. As a southward-flowing current, it brings warm, low salinity water past the Abrolhos region. The current usually peaks in winter., becoming weak in summer (Pearce, 1991). It flows along the outer continental margin, intercepting offshore islands such as the Abrolhos. Peak current speeds can exceed 1.5 m/s. The western (offshore) boundary of the current is well defined, with differences of 2-5°C between the warm current water and that offshore. The inshore boundary is, however, less clearly defined, and the thermal gradient is weaker. Though the Leeuwin Current often rides the continental slope 15-20 km west of the Abrolhos platforms, there appears to be a persistent, large-scale cyclonic eddy in the current at this latitude (Pearce & Griffiths, 1991; Hatcher, 1991). Sporadically, the warm waters of the current flood the shelf edge around the Abrolhos, while at other times it forms a narrow jet well to the west (Pearce & Griffiths, 1991). The Leeuwin Current is believed to be an important control in the maintenance of vigorous reefs near the limits for reefbuilding coral growth.

Biogeography

The Abrolhos region is located within a biotic transition, the Western Coast Overlap Zone (Morgan & Wells, 1991) which lies between the Northern Australian Tropical and Southern Australian Warm Temperate provinces. It is characterised by the gradual replacement of a tropical fauna in the north by a predominantly temperate fauna in the south, as reflected in a variety of shelf and reef biotic elements, including corals, macroalgae, molluscs, echinoderms and fishes (Morgan & Wells, 1991). The sediment-forming community on the shelf is dominated by bryozoans and coralline red algae, whilst corals and coralline algae are most significant on the platforms, with contributions from molluscs, foraminifers and echinoderms in both settings.

Coral faunal communities are highly diverse: 184 species and 42 genera are recorded (Veron & Marsh, 1988). The number of genera is much higher than for other 'high latitude' coral reefs (e.g. Veron, 1974: the Solitary Islands; Dana, 1971: Kure Atoll; Garrett et al., 1971: Bermuda Reefs). *Acropora*, which is missing or vary rare on many 'high latitude' reefs (Garrett et al., 1971, Smith, 1981) is the dominant coral. Although there are substantial numbers of temperate species and Western Australian endemic species the fauna at the Abrolhos is, on balance, considered to be essentially tropical (Morgan & Wells, 1991), and the Abrolhos is generally considered to be the southern limit in Western Australia of the tropical biota.

Seismic Structure

A shallow seismic survey investigated the structure of the windward reef, leeward reef, and windward and leeward lagoons (including 'blue-holes') of the Easter platform (Collins et al., 1996), and representative seismic profiles are shown in Figs 5 &6. The windward reef is terraced, and has little Holocene coral growth, consistent with drilling results. There is an absence of continuous seismic reflectors beneath the terraces (Fig. 6A). The windward lagoon has thin 3 m) sand sheets over a rocky

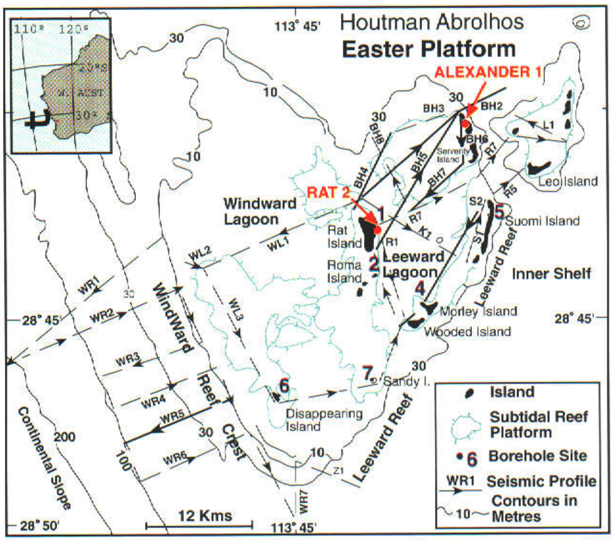

Figure 5: Map of Easter Platform showing location of seismic lines and drillholes.

substrate with Holocene coral veneers. Dense, calcretised limestones of the central platform were not penetrated seismically, so little data were obtained on platform structure. The leeward lagoon has a prominent seismic discontinuity at 40 m below sea level (Fig. 6B). The Last Interglacial surface (reflector R1) can be traced from the emergent surface of the central platform (Rat Island), to beneath White Bank and the lagoon sand sheet as an essentially flat horizon, to beneath the 'blue hole' terrain to the northeast of the lagoon. This reflector defines the base of the Holocene sequence.

Holocene coral reefs are uniformly 40 m thick in the leeward reefs, rising from the -40 m discontinuity which is identifiable as the Last Interglacial surface by lateral correlation into the central platform outcrops. 'Blue hole' topography of the leeward lagoon developed from a nearly flat antecedent surface of relief 1 m. and elevation of 40 m below sea level. In the leeward lagoon, below 'blue-hole' terrain, beneath the leeward reefs and onto the adjacent shelf, a total of four subhorizontal seismic discontinuities were identifed as continuous horizons at 40, 48, 56 and 60 m below sea level (Collins et al., 1996). Line BH5 (Fig. 6C) and BH6 (Fig. 6D) show Holocene pinnacle reefs within 'blue-hole' terrain underlain by three subparallel reflectors, the uppermost of which (R1) is uniformly at -40m, and the lowermost (R4) is at -60 m. Apparent relief on the reflectors is largely due to velocity pull-up/pull-down effects. Seismic line S2 (Fig.6E) shows the leeward lagoon floor with a sand sheet and pinnacle reefs, within reticulate leeward reef terrain. At the Morley 1 drillsite, where over 26 m of Holocene reef has been recorded, the interpreted Holocene reef thickness (above R 1) is 40 m. Reflectors 2 and 3 are present at 47 m and 53 m respectively, and Reflector 4, at 64 m, is visible at left. A buried reef terrain is present beneath the sand floor of a large 'blue hole' adjacent to the drillsite.

The structure of the leeward reef crest and adjacent shelf to the east is shown in line BH 1 (Fig. 6F), where the Holocene reef buildup is 40 m thick. Also visible are four sub-parallel reflectors (R1-R4) which extend from beneath the 'blue-hole' terrain and the leeward reef crest, to the adjacent shelf, where R1 is practically exposed, and underlies a thin, Holocene sediment veneer.

The model generated from analysis of the seismic results allowed subsurface mapping of the Holocene and Last Interglacial reefs, and provided targets for deep stratigraphic coring.

Platform Facies, Evolution, and Sea Level History

The seismic model for the Easter Platform was investigated by two cores (Fig. 7) taken to 60 m; one in the central platform islands (Rat 2) to investigate platform foundations and early Pleistocene history, and one in the leeward reefs (Alexander 1) to verify Holocene reef thickness and to investigate continuous seismic reflectors at depths of 40–60 m below the leeward reefs. This was in addition to shallow (<30 m) cores which were dated by U-series and AMS 14C to assess Holocene and Last Interglacial reef development.

The model developed for the platform (Fig. 8) is incomplete with respect to the pre-upper Pleistocene sequences due to the lack of seismic penetration of deeper parts of the central platform, and limited core data from the windward platform margin which presents access problems to drilling equipment. Nevertheless, it has been possible to develop a generalised model of platform evolution, facies and sea level history from the available subsurface data.

Platform Foundations

The basal 30 m of the Rat 2 core in the eastern central platform margin consists of recrystallised skeletal packstone to wackestone which is cavernous and vuggy, and of calcitic mineralogy. The sequence is monotonous and has a poorly preserved molluscan assemblage whilst lacking reef-building corals. A Pliocene molluscan assemblage has been identified from similar (but not identical) lithofacies at the base of the Alexander 1 core below the leeward reefs, and a similar age is tentatively assigned here. This shelf carbonate unit originally formed a topographic high, 6 m above the contemporary shelf surface, on which reef and platform facies subsequently developed. On the basis of the elevation of this facies (34 m below sea level and 6 m above shelf plain level in Rat 2; 20 m higher in Rat 2 than in Alexander 1; see Fig. 7), we speculate that the Abrolhos reefs were initiated on a

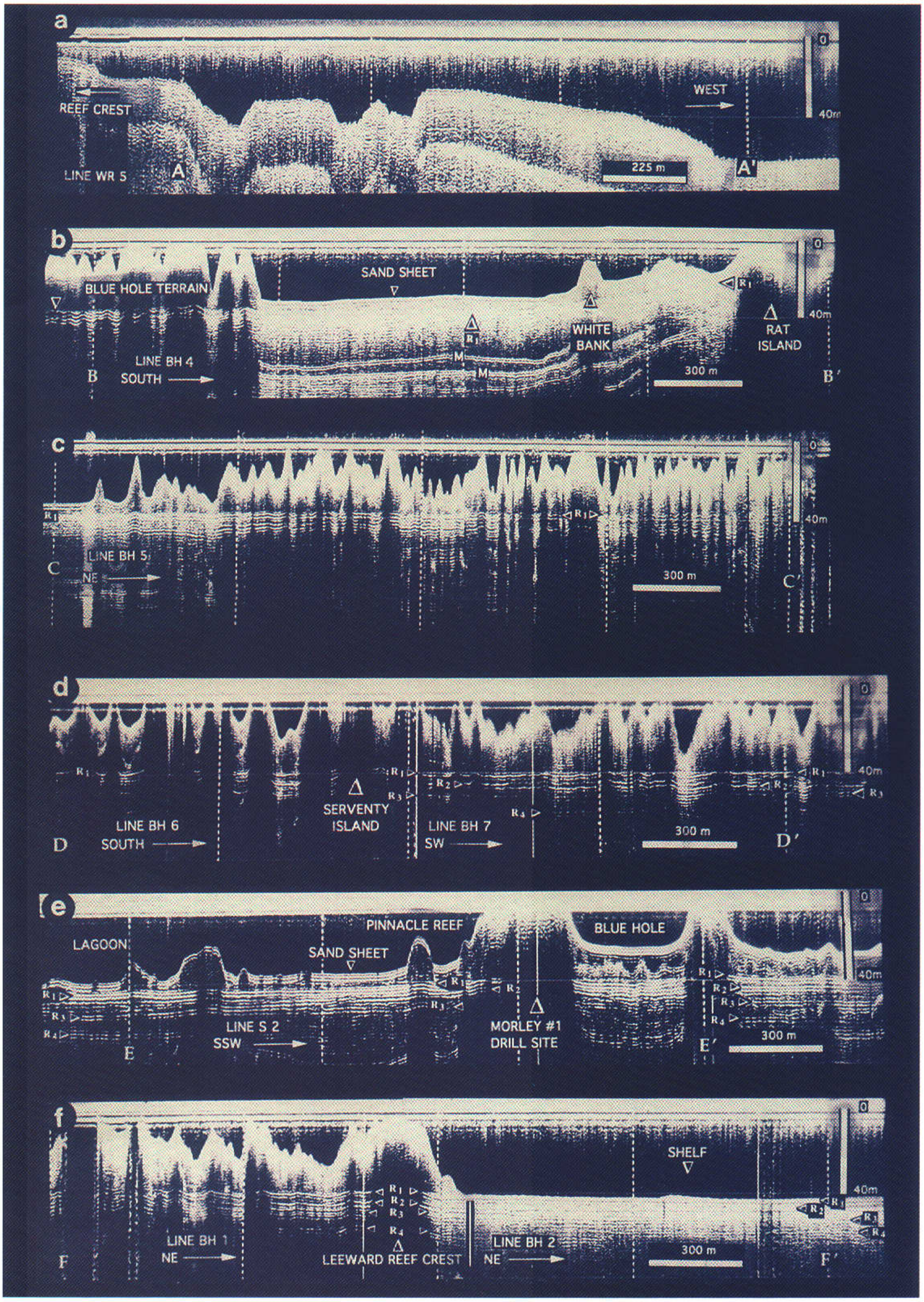

Figure 6: Seismic profiles of Easter Platform. A. Windward reef, showing terraced morphology. B. Seismic line across the northern part of the leeward lagoon. The Last Interglacial surface (R1) defines the base of the Holocene sequence. (M=multiple). C. Line BH5 shows Holocene pinnacle reefs within 'blue-hole' terrain underlain by three subparallel reflectors. D. Seismic line BH7 shows development of coalescent pinnacle reefs, within 'blue-hole' terrain. E. Seismic line S2 shows leeward lagoon floor with sand sheet and pinnacle reefs, within reticulate leeward reef terrain. Note buried reef terrain beneath the sand floor of 'blue hole' adjacent to drillsite. F. Seismic line BM1 shows leeward reef crest and adjacent shelf to the east. Note continuity of reflectors 1, 2, 3 and 4 from beneath 'blue-hole' terrain to the adjacent shelf.

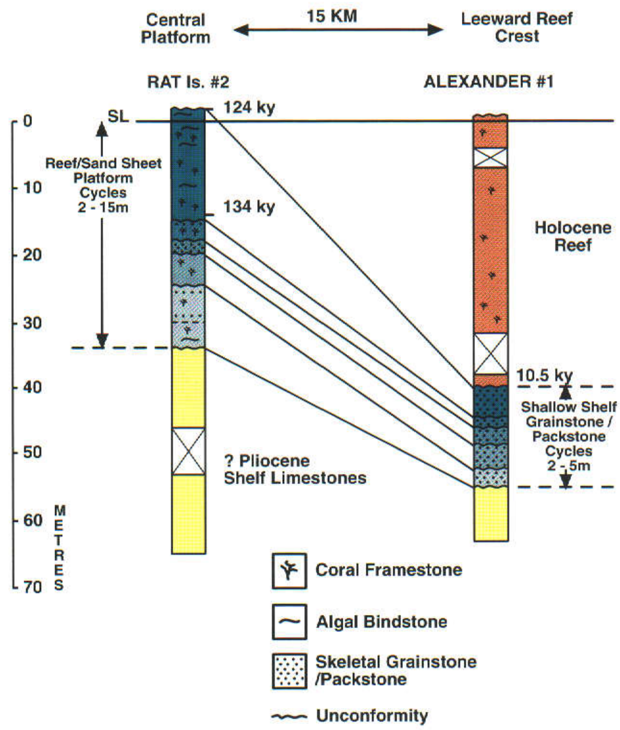

Figure 7: Summary logs of Rat 2 and Alexander 1 cores in central platform and leeward reefs, respectively, Easter Platform.

pre-Pleistocene topographic high which was probably tectonically produced. It should be emphasised that these data are available only for the Easter Platform.

Lower–Mid Pleistocene Platform and Shelf Facies

Whilst the age of the Late Pleistocene (Last Interglacial; oxygen isotope Stage 5e) reef facies are well known, the underlying lower-mid Pleistocene units also intersected by the Rat 2 and Alexander 1 cores are still undetermined. The correlation of the unconformity-bound packages between the two cores (from central platform to the shelf beneath the leeward reef; see Figs 7 & 8) is regarded as tentative until further U-Series dates are available. The correlation is based on the laterally traceable unconformity of top Last Interglacial age, and the matching of successively lower unconformities between the two cores. Thin laminar calcrete horizons mark cycle tops in the cores, and these closely match seismic discontinuities at the Alexander 1 site. In each of the cores there are at least three clearly identified unconformity-bound cycles of only a few metres thickness (Fig. 6).

Platform Facies

The lithofacies represented in the platform cycles in Rat 2 are coral reef framestone with thin intercalations of algal bindstone and skeletal grainstone (similar to Late Pleistocene and Holocene reef facies cored elsewhere in the platform), and one cycle of skeletal grainstone (platform sand sheet facies) is also present. The cycles are thin (2–6 m), and are bounded by unconformities expressed as laminar calcrete horizons (Fig. 7).

Shelf Facies

In contrast to platform facies, shelf facies consist of skeletal grainstone to packstone, in which articulate coralline algal rods, foraminifers (notably the discoid larger foraminifer *Amphisorus* sp.), echinoid and molluscan shells and skeletal debris are present. These facies represent shallow shelf, open sandy to sparse seagrass substrates similar to those of the present-day shelf, particularly in the lee of the Abrolhos platforms. The cycles are thin (3–6 m) and are bounded by similar calcrete horizons to those of the platform cycles.

Lower-Middle Pleistocene Evolution

During the Lower-Mid Pleistocene the topographic high which formed the proto-Easter Platform was shallowly drowned on at least three occasions by sea levels approximating 20–30 m below present, based on the cycles preserved in the Rat 2 core (Fig. 7). Though these cycles of reef growth and platform sedimentation are as yet undated, they are expected to equate to pre-oxygen isotope Stage 5e (Stages 7, 9, and 11), representing the record of successive transgressive peaks or highstand deposits, with intervening lowstands represented by thin calcrete horizons. The correlative shelf cycles to the platform facies are sheetlike highstand deposits which represent open shelf to seagrass bank facies .

Late Pleistocene Reef Limestones

Late Pleistocene (Last Interglacial) reef limestones are known from both outcrop in coastal sections of central platform islands, and core. In outcrop, reef limestones of Last Interglacial age are dense and calcretized. Coral framestone facies of the Last Interglacial consist mainly of branching coral or head coral, with minor encrusting coralline algae and white lime mud. The exposed uppermost part of the Last Interglacial reefs in islands of the central platforms normally consists of an upward-shallowing sequence (Fig. 10A), commonly 2–3 m thick and locally up to 6 m thick, consisting of coral framestone and/or coralline algal bindstone. This lithofacies is gradationally overlain by up to 50 cm of medium- to coarse-grained, shelly, skeletal grainstone to rudstone, in which molluscan debris and whole shells of bivalves and gastropods are common (Fig. 10A). This unit is overlain in the 'large' islands of the Wallabi Group by 2–6 m of

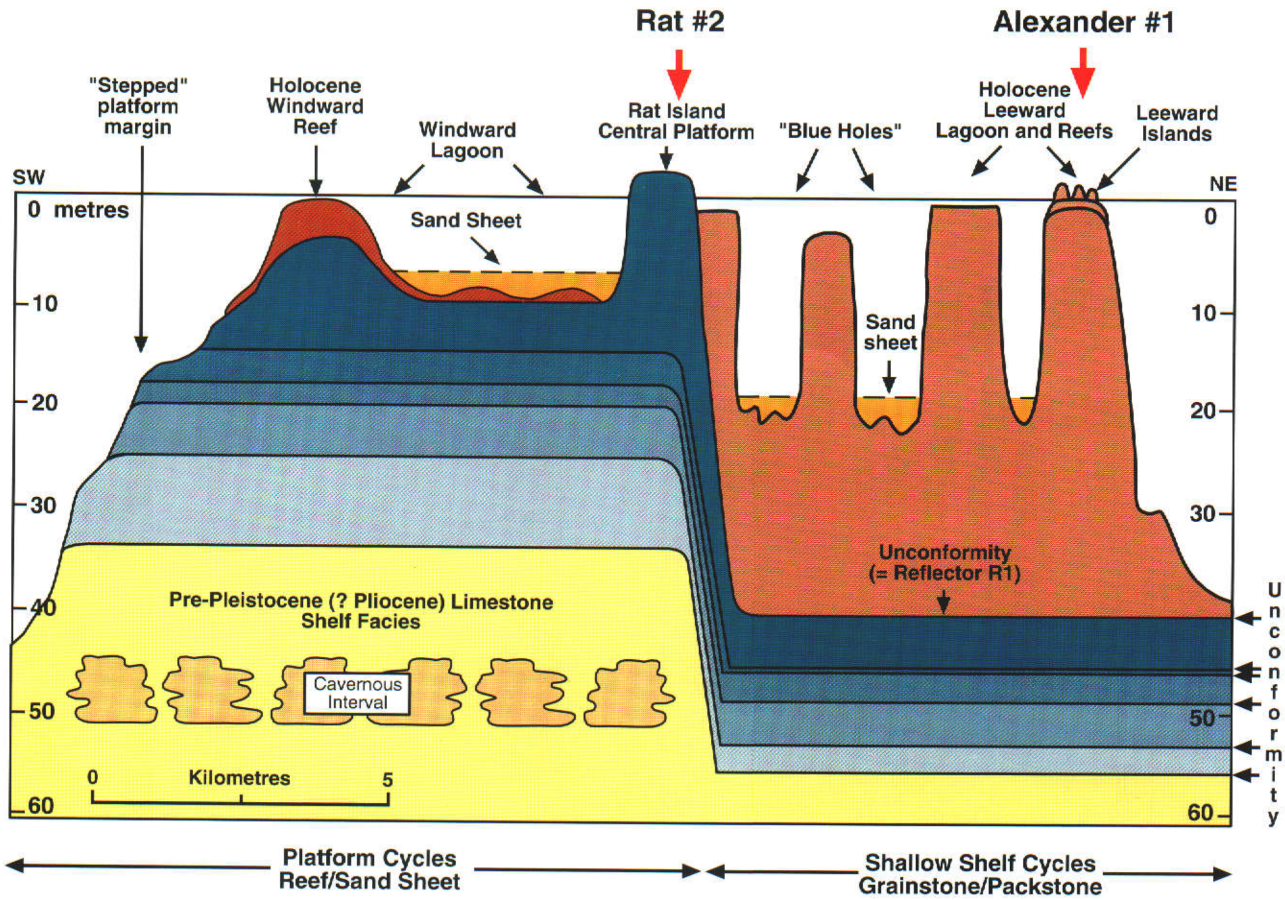

Figure 8: Model of Easter Platform, based on deep core results and seismic profiles.

well sorted, fine- to medium-grained, skeletal grainstone which is aeolian cross-bedded and has well developed calcrete horizons.

The cored Last Interglacial reef in the Easter Platform (Figs 7, 9) is 18 m of coral framestone composed of branching corals and lesser amounts of head corals, with minor intervals of algal bindstone and skeletal grainstone.

Late Pleistocene Evolution

During the Late Pleistocene (oxygen isotope Stage 5e) transgressive event there was up to 18 m of vertical reef growth on the Easter Platform, creating much of the central platform morphology. This applies also to the Pelsaert and Wallabi platforms, except that the latter was

FACIES	ASSEMBLAGE	ENVIRONMENT	THICKNESS
Coral gravel	Branching and platy *Acropora*	Storm ridges on leeward islands	1-4m
Bedded coral rudstone, well lithified	Encrusting coralline algae; branching and platy *Acropora*	Peritidal reef-flats, leeward islands	0.5-2m
Algal bindstone	Encrusting coralline algae	Reef-encrusting veneers, leeward reefs	0.2-0.5m
Coral framestone; inter-bedded coral rudstone	Branching *Acropora;* coralline algae	Leeward reefs	40 m
Algal-serpulid bindstone; inter-bedded coral framestone	Encrusting coralline algae, serpulids, forams; corals	Windward reefs	1-9m

Table 1: Holocene reef and related lithofacies of the Easter Platform.

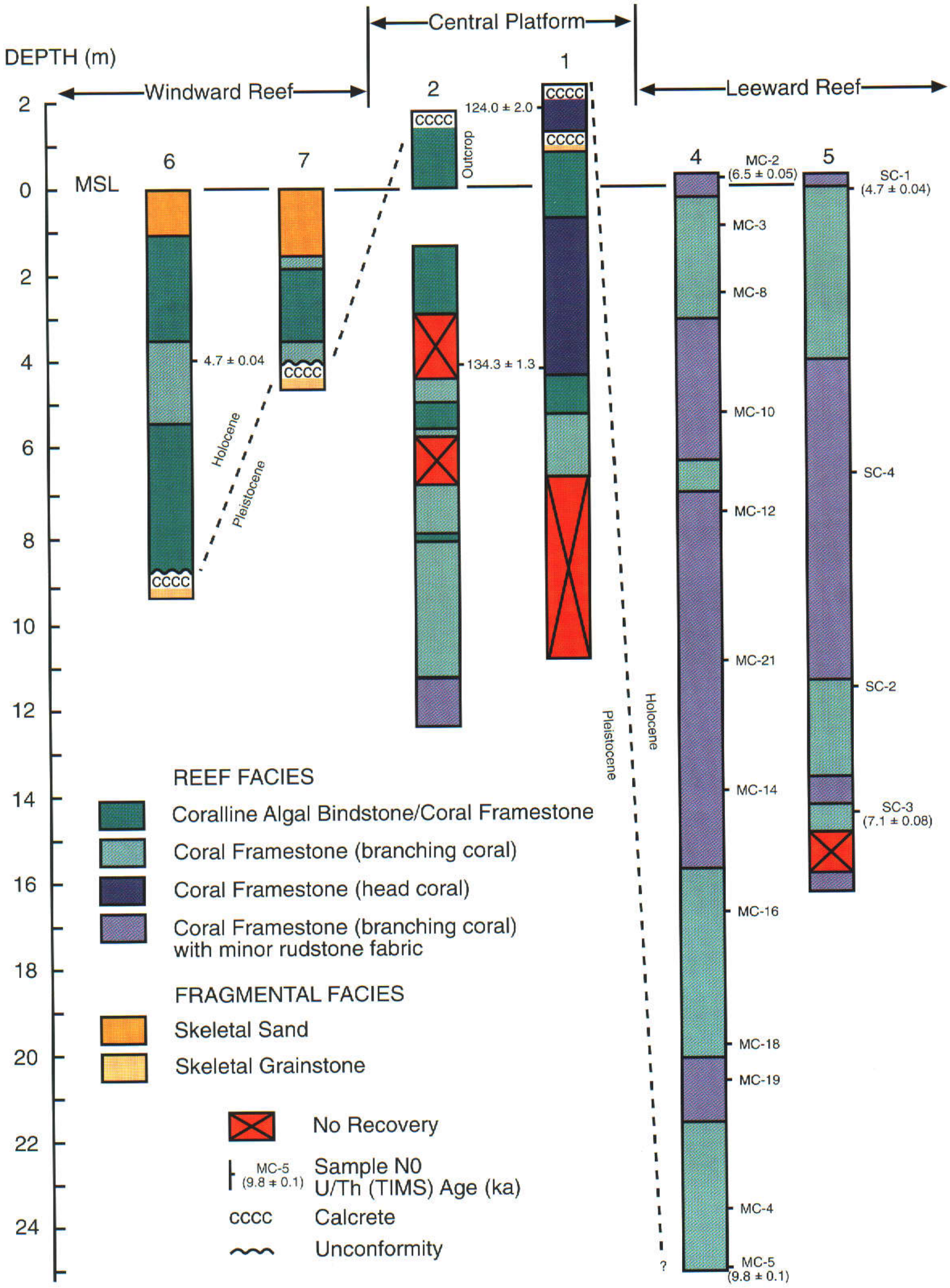

Figure 9: Core logs of windward and leeward Holocene reefs, and central platform for Easter Platform. For borehole locations see Fig. 5.

further modified by development of aeolianites. Distinct windward and leeward reefs developed at the margins of the central Easter Platform, but the present-day leeward islands and reefs had not yet developed. The Easter Platform underwent erosional modification during subsequent lowstands, especially on the windward side, but retains most of its constructional morphology on the lee side.

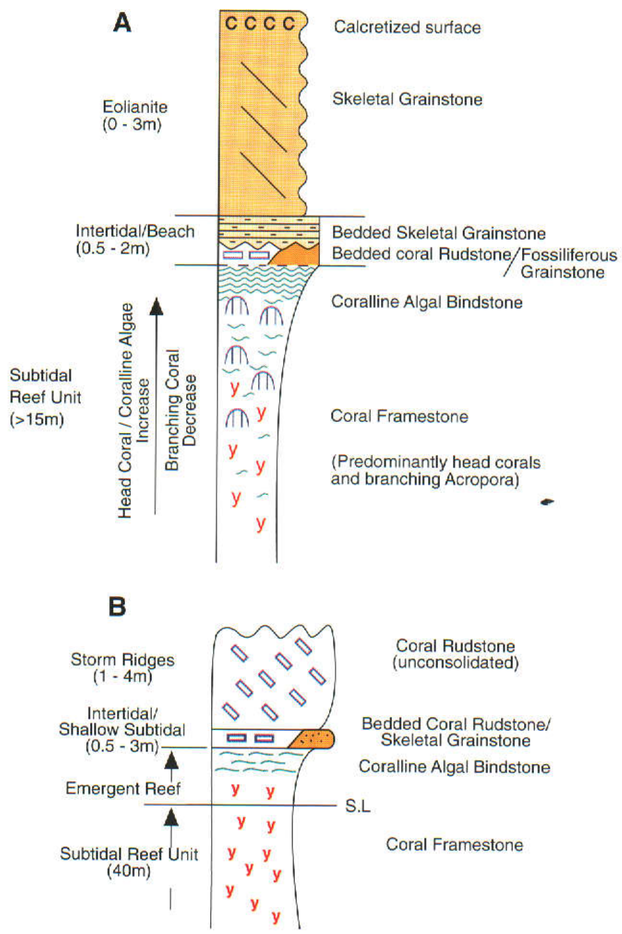

Figure 10: Island outcrop sections showing: A. Last Interglacial facies; and B. Holocene facies.

Holocene Reef Limestones and Sediments

In contrast to the central platform limestones, the Holocene facies are relatively poorly lithified and lack calcrete (Fig. 9). The Holocene sequence consists of five facies types (Fig. 10B): coral framestone; algal bindstone; well-bedded coral rudstone; unlithified coral rudstone; and skeletal grainstone. The first three of these facies are found within the reefs; the fourth comprises the leeward islands and caps an upward-shallowing sequence; and the fifth is in lagoonal sand sheets of platform environments (see Table 1).

Windward–Leeward Reef Facies, Contrasts

The Holocene windward and leeward reefs differ in their thickness and lithofacies. The windward reef grew on the wave- exposed margin of the Last Interglacial platform and reef thickness is less than 9 m; in contrast the leeward reefs exceed 40 m. While the windward reef is composed of an assemblage of coralline algae, serpulids and corals, the leeward reef consists predominantly of platy and branching corals. The sequence in the leeward reefs indicates that when the reef grew to sea level it was progressively overlain by peritidal and subaerial facies units, which now form the emergent leeward islands, whereas the windward reefs are wave-swept and subtidal.

Holocene Evolution

The evolution of the 40 m thick Holocene coral reefs is a consequence of the postglacial marine transgression. These reefs provide the most detailed records to date of Holocene sea level history, both at the Abrolhos, and along the continental margin of Western Australia (see Eisenhauer et al., 1993; Collins et al., 1993a, b). In summary, the salient features of Holocene reef growth (see Figs 11 & 12) are:

1. most Holocene reef growth took place on the lee-side of the antecedent platform, and colonised an essentially flat surface at 40 m below Sea level. This also generated Holocene constructional topography characterised by 'blue-hole' terrain, previously interpreted as karst;
2. the leeward reefs commenced growth about 11 500 U/Th years ago and the Morley reef grew to 0.3 m above present sea level by 6400 14C years BP, recording a relative high sea level event. Windward Holocene reef growth commenced after 8200 U/Th years BP following erosion of the windward part of the Last Interglacial platform;
3. high wave energy and competition with macroalgae limited windward reef coral growth, and the coralline algal-dominated windward reefs grew more slowly to sea level than the fast growing leeward coral reefs, which thrived with less competition and lower wave energy;
4. the Late Holocene highstand, recorded as 5500 U/Th year old reef facies in outcrops in the leeward reefs, may have been influenced by hydro-isostatic rebound effects (see Lambeck & Nakada 1990; Eisenhauer et al., 1993). However, there is no evidence of Late Quaternary tectonism at the Abrolhos.

Late Quaternary Sea Level History

There have been at least five periods of reef development at the Abrolhos platforms; Holocene, Last Interglacial, and three pre-Last Interglacial episodes. The growth of the first two phases has been accurately dated (Fig. 12 A, B). All episodes of reef building took place from 15-20 m above the surface of the inner shelf which is at 40 m below sea level, and therefore the chronological data obtained provide estimates of the timing of transgressive drowning of the shelf during the Quaternary. Fluctuations of sea level over the last 150 000 years are well known from oxygen isotope and other data (Chappell

& Shackleton, 1986; Chappell & Polach, 1991), and reef growth history from dated cores in the Abrolhos platforms (Fig. 12). It can be estimated that, for the Holocene transgression, drowning of the inner shelf took place about 12 000 years ago, or earlier if startup time for reef growth is allowed for. Prior to transgressive drowning of the shelf, sea level is estimated to have stood at - 120 m at 18 000 years ago, as documented for the eastern Australian shelf and elsewhere (Chappell & Shackleton, 1986; Fairbanks, 1989).

The coral reef data for the Last Interglacial (Stage 5e, Fig. 12A) indicate that drowning of the inner shelf took place about 136 000 years ago. Earlier, as yet undated, phases of reef development also record periods of inner shelf drowning. During intervening lowstands, the inner shelf would have mainly been emergent, whereas the outer shelf below a depth of 120 m would have remained submerged prior to the Postglacial transgression. However, assuming similar wave conditions to those currently experienced, wave reworking of outer shelf substrates was a significant process during lowstands.

Diagenesis of Reef Facies

Petrological investigations have shown that the reefs, whilst retaining high primary porosity and permeability, have experienced both marine and meteoric diagenesis. The most important diagenesis in the marine environment is cementation by aragonite and Mg-calcite. This includes micritic, peloidal, and bladed Mg-calcite cements, and fibrous and botryoidal aragonite cements. While the aragonite occurs mostly in intragranular cavities of organic skeletons, Mg-calcite cements are present in both inter- and intra-granular cavities. Marine cementation plays a significant role in the formation of rigid reef framework, particularly in the leeward reefs where the porous branching coral framework has been partially filled by a matrix of skeletal fragments which are cemented by Mg-calcite and aragonite (Fig. 4F).

The most pronounced meteoric diagenesis occurs in the upper part of the Last Interglacial reefs which are extensively calcretised. In the calcrete zone, dissolution of carbonate skeletons and reprecipitation of calcite cements are common, and neomorphic transformation of coral skeletons to calcite is frequently observed. The overall meteoric diagenesis of the Abrolhos reefs is not as strong as that of most tropical Pleistocene reefs (e.g. Matthews, 1968; Dullo, 1986; Zhu et al., 1989; Quinn, 1991). Corals beneath the calcrete zone normally retain their original aragonite mineralogy. Sparry calcite cements are not as common as observed in other tropical Pleistocene reefs, and primary pore space is retained. The relatively lower diagenesis in the Abrolhos reefs may be related to climatic features, such as the comparatively low rainfall and low temperature of this temperate area.

Discussion and Conclusions

This study has established the pattern of reef growth and carbonate platform evolution for the Abrolhos. It has also shown that the Abrolhos Shelf is a region of overlap and transition between warm-water and cool-water carbonate sedimentation, with attributes of both warm and cool water environments as defined by Lees and Buller (1972), Nelson (1988), and James (1997).

Platform Evolution and Controls on Reef Growth

Lithostratigraphic analysis and radiometric dating of cores and outcrops, whilst still in progress for Lower-Mid

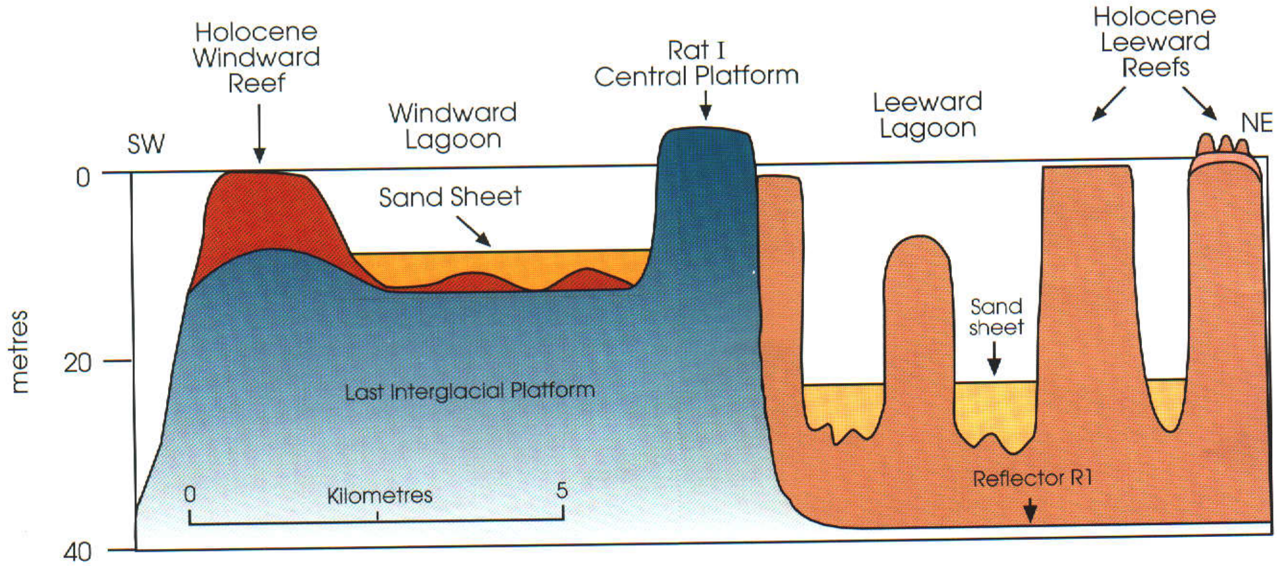

Figure 11: Cartoon showing the relationships of Holocene and Last Interglacial reef growth for Easter Platform.

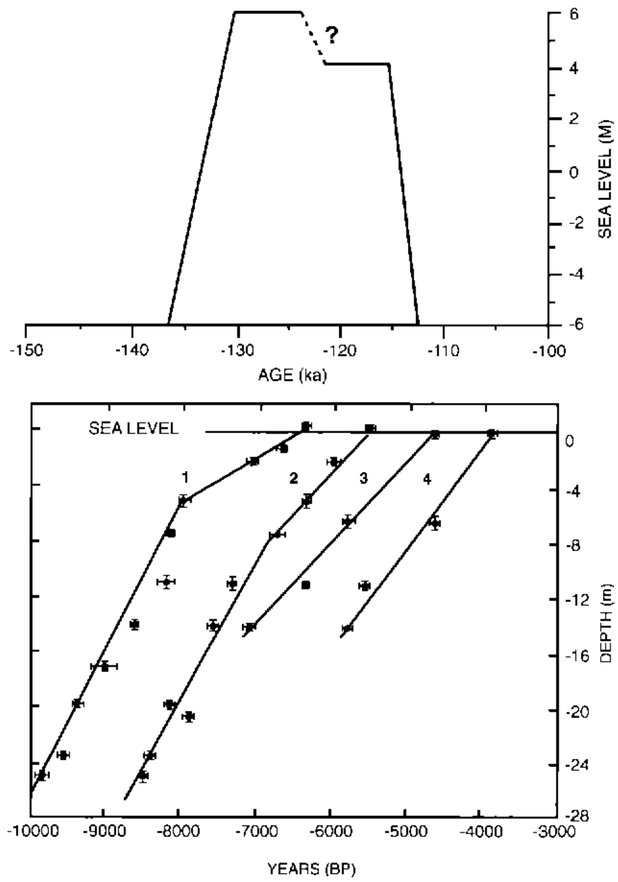

Figure 12: A. Coral reef growth history curve for Abrolhos platforms for Last Interglacial reef growth. Based on U/Th (TIMS) dates of coral cores and outcrops; after Zhu et al., (1993). B. Holocene reef growth history curve, from U/Th TIMS and AMS 14C data for Morley Reed core (Curve 1 and 2) and Suomi Reed core (Curve 3 and 4) Easter Group; after Eisenhauer et al. (1993), Collins et al. (1993a, b).

Pleistocene reefs, has revealed the growth history of coral reefs during the Late Quaternary. Upper Pleistocene reefs started to grow earlier than 135 000 years ago, with the rapid transgression of the Last Interglacial seas. The reefs were active during the Last Interglacial high stand (132 000 to 117 000 years ago). forming extensive reef platforms in the area. The Pleistocene reefs provided a suitable substrate for colonization by the Holocene reefs, except in the central parts of platforms. where Pleistocene substrates are usually 2–3 m above present sea level. Holocene reefs grew asymmetrically about the Last Interglacial platform in response to substrate elevations, macroalgal competition and wave energy regimes.

The persistence of reef growth at the Abrolhos is believed to be related to the presence of the warm, southward-flowing Leeuwin Current (Cresswell & Golding. 1980; Pearce. 1991). The Leeuwin Current influences many of the factors essential for coral reef accretion, such as temperature, larval delivery and nutrient concentration, and favours the maintenance of the coral communities at such a high latitude (Hatcher. 1991). Although little is known about the behaviour of the Leeuwin Current during the Late Quaternary (Kendrick et al., 1991), it appears to have favoured coral growth during the Early-Mid Pleistocene, Last Interglacial and Holocene.

While transgression controlled the timing and rate of reef growth, substrates affected the onset and distribution of the reefs. Holocene reef growth was asymmetrical about the Last Interglacial platforms. The shallow, and relatively high, windward margins of platforms were colonised by relatively thin coralline algal-dominated reefs (less than 9 m thick). In the leeward reefs where elevations of pre-Holocene substrates were relatively low, Holocene reefs reached thicknesses of 40 m.

The most likely control on the lithostratigraphic features of the windward and leeward reefs seems to be different wave energy regimes in these areas. The emergent and shallowly-submerged central platforms of Last Interglacial reefs form barriers and refract waves, producing two distinct environments on their southwest (windward) and northeast (leeward) sides in terms of wave energy, nutrient concentrations and habitats for coral growth. High wave energy and the abundance of large, canopy-forming algae has resulted in the dominance of coralline algae and slow growth rates of the windward reefs. compared to the fast-growing coral-dominated leeward reefs.

Contrasts with Tropical Reefs

Because of their location at latitudes where conditions for reef development are not as favourable as those in tropical environments, the Abrolhos reefs have distinctive geological and sedimentary features in comparison to tropical coral reefs. Although the lagoon sand sheets are similar to tropical/subtropical chlorozoan-type skeletal carbonates (Lees & Buller, 1975) and are mainly composed of corals, coralline algae and molluscs, they almost totally lack green *(Halimeda-type)* algae which are significant sediment producers in tropical reefs (Goreau & Goreau, 1973; Scoffin & Tudhope, 1985; Liddell et al., 1989). and also lack non-skeletal grains such as ooids. The reef corals. e.g. *Acropora*, are relatively poorly calcified (Crossland, 1984). Also, although the accumulation rates of reefs are comparable with those of tropical reefs, the Abrolhos reef facies generally lack sandy infill sediment and have a high porosity. These characteristics reflect a combination of the fast growth of branching *Acropora*, the relatively slow destruction of framework by biological and physical processes, and the low production rates of sand-size carbonate sediments.

Latitudinal Gradient

The study area lies between warm- and cool-water carbonate provinces. Though shelf sediments are poorly known to the north, coral reefs are well developed at North West Cape (the Ningaloo Reef), and on the seaward margins of offshore islands at Shark Bay (Hatcher, 1991); also, the embayment sediments at Shark Bay are distinctly warm water in character (Logan, 1970). Shelf sediments to the south, between latitudes 32-34°S, are dominated by bryozoans and coralline algae (Collins, 1988), with significant amounts of molluscs and foraminifers, and are of cool water type. Similar sediments are present on the Abrolhos Shelf, adjacent to the reefal platforms. Whilst the southerly extension of Abrolhos coral reef facies is attributed to southward flowing, warm Leeuwin Current waters, the northerly extension of Outer Shelf, cool water bryozoan shelf carbonates is probably due to the cool, Leeuwin Undercurrent as it extends northward below the Leeuwin Current.

Morphology and Stratigraphy

During the Tertiary to Quaternary, the Abrolhos region evolved from a cool-water carbonate ramp (in the Eocene), to a discontinuously rimmed shelf, with the growth of the Abrolhos platforms during the Pleistocene and Holocene. From our data on coral reef growth it is evident that the Leeuwin Current came into existence in the Early to Middle Pleistocene, and this is supported by molluscan faunal data in the regional stratigraphy (Kendrick et al., 1991). The Leeuwin Current is believed to have influenced many of the factors necessary for coral growth, such as temperature, larval delivery and nutrient concentration, and to favour the maintenance of coral communities (Hatcher, 1985, 1991). The core and petroleum well data (see Fig. 2) indicate that cool-water ramp sedimentation prevailed during the Miocene and Eocene.

Feary and James (1995) consider that a warm-water, reef-building phase occurred during the latest Early Miocene or early Middle Miocene climatic optimum, as an interuption to cool-water ramp sedimentation on the southern Australian margin, based on seismic data. This event is attributed to a combination of a global warming episode and a warm current flow, perhaps from a proto-Leeuwin Current. There is no evidence of such a current from Abrolhos data, though a detailed analysis of regional high quality seismic and sedimentological data is still in progress.

Oceanography, Biota and Sediments

The sea surface temperature range (18-26°C) produces conditions which are at the limits of reef-building coral growth, and a recognisable tropical-temperate transition modulated by Leeuwin Current and opposing cool undercurrent activity. The sediment-generating biota of the platforms is tropical in character, whilst on the shelf temperate species are most significant as sediment contributors. As the generally accepted temperature 'boundary' between warm- and cool-water carbonates is 20°C (James, 1997), the Abrolhos region lies close to this limit. In terms of skeletal grain assemblages, Abrolhos Shelf sediments are Foramol (Lees & Buller, 1975), Bryomol (Nelson, 1988), Rhodalgal (Carranante et al., 1988), or Heterozoan (James, 1997). In contrast, platform sediments (reefal and sand sheet facies) are similar to warm-water carbonates (termed Chlorozoan by Lees & Buller, 1975; Photozoan by James, 1997), but differ in that they lack green (*Halimeda*-type) algae, and nonskeletal grains such as ooids.

The latitudinal position (28-29.5°S) of the transition zone contrasts with a similar transition on the eastern Australian shelf at 24°S, (Marshall & Davies, 1978), and the Leeuwin Current is probably responsible for this distinction. There are several recorded modern examples of transitions from warm- to cool-water carbonates: Carranante et al. (1988) consider that lithofacies distribution is subject to 'complex environmental factors that seem related primarily to water temperature, controlled by latitude and depth'. The regional oceanographic circulation often drives these interactions.

Palaeoenvironmental Implications

Since the early Tertiary, the Australian continent has drifted northward by 27° of latitude (Veevers et al., 1991). Such changes in palaeolatitude, and consequent changes in palaeoceanography, may well be reflected as changes from Tertiary cool-water ramps to Quaternary incipient rimmed shelves, with transitional cool-warm water carbonates, as exemplified by the sedimentary evolution of the Abrolhos region. Conversely, rimmed shelf phases within cool-water ramp sequences, such as occurred briefly during the Miocene along the southern Australian margin (Feary & James, 1995), may signal short-lived warming episodes, in this case possibly associated with proto-Leeuwin Current activity. A transition from carbonate rimmed shelf to cool-water ramp phase in the Upper Ordovician of eastern Canada has been attributed to changing oceanographic conditions caused by Late Ordovician glacial onset (Lavoie, 1995). The recognition of vertical facies transitions between cool- and warm-water carbonate settings, and an understanding of the driving mechanisms such as changes in ocean circulation and palaeotemperature is an important aspect of palaeoenvironmental analysis.

Sea Level Cycles and Sequence Development

Changes in the frequency of sea level oscillations controlled a transition from relatively thick (50 m) late Tertiary third order cycles, to fourth and fifth order Milankovitch cycles during the Quaternary. Seismic investigations and coring have confirmed the existence of 4-6 m thick, unconformity- bounded shelf sequences, capped by thin calcrete horizons, which are the lateral equivalents of reef buildups within the platforms during the Quaternary.

If an ancient analogue of the Abrolhos reefs and shelf were investigated in the subsurface, the contrasting facies geometry of reef and shelf facies would be evident; strong vertical relief of the reef buildups, and thin (4-6 m) unconformity-bound units characteristic of the adjacent shelf. In the event of available core for both reef and shelf facies. the contrasting warm and cool-water attributes would be readily identified.

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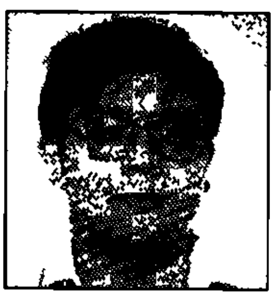
Lindsay Collins was educated in Perth, gaining a BSc (Honours) and PhD in Geology from the University of Western Australia. He was a consultant sedimentologist before joining Curtin. Research interests are in applied sedimentology, petroleum and marine geology and he has worked on carbonate and clastic depositional systems. Whilst with WMC (Petroleum Division) he worked on the South Pepper, North Herald and Chervil discoveries. He subsequently worked on the sedimentology of the Harriet Field, and Cretaceous of the North West Shelf. Presently Associate Professor in the School of Applied Geology at Curtin University, he has served on the committees of PESA and GSA (WA Divisions), was Treasurer of the PESA Canning Basin Symposium, and is a current PESA Committee Member.



Zhong Rong Zhu is a Research Associate at the School of Applied Geology, Curtin University. He obtained his BSc from Chengdu Institute of Geology in China in 1982, with a major in petroleum geology. His MSc was awarded from Academia Sinica, China in 1985. He obtained his PhD from the Australian National University in 1991. His main interests are in carbonate sedimentology, petrology, diagenesis, and Quaternary geology and sea level change.

Karl-Heinz Wyrwoll is a graduate of University College, London (BSc Honours-Geography /Geology) and subsequently completed an MSc at McGill University. After this he returned to University College, London to undertake a PhD study on Quaternary Geology /Geomorphology. His research interests focus on Quaternary Geology/ Geomorphology. He is presently a Senior Lecturer in the Department of Geography, at the University of Western Australia.