

# Tertiary Foundations and Quaternary Evolution of Coral Reef Systems of Australia's North West Shelf

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## Abstract

The North West Shelf is a modern tropical ramp, which is underlain by Cretaceous-Tertiary carbonates, with clastic reservoirs at depth. Coral reef systems, discontinuously developed during the Late Tertiary-Quaternary, vary from fringing reefs to isolated reefs which rise from deep-ramp settings. Quaternary evolution of the reef systems is being documented using regional mapping, seismic imaging, coring and U-series dating. The well-constrained sea level data from the Houtman Abrolhos carbonate platforms (at 28-29°S) have also been applied to the North West Shelf reefs. The Ningaloo fringing reef at 20-22°S, records Holocene and Last Interglacial phases of reef growth in a tectonically stable environment. It overlies Tertiary carbonates of the Cape Range, which is flanked by uplifted Plio-Pleistocene terraces and reefs. Scott Reef (at 14°S) is a macrotidal, isolated reef which overlies a carbonate platform and a major gas discovery. Seismic profiles reveal a Last Interglacial (ca. 125,000 year) reef system, but reefs which apparently grew to sea level are 30 m below present sea level, indicating significant subsidence in the Late Quaternary. Contemporary reefs grew during the Holocene in the accommodation space provided by subsidence and are up to 35 m thick. The Rowley Shoals (15-17°S) comprise one of the most perfect morphological series of reefs known, and these emergent, annular reefs rise from depths of 200-400 m. Seismic profiles suggest Late Quaternary subsidence has been an important control

on reef growth, while differential subsidence has influenced reef morphology.

The spatial association between reef systems and hydrocarbon seeps and the reservoir potential of the Tertiary section are now receiving attention. As further exploration and development occur in and around coral reefs, and the level of management intensity increases, there is a need for better understanding of human and natural impacts (cyclones and coral bleaching), biological processes, and the geological controls on reef growth and development, as part of management plans.

## Introduction

The western continental margin of Australia and the North West Shelf are bordered by Cretaceous-Tertiary carbonate ramp systems, which overlie clastic reservoirs. The carbonates have been cored infrequently and their hydrocarbon potential has been considered marginal, but they are known to cause velocity problems for seismic interpretation. More recently the reservoir potential of the carbonates has received attention by industry and research groups, and this work is continuing.

During the Late Tertiary-Quaternary coral reefs developed discontinuously along the North West Shelf, in a range of latitudinal, oceanographic and topographic settings. Their geological record is preserved on a number of timescales, from inter-annual isotopic records of sea surface temperature change, with continuous records up to 200 years in length (Kuhnert et al., 1999), to glacio-eustatic sea level records through the Quaternary (Collins et al., 1998, 2002), preserved as fourth and fifth order cycles.

Coral reef systems are known as repositories of biodiversity which are sensitive to environmental change and events such as coral bleaching. Less well known, however, is the potential spatial association between coral reefs and active and palaeo-hydrocarbon seeps (O'Brien et al., 1999). As a pre-condition for exploration and development in coral reef terrains, it is important that both the biological and geological controls on reef growth and survival are understood, particularly as the need for environmental management increases.

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Coral reefs of the North West Shelf (Fig. 1) include isolated oceanic reefs (Ashmore Reef, Seringapatam and Scott Reefs, Rowley Shoals), island-associated shelf reefs of the Kimberley coast and Dampier Archipelago; Pilbara reefs (Barrow and Montebello Islands) and Ningaloo Reef, adjacent to the North West Cape. This paper describes the oceanographic setting, morphology and sedimentology of some of the North West Shelf coral reef systems (Fig. 1), particularly Ningaloo Reef in the south (latitudes 20-22°S), the more central Rowley Shoals (15-17°35' S) and Scott Reef (14°S) in the north. Ningaloo Reef is a fringing reef where drilling has occurred close to marine protected areas, and there is the recent discovery to the west. Rowley Shoals and Scott Reef are isolated reefs; there has been some exploration near Rowley Shoals, which are marine parks, and Scott Reef is the site of a major undeveloped gas discovery.

The current generation of geological research on coral reefs of the WA margin began in the early 1990's with a major study of the Houtman Abrolhos, shelf-edge reefs in the Perth Basin (summarised in Collins et al., 1998). A shallow seismic survey tied to cored reef drillsites, accurately dated by high precision U-series methods, resulted in a detailed understanding of reef morphology and Quaternary sea levels and growth history, and in particular the Last Interglacial and Holocene phases of reef development. This approach was later extended to the fringing Ningaloo Reef, as reported in this paper (see also Collins et al., 2002). The Rowley Shoals and Scott Reef are remote from the coast and difficult to access, and these were recently investigated seismically but await shallow coring.

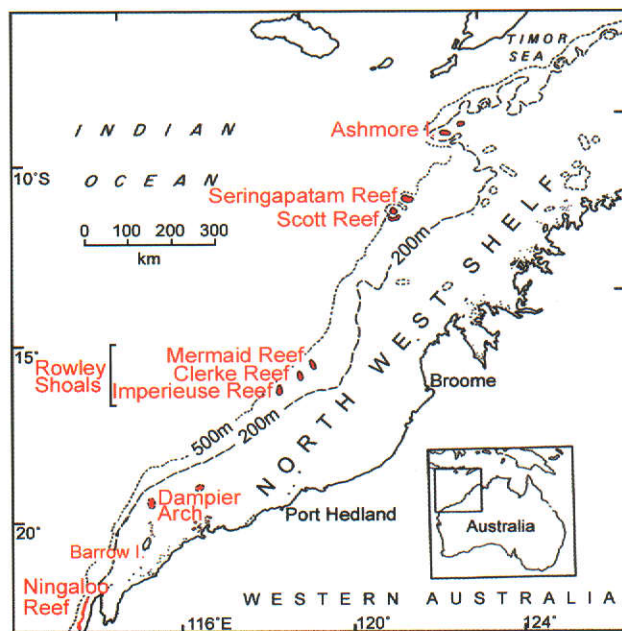


Figure 1: Location map of coral reefs of the North West Shelf, showing Scott Reef, Rowley Shoals and Ningaloo Reef.

## Methods

The Ningaloo Reef study is based on sediment grab samples (10 from the reef lagoon and 10 from the adjacent shelf), 12 cores from lagoon, shelf and reef-front locations in water depths ranging from 5 to 30 m, and five shallow seismic lines. Cores were taken using diver-operated and remotely operated seafloor systems deployed from an anchored barge, using rotary drilling and wireline recovery. Maximum penetration achieved was 24 m, but was more typically 3-5 metres, and recovery varied from 30-90%. Following core logging and description selected coral samples were dated using the U-series TIMS method (Zhu et al., 1993). Sample selection was based on mineralogical, petrological and isotopic criteria developed by Zhu et al., (1993). Seismic surveys were performed from a 7 m shallow draft vessel using passes in the reef, and shot using shallow (Boomer) seismic equipment, which obtained half-second records using an ORE Feranti Boomer, EPC recorder, 360 J monopulse acoustic transducer, and 10 element streamer. This system profiled 15 line kilometres at speeds of 4-6 knots. Position fixing was by compass bearings on shore stations and onboard GPS (accurate to 40 m), and 5 minute interval position fixes were keyed to seismic profiles.

The Rowley Shoals and Scott Reef studies obtained oceanographic (CTD), bathymetric (PDR), sedimentological (Epibenthic Sled and Gravity Corer) and seismic data using the CSIRO research vessel RV *Franklin* (55 metres), during Cruise FR05/00. Both shipboard and small (5m) vessel seismic surveys were conducted using an ORE Model 5813A Acoustic Source (Boomer), driven by a Geopulse 5420A power supply. A Benthos multi-element streamer was used for small vessel work and a Teledyne 4 channel streamer was used for *Franklin* work. The seismic acquisition system used was a Geoacoustics SE881 Sonar Enhancement System, and a Garmin GPS unit supplied GPS data to the acquisition system on the small vessel. *Franklin* DGPS data were supplied and processed by Navipac software for onboard seismic acquisition.

## Oceanography, climate and biogeography of North West Shelf reefs

The regional oceanography of the North West Shelf is influenced by the South Equatorial Current, at 5-15°S latitude, driven by easterly tradewinds, and the Indonesian Throughflow, which floods the North West Shelf with warm, low salinity water, resulting in sea levels in the tropics being 0.5 m higher than along the southern coast of Australia (Pearce & Griffiths, 1991). With higher tropical sea levels, the formation of a north-south pressure gradient induces a weak easterly flow of central Indian Ocean subtropical water towards the Australian coast between 15-35°S (Pearce & Griffiths, 1991). This easterly flow is deflected south by the coastline, eventually contributing to the Leeuwin Current (Fig. 2), a warm low salinity current which flows from the



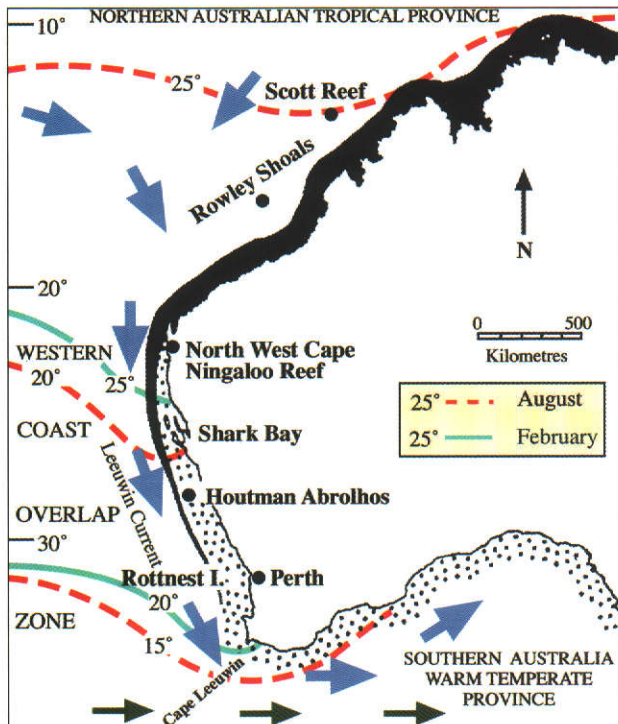


Figure 2: Location of Scott Reef, Rowley Shoals and Ningaloo Reef on Australia's western margin, biotic zones (northern Australian tropical province -black; southern Australian temperate province -dots), seasonal migration of isotherms, and the poleward-flowing Leeuwin Current (blue arrows).

Indonesian Throughflow, southward along the adjacent shelf in winter, close to the Ningaloo Reef. The Indonesian Throughflow delivers larvae of both Pacific and Asian reef species to the North West Shelf, and the Leeuwin Current is an important control on southward larval delivery, whilst suppressing upwelling.

The North West Shelf is tidally dominated, with mean spring range increasing from 1.7 m at Exmouth to to 9.2 m in King Sound (Harris et al., 1991). Both Scott Reef and Rowley Shoals have semi-diurnal tides with a spring range of 4.5 m. Lagoon outflows at Rowley Shoals are limited by narrow channels, so that enclosed lagoon water levels are impounded by the reef rim at about half ebb tide. However, the southwesterly reef flats are widest, reflecting the influence of swell waves. This is in contrast to the more open, tidally-driven circulation and sediment transport at Scott Reef, where internal waves have also been reported (Wolanski & Delleersnijder, 1998).

Both Scott Reef and the Rowley Shoals are remote from the coast, whilst the hot and arid coastal climate of the adjacent Cape Range region has a strong influence on Ningaloo Reef, where the annual average sea temperatures are 17 to 27°C offshore. Rainfall averages 300 mm but evaporation is 1700-3050 mm annually. Both cyclones (frequency 1 per 3-5 years) and mid-latitude depressions cause peak falls in summer and winter. Runoff is confined to stormwater discharge events,

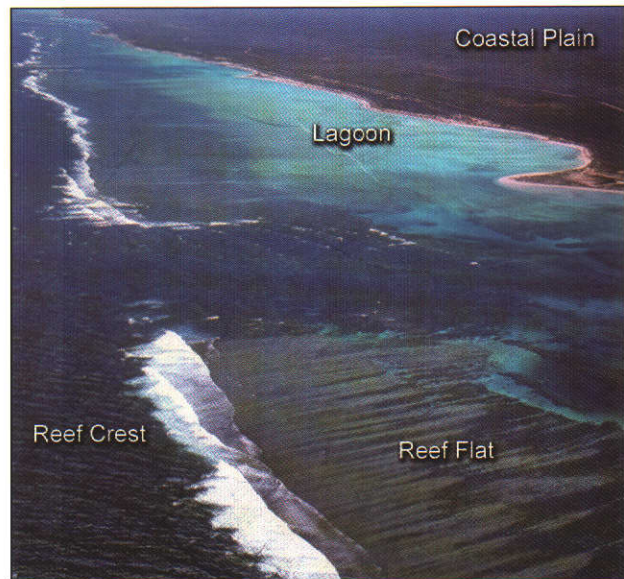


Figure 3: Oblique aerial photograph of the northern Ningaloo Reef, looking north. The narrow reef crest to the west (left) is backed by a reef flat, sandy lagoon, and coastal plain. Width of lagoon is 2 km (approx).

which flow through creeks often situated near passes in the reef. Sea surface temperature nearshore ranges from a high of 28°C to a low of 22°C and is always tropical, and tidal range in the northern part of the reef is 1.7m. The mean annual wind direction of 184° is parallel to the axis of the northern Ningaloo Reef. Both Scott Reef and Rowley Shoals lie in the monsoonal belt with prevailing westerly or northwesterly rain-bearing winds from November-March, and dry southeasterly or easterly trade winds from May to September. The region (10-15°S) is cyclone-influenced, has southwest prevailing swell, and sea surface temperatures of 24 to 29°C.

Coral assemblages at Scott Reef and Rowley Shoals are tropical Indo-Pacific and diverse, with 56 genera and 233 species recorded for Scott Reef, and 52 genera and 184 species recorded for Rowley Shoals (Berry & Marsh, 1986). Hard coralline algal pavements and stunted corals characterise high energy areas, with high coral cover and diverse growth forms in sheltered habitats (Wilkinson, 2000). Average coral cover in monitored reef slopes reduced from 47% to 1% after a cyclone in 1995, and extensive bleaching was recorded at Scott Reef in 1998 following a period of warm water temperatures for several weeks; sites with 54% coral cover were reduced to 10% live cover by this event (Wilkinson, 2000).

Two biotic zones, the northern Australian tropical province and the southern Australian warm temperate province have a broad overlap on the central west coast (the western coast overlap zone), and Ningaloo Reef (Figs 2 and 3) lies at the northern extremity of the overlap zone. Ningaloo reef corals have strong Indo-Pacific affinities, and 54 genera and 217 species of hermatypic corals have been identified (Hatcher, 1991; Veron, 1995). Coral cover reaches 40% on the swell-

exposed reef front, but the outer reef slopes lack rich coral communities. Behind the reef crest coral cover varies from 5-40%, with best reef development in passes and in the lagoon.

### Ningaloo Reef: regional setting and Tertiary foundations

#### Geological structure

The Cape Range Anticline is fringed by Ningaloo Reef to the west and backed by Exmouth Gulf to the east, in part of the Northern Carnarvon Basin. Exmouth Gulf is flanked on the east by the Yanrey Tidal Flat, and on the west and south by the MacLeod Region. This part of the Carnarvon Basin consists of a series of variably dissected anticlinal domes separated by low-lying areas infilled by Pleistocene eolian and marine sediments (Hocking et al., 1987; Wyrwoll et al., 1993). The domes consist of hard Tertiary limestones (at times karstified) and formed through post-Eocene reverse movement on pre-existing faults, which resulted in folding. The Cape Range Anticline is 100 km long and 20 km wide, reaches 315 m above sea level and is cut by deep gorges. The Rough Range and Giralia Anticlines are somewhat smaller, breached structures, and where a hard limestone cap has been removed, dip-slope ranges have resulted from erosion into the softer limestones beneath. The post-breakup Cretaceous-Tertiary marine succession is represented mainly by carbonate progradation, which continued through the Tertiary. The succession contains minor hiatuses and thickens from east to west. A Middle Miocene tectonic event renewed right-lateral strike-slip faults and rejuvenated the breakup anticline folds (Crostella, 1996). Late Miocene-Holocene deposition continued in adjacent offshore basins, but was restricted to the flanks of the uplifted and emergent North West Cape, where Plio-Pleistocene eolianites and associated strandline and reef sediments were deposited.

#### Tertiary foundations

The Cenozoic sediment pile in the Carnarvon Basin occurs as a prograding wedge, thin at the coast and thickening to 2,500 m at the shelf edge. Unconformity-bounded sedimentation cycles in western margin basins correlate across the basins (McGowran et al., 1997). The cycles are:

Cycle 1 (Late Paleocene-Early Eocene): this cycle is bracketed by regression and hiatuses at the Cretaceous/Tertiary and Early/Middle Eocene boundaries, with maximum extent occurring in the Late Paleocene.

Cycle 2: (Middle-Late Eocene): this cycle is characterised by transgression in the Middle Eocene, with maximum extent occurring in the Late Eocene. It is further subdivided into 2A (Middle Eocene) and 2B (late Late Eocene).

Cycle 3: (Late Oligocene-middle Late Miocene): The cycle's most prominent transgressive event, reaching maximum extent during the Early/Middle Miocene, punctuated during this time

by a widespread hiatus, enables further subdivision into 3A (Late Oligocene-Early Miocene) and 3B (Middle Miocene).

Cycle 4: (Late Miocene-Holocene): This cycle is varied in terms of facies distribution, due to increased tectonism and pronounced waxing and waning of glaciation.

All cycles are carbonate-dominated. Cycles 1 and 2 are exposed in the Giralia Anticline, southeast of the Cape Range. Cycle 3 is exposed in Cape Range and Rough Range, and parts of it (Trealla Limestone, Lamont Sandstone, and Pindilya Formation) are exposed in much of the onshore Carnarvon Basin. Cycle 4 is exposed along the coast of North West Cape and elsewhere.

The facies associations observed within the ramp packages show increasing planktonic foraminiferal content and decreasing grainsize/increasing matrix content to basinward and are:

1. Bryozoan-dominated grainstones, packstones and wackestones with heterozoan skeletal assemblages; these are cool water ramp systems with a subphotic biota. Examples are documented from the Eucla Basin, but also the Abrolhos Sub-basin on the western margin at latitude 28°S underlying the Abrolhos reefs (Collins et al., 1997).

2. Lepidocyclinid-dominated grainstones, packstones and bioturbated wackestones, with lepidocyclinid storm lags and lesser amounts of echinoids, molluscs and bryozoans; shallow ramp facies are foraminiferal packstone/wackestone derived from seagrass assemblages, with associated compound corals. This is a warm water association exemplified by the Cape Range Group.

3. Mixed glauconitic/phosphatic sands (some with condensed sequences) interbedded with chalky skeletal packstones/wackestones in which bryozoans, echinoids and foraminifers are common. Examples are the Cardabia and Giralia Calcarenites of the Giralia Anticline. The subsurface, downramp silty to marly units have planktic foraminiferal associations which are warm-water or reflect oscillating cool-warm temperature conditions.

#### Pliocene-Quaternary terraces

Emergent, tectonically warped terraces overlying Mid-Late Tertiary units (Fig. 4) are present on the western side of Cape Range, indicating that uplift and warping continued into the Quaternary (van de Graaff et al., 1980). Deposits of the Jurabi Terrace are tentatively dated as Late Pliocene (Wyrwoll et al., 1993). The youngest terrace, the Tantabiddi Terrace, is of Last Interglacial (ca 125,000 y BP) age, and is of uniform elevation and lacks deformation, attesting to the tectonic stability of the region since this time. A narrow (2-5 km) coastal plain composed of emergent Tantabiddi reef and lagoon deposits, and alluvial fans, fringes the east and west flanks of the Cape Range and comprises emergent coastal exposures in the reef tract.

#### Reef morphology

The reef complex consists of a narrow reef crest, which is emergent at low water, with well-developed spur and groove



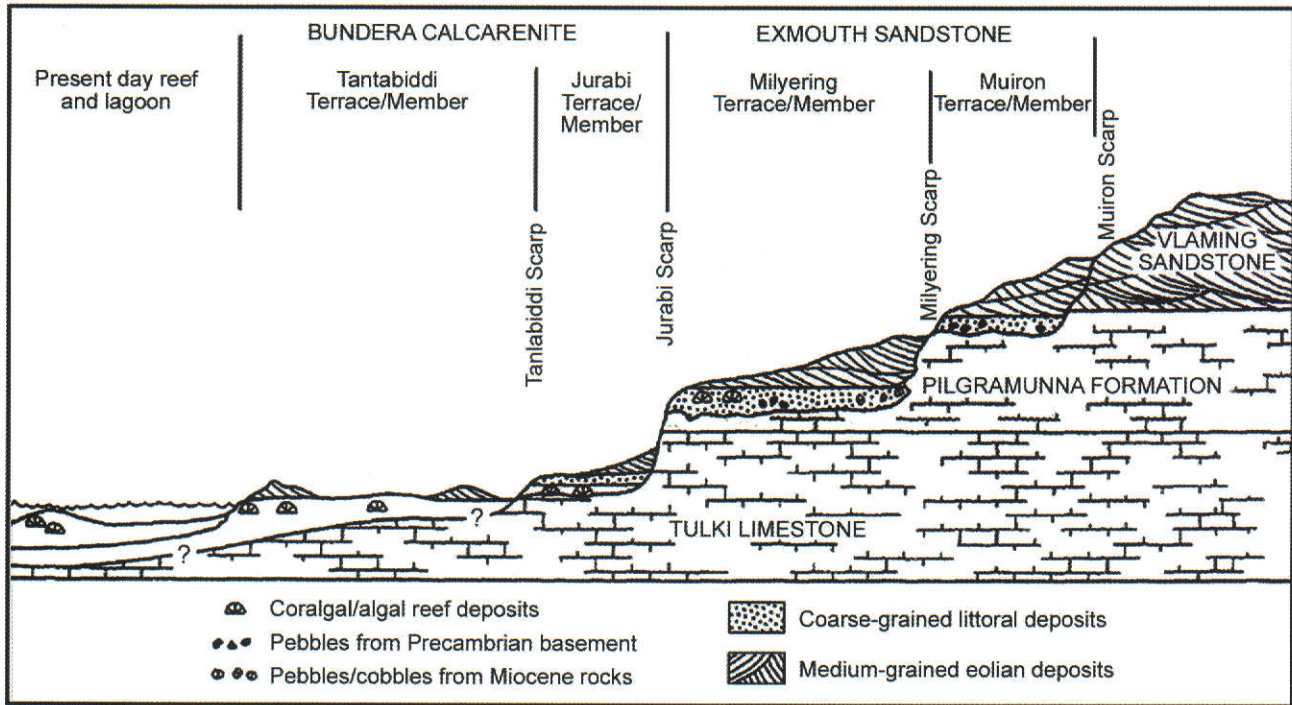


Figure 4: Schematic cross-section of raised Pliocene-Quaternary terraces present to landward of Ningaloo Reef, overlying Tertiary limestones. The youngest and most precisely dated of these is the Last Interglacial Tantabiddi Terrace, whose lagoonal and reef facies shallowly underlie the coastal plain and crop out in the coastal zone. After van de Graaff et al. (1980).

morphology present on most outer reef slopes; complex multiple developments of spur and groove are also present. The reef crest is backed by a reef flat (usually <150 m wide), which has robust coral communities, as well as coral rubble veneers, and deep grooves floored by sandy sediment which shallow and broaden to landward. A shallow (0-4 metres water depth (mwd)) lagoon of width 1-5 km consists of rock pavements with sparse corals, and mobile sandy substrates with scattered coral communities (Fig. 3). The lagoon shore is sandy or consists of rock pavements vegetated by macroalgae, and low cliffs and emergent platforms of Last Interglacial reef limestones. Reef development is interrupted by passes and transverse channels, up to 200 m wide, which are sites for water exchange between the lagoon and the adjacent shelf. Best coral growth and reef development occur along reef passes and in the lagoon, while the outer reef slopes do not host such rich coral communities.

**Seismic structure of Ningaloo Reef**

Both bathymetric-topographic detail and subsurface structure of the reef along reef passes are evident on east-west seismic profiles (Figs 5 and 6), which are of two profile types, as represented by Line T9 along the drilled Tantabiddi transect, and by Line N3 which is 8 km to the south of Line T9. A prominent seismic reflector identified on all profiles can be traced from a few metres depth beneath the lagoon floor, then sloping seaward beneath the reef crest, eventually to merge with the surface of the shelf in front of the reef at depths of 30-32 m.

This reflector is interpreted as the Last Interglacial surface, and defines the pre-Holocene topography on which subsequent reef development occurred (Fig. 6). The landward rise of this surface beneath the lagoon is consistent with the presence of coastal exposures of Last Interglacial reef limestones.

The Tantabiddi transect (Line T9 and all adjacent profiles) has a prominent bulge that extends for up to 500 m to seaward of the reef crest position, and this is usually terminated by a 10

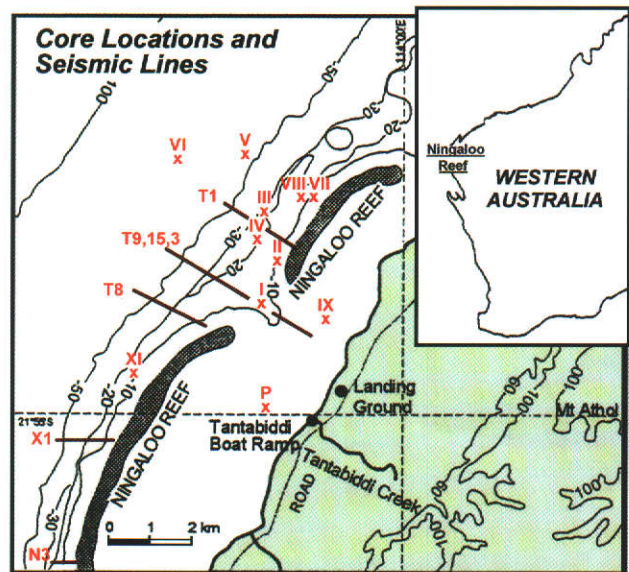


Figure 5: Core locations and seismic lines on the Tantabiddi traverse, northern Ningaloo Reef.



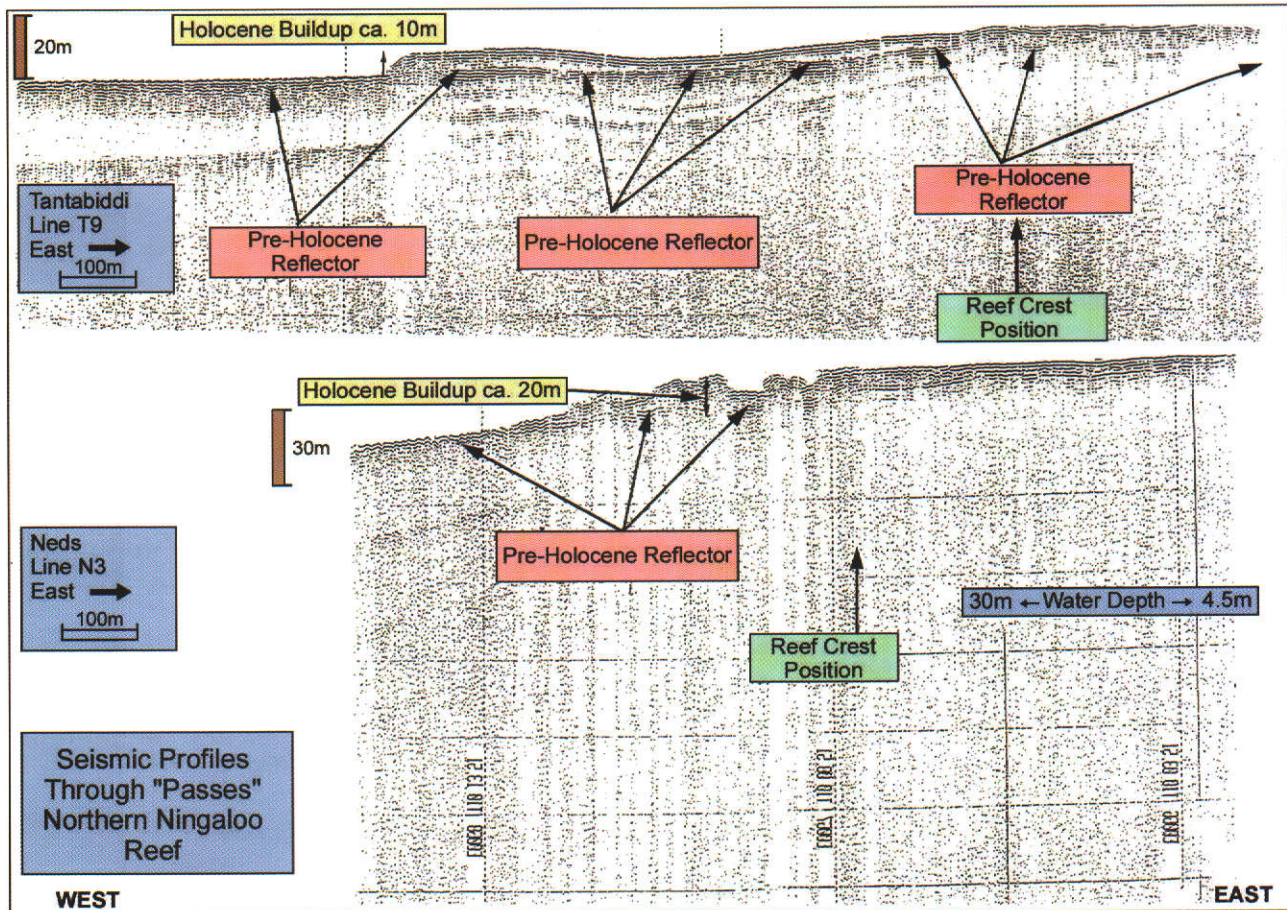


Figure 6: Seismic sections T9 (Tantabiddi traverse) and N3 (8 km to the south) through passes in the reef showing the interpreted pre-Holocene surface (Last Interglacial reflector), inferred thickness of Holocene reef, and contrasting styles of reef morphology. Approximate position of the reef crest is shown.

m high reef slope, beyond which the flat surface of the continental shelf extends at depths of 25-30 m. The shelf is known to have a 1-2 m thick sediment veneer overlying rock substrate. The interpreted Holocene reef thickness in this region is 10 m, decreasing to landward as the pre-Holocene reflector rises towards the crestal position of the reef, then shallows beneath the lagoon. Profile N3 (Fig. 6), taken at Ned's reef pass located 8 km south of T9, has more complex Holocene topography above the pre-Holocene reflector. Seaward of the reef crest and its low gradient reef slope there are multiple patch reefs separated by flat surfaces, and this topography continues with decreasing relief to grade into a smooth shelf surface at a depth of 30 m. The maximum Holocene patch reef thickness is estimated at 20 m.

The seismic data suggest that the bulk of the Holocene reef buildup is in depths of <30 m, beyond which a smooth shelf extends seaward. The maximum Holocene reef buildup is estimated at 10-15 m beneath the modern reef crest, thinning to 10 m and less in the bulge to seaward, and pinnacle reefs along passes are up to 10 m thick, decreasing to seaward. The landward-sloping Last Interglacial surface rises to underlie shallowly the lagoon substrate and eventually crop out in coastal exposures.

### Composition and age of Ningaloo Reef

Cores were taken along the Tantabiddi transect (Fig. 5) in the lagoon, at the reef crest and to seaward of the reef in depths ranging from 4-30 m, close to the T9 seismic line. There is apparently no reef growth below 30 m. Two stages of reef growth were identified from stratigraphy and U-series dating, of Holocene and Last Interglacial age respectively. The reef buildups overlie a cream-white skeletal grainstone which is of uncertain age. Last Interglacial reef is present in Core Tant II which was collected in 11 m of water, some 100 m seaward of the reef crest, and contains a 25 m thick section of reefs (Fig. 7). The Holocene section here is 7 m thick, indicating that the Holocene reef thickness at the reef crest position is about 18 m. The base of the underlying 11.5 m thick Last Interglacial reef was intersected at 18.5 m, where it unconformably overlies cream-white skeletal grainstone. Lithofacies units identified in Core Tant II ( Figs 8 and 9) are:-

Holocene

Unit A (0-7.3 m): Coral framestone, dominated by massive corals, with minor intervals of encrusting coralline algae and skeletal grainstone; also coral rubble intervals;



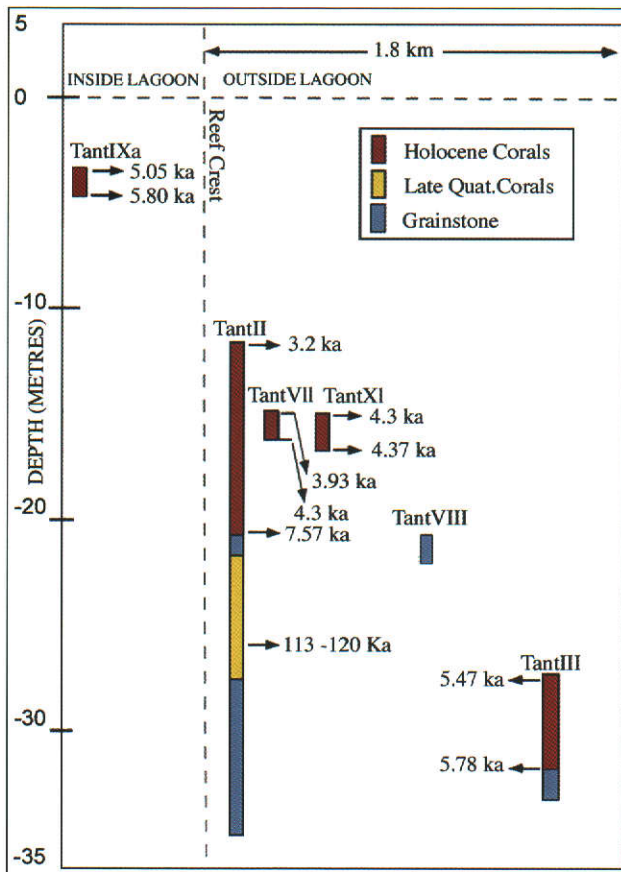


Figure 7: Cored transect at Tantabiddi showing position and elevation of cores relative to reef crest and sea level, also stratigraphy and U-series ages. For core locations see Fig. 5. After Collins et al. (2002).

#### DISCONFORMITY

##### Pleistocene

Unit B (7.3-7.45 m): Coralline algal bindstone and rudstone, and bioclastic grainstone, with horizons of sponge borings;

Unit C (7.45-7.6 m): Rudstone, bioclastic and coralline algal bindstone;

Unit D (7.6-8.1 m): Rudstone/floatstone, brown-stained; abundant red algal and coral debris;

Unit E (8.1-10.4 m): Coral (*Acropora*) framestone, with well developed in situ branching coral framework bound by encrusting coralline algae, with borings filled by skeletal grainstone;

Unit F (10.4-10.85 m): Thin interbeds of skeletal grainstone, coralline algal bindstone, and coral framestone;

Unit G (10.85-15.85 m): Coralline algal bindstone with intervals of coral framestone, the latter dominated by plate corals; bindstone fabric includes vermetid gastropods and has cm scale borings filled by cemented skeletal grainstone;

Units H (15.5-16.5 m), I (16.5-17.5 m), J (17.5-18.3 m): thin units of bioclastic rudstone and skeletal grainstone with intervals of coralline algal bindstone;

#### UNCONFORMITY

Unit K (18.3-24.5+ m): Cream, well lithified bioclastic skeletal grainstone, cross-bedded; composed of sand-sized coral

and coralline algal fragments; the contact with Unit J is heavily bored and stained.

The 7.5 m thick Holocene reef (Fig. 9a) is differentiated by relatively high porosity and an open framework with many unfilled voids. It has a basal date of 7.57 ky and a near-surface age of 3.2 ky. It is relatively homogeneous and composed of robust coral framestone, often bound by encrusting coralline algae. The contact with underlying Last Interglacial reef is identified by heavily bored surfaces in Units B and C/D (Fig. 9b), and Unit D corals have a U-series age of 115 ky. The 11 m thick Last Interglacial reef grew on a bored limestone pavement (Unit K; Fig. 9f) and consists of, from base to top: a) a 3 m interval dominated by bioclastic rudstone in which pelecypods are common and framework is subordinate; b) a 4.5 m interval of mainly coralline algal bindstone which contains thin coral framestone units (Fig. 9d, e); and c) a 3.5 m interval of branching *Acropora* coral framestone (Fig. 9c). The Last Interglacial reef ranges in age from 119-115 ky, with an unexplained age inversion in the core of 134 ky at 10.2 m.

Holocene cores at other sites (Fig. 7) are composed mainly of coral framestone, with lesser amounts of coralline algal bindstone and bioclastic rudstone. The most seaward of these cores (Tant III) was drilled at 27 m below sea level, and contains 4 m of massive coral framestone, overlying skeletal grainstone. The basal age of the reef unit here is 5.78 ky, and this core lies close to the seaward limit of Holocene reef growth.

#### Ningaloo Reef: discussion

Both Last Interglacial and Holocene sea level histories along the western continental margin are known from dated reefs, chiefly at the Houtman Abrolhos Islands, which are shelf-edge reefs located some 600 km south of the Tantabiddi cored transect. There the Last Interglacial sea level reached 1-2 m by 132 ky, and persisted until ca. 116 ky, maintaining an elevation of +4 m for most of the time (Zhu et al., 1993; Eisenhauer et al., 1996). The Holocene sea level reached -25 m at 9.8 ky, and rose to a high of -0.5 m at 6.4 ky (Eisenhauer et al., 1993; Collins et al., 1993). These data, which agree reasonably well with those from other dated reefs, are far more detailed than the dates available from Ningaloo Reef in this study. The primary difficulty in obtaining optimum core data was the inaccessibility of reef crest drillsites due to the high wave energy, and equipment limitations.

The stratigraphic cross-section for the Tantabiddi area (Fig. 10) is based on short cores in the lagoon and in front of the reef, and from the 25 m cored hole (Tant II) drilled in 11m of water immediately seaward of the reef crest (Fig. 5). The cored section in Tant II is 7m of Holocene reef (giving a projected Holocene thickness of 18 m at the reef crest), underlain by 11 m of Last Interglacial reef, which unconformably overlies well-lithified coarse skeletal grainstone with gravel lags (interpreted as a lagoon sand sheet deposit). These data indicate that Holocene reef growth recolonised the Tantabiddi Terrace (Last



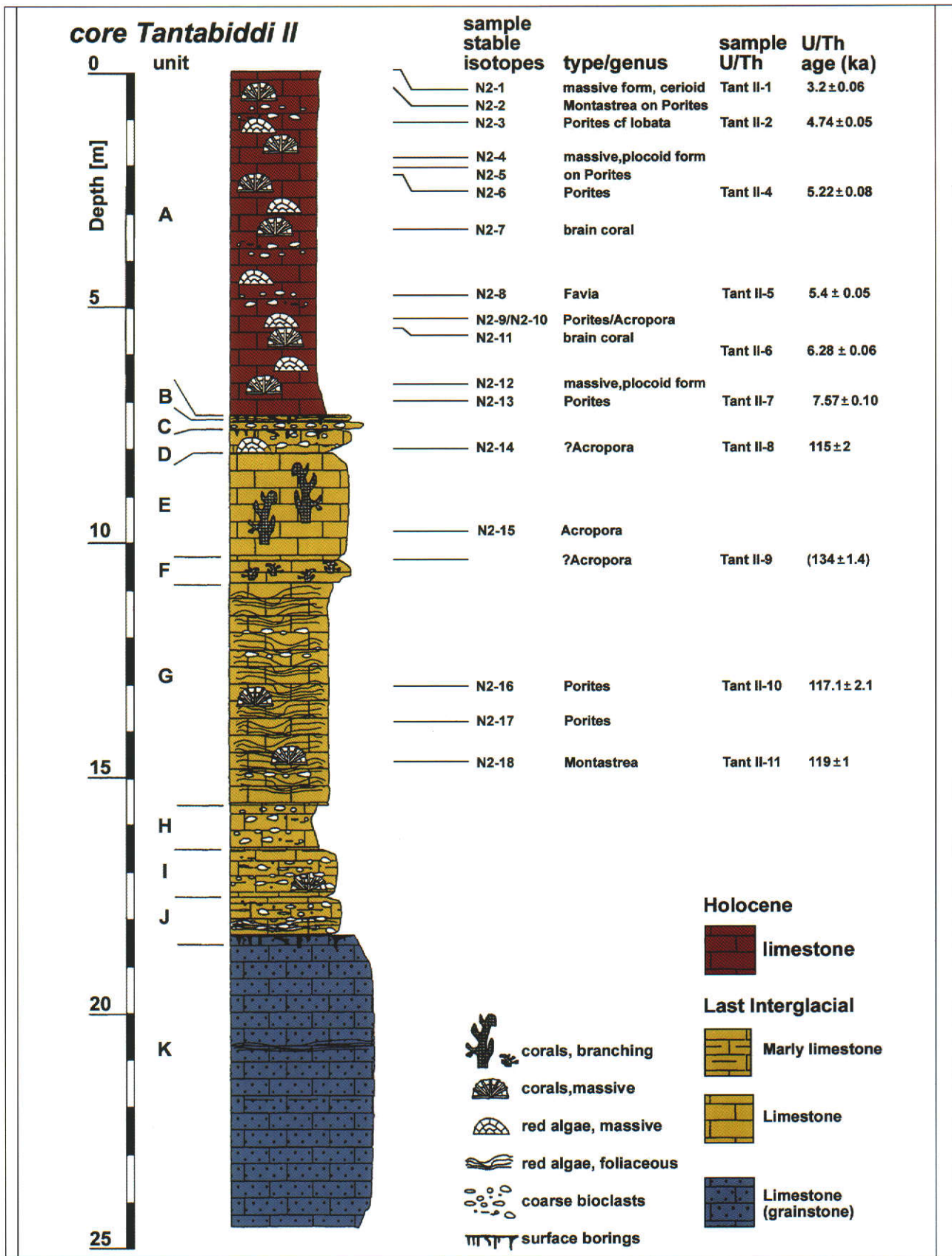


Figure 8: Tantabiddi II core log showing stratigraphy, lithofacies units and age relationships of Holocene and Last Interglacial reefs. For core location see Fig.5. After Collins et al. (2002).



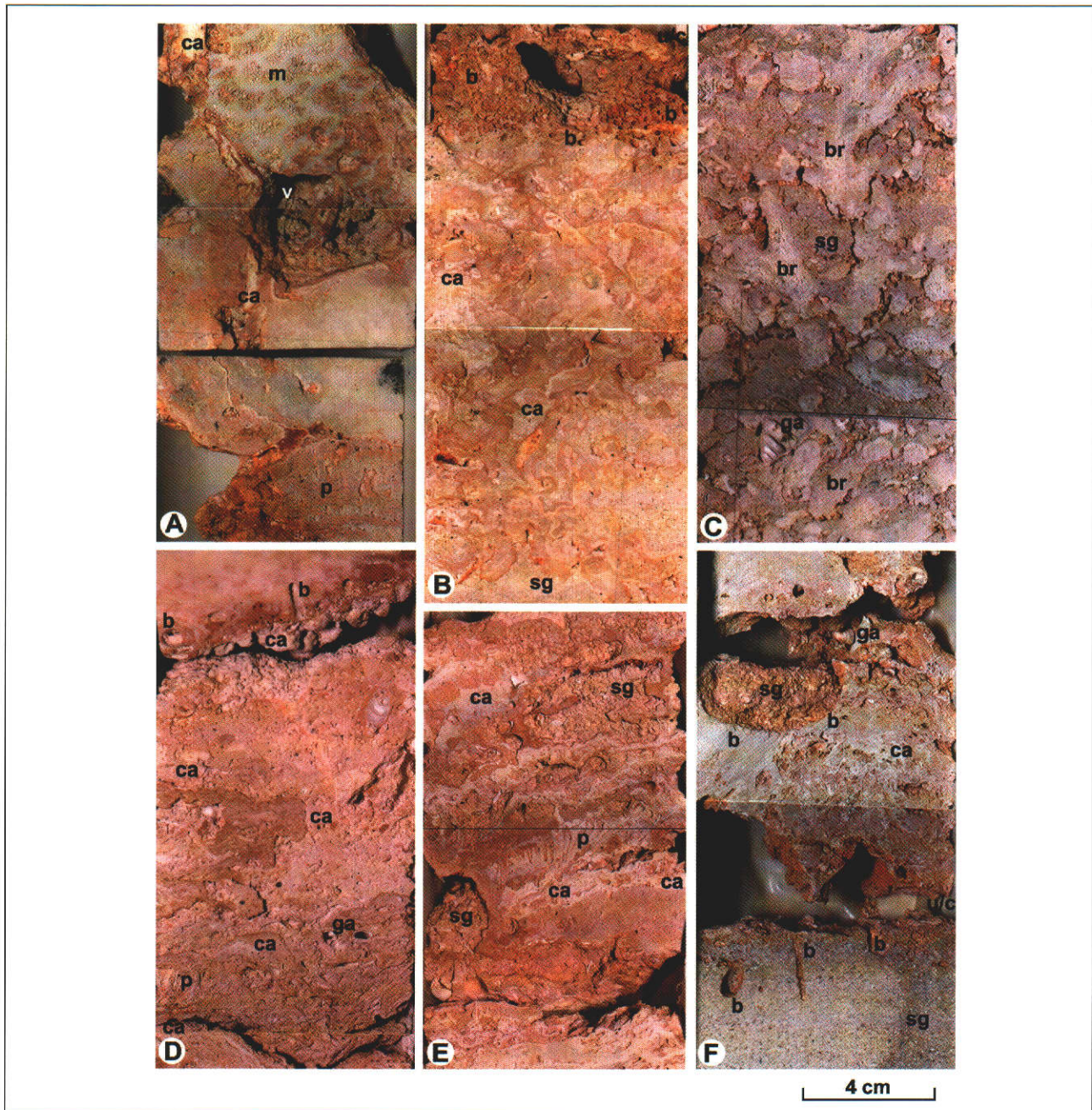


Figure 9: Core slabs showing lithofacies of Tantabiddi II core.

- a). The Holocene reef (Unit A; core depth 0.5 m) consists of coral framestone with massive corals (m) and plate corals (p) throughout, often with rinds of coralline algae (ca). Voids (v) are partially filled with rudstone and grainstone.
- b). The uppermost Last Interglacial reef (Unit B, core depth 7.5 m) is represented by a prominent bored horizon (b) at the unconformity at the base of Unit A. Here the rudstone fabric of Unit B is bound by encrusting coralline algae (ca), overlying skeletal grainstone (sg).
- c). Branching coral (br) framestone dominates Unit D (core depth 8.7 m) with corals (*Acropora*) in near-growth position; note infill of skeletal grainstone (sg); also small gastropod (ga).
- d). Unit G (core depth 13.5 m) is predominantly coralline algal (ca) bindstone, with layers of framestone (p= plate coral). Bored horizon (b) is coralline algal (ca) encrusted.
- e). Skeletal grainstone (sg) cemented sediment fills borings in algal bindstone fabric of Unit G (core depth 15.5 m); note framestone interval at base (p=plate coral).
- f). Basal unconformity beneath Last Interglacial reef is represented by a bored surface (b) overlying well lithified skeletal grainstone (Unit K); core depth is 18.3 m. Note overlying rudstone and algal bindstone of Unit J which is heavily bored (b) and infilled by skeletal grainstone (sg) and gastropods (ga).



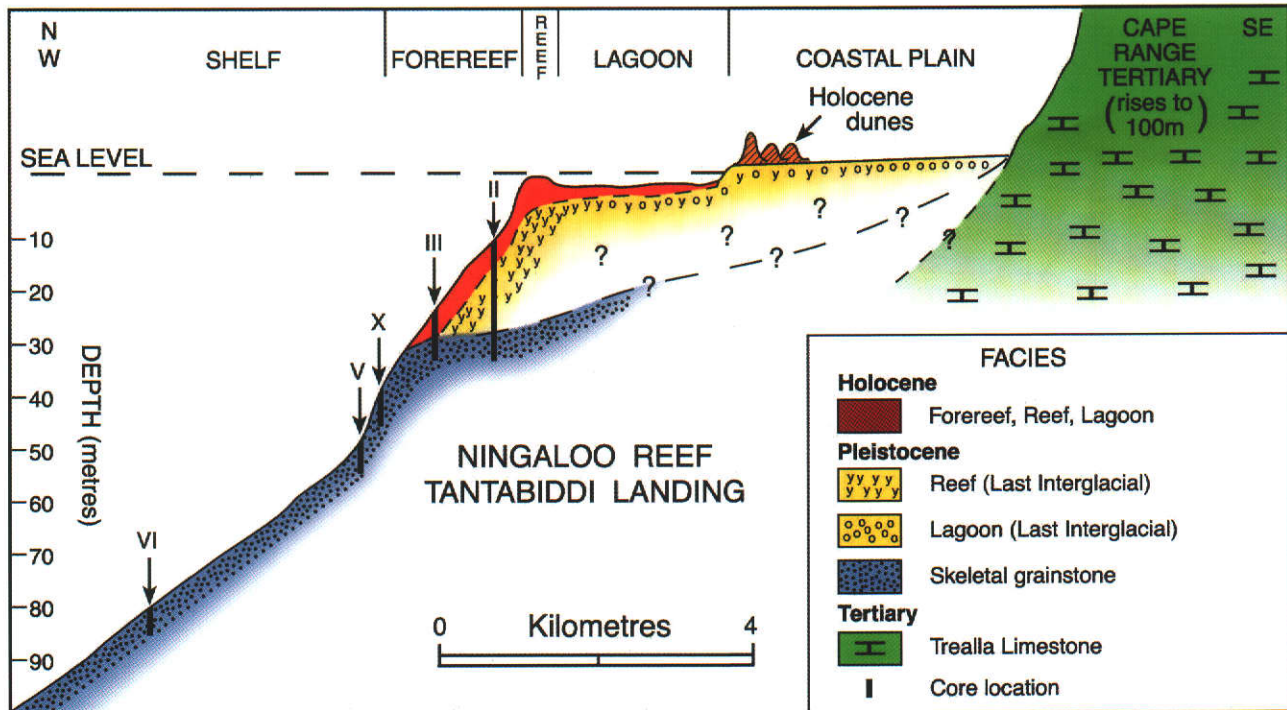


Fig. 10: Idealised northwest-southeast cross-section of northern Ningaloo Reef based on the Tantabiddi cored transect and seismic data (see Figs 5 & 6).

Interglacial reef) near its submerged, seaward margin, and is relatively thin (eg. when compared to the 40 m of Holocene growth at the Houtman Abrolhos). The basal age of the cored Holocene reef in Tant II is 7.57 ky U/Th (range 4.3-7.57 ky in all cores; see Fig. 7), compared with 11 ky U/Th for the Abrolhos Holocene reefs.

The envelope of Last Interglacial U/Th reef ages (115-120 ka) represented by the Tant II cored section (at SL -18 to -36 m) lies toward the end of the Last Interglacial highstand (132-116 ky; Zhu et al., 1993), suggesting that this submerged, distal part of the Tantabiddi Terrace grew later than most of the Last Interglacial reefs which comprise the emergent terrace in the coastal zone. The facies transition in core Tant II (bioclastic rudstone lacking reef frame, to coralline algal bindstone with framestone intervals, to branching *Acropora* framestone) represents, after colonisation, falling energy conditions, probably associated with a constructional phase of reef development.

The relationship between the Holocene and Last Interglacial phases of reef development is clearly shown from seismic and core data, in addition to outcrop. The Last Interglacial reef is widespread, comprising the Tantabiddi Terrace onshore (Fig. 3) and extending beneath the lagoon of the contemporary reef. The greater southerly extent (to 32°S, at Rottneest Island; Playford, 1997) and more vigorous development of Last Interglacial reef is considered to represent a stronger Leeuwin Current at that time (Kendrick et al., 1991). The Holocene transgression in the Ningaloo reef tract reached a height of +1 m some 4000y ago (Wyrwoll et al., 1993), compared to the Last Interglacial high stand of +4 m.

The Holocene reef crest grew along the seaward margin of the Last Interglacial reef system, so its vertical growth potential of ca. 18 m was limited by the elevation of the reef system it colonised.

The pattern of reef growth for the fringing Ningaloo Reef differs markedly from that of the shelf-edge Houtman Abrolhos reefs to the south, where accommodation space was sufficient to allow the growth of "keep up" Holocene reefs in the lee of emergent Last Interglacial reefs, and relatively long and complete Holocene sea level records resulted (Collins et al., 1997). The core data used in this study are limited and localised to the northern part of the reef, and further studies are needed along the reef tract.

### Scott Reef: regional setting and Tertiary foundations

#### Geological structure

Scott Reef (Fig. 11) is a complex of two large isolated coral reefs developed on top of an anticlinal structure of Triassic age, faulted down to the northwest on the northwest side by Late Triassic movement (BOC, 1971a,b; BOC, 1972). A Carnian to Norian age for onset of inversion and initiation of the Scott Reef high is based on biostratigraphy (Struckmeyer et al., 1998).

The Scott Plateau and its northeastern extension delineate the western limit of the Browse Basin. Seismic data suggest that the plateau consists of uplifted, relatively shallow Palaeozoic and Precambrian rocks overlain by thin (<1000 m)



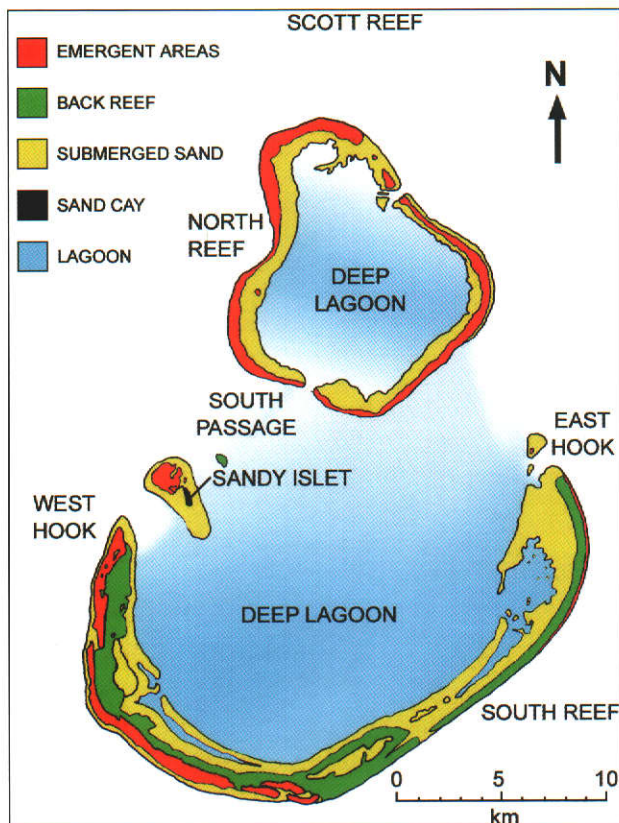


Figure 11: Scott Reef, showing interpreted environments.

Cretaceous and younger sediments (Stephenson & Cadman, 1994; Symonds et al., 1994). Throughout the Permian and Jurassic, the Scott Plateau was probably above mean sea level, providing a source of clastic sediments for the Browse Basin (Stagg, 1978). The Browse Basin developed in the Carboniferous to Early Permian as a result of north-northwest extension, which led to continental breakup in the Early Permian (Struckmeyer et al., 1998). Upper crustal faulting resulted in half-graben morphology and compartmentalisation into distinct depocentres. Resultant structures influenced the subsequent features, and near the end of the Triassic a major compressional event (defined by a regional unconformity) resulted in the generation of a series of large anticlines and synclines, including the Scott Reef and Brecknock trends (Struckmeyer et al., 1998). Post-breakup transgressive marine shales and claystones covered the Scott Reef trend by the Late Tithonian, and claystones, siltstones and marls dominate the Cretaceous section.

#### Tertiary foundations

A 3,515 m section of Paleocene-Quaternary carbonates (mainly calcarenite, calcilitite and marl, with minor chert) underlies the Scott Reef platform (BOC, 1971a,b; BOC, 1972). The top 1,700 m consists of an undated reef complex which is dolomitised. A Middle Miocene to Burdigalian age was obtained within calcarenite, calcilitite and dolomite sections between 1,700-2,198 m. Aquitanian calcarenite and

marl sections at 2,198-2,379 m unconformably overlie the Oligocene and Upper Eocene calcarenites, which continue down to 2,458 m. Eocene and Upper Paleocene fine grained carbonates and cherts continue from 2,458-3,484 m. The remainder of the Upper Paleocene (claystones and marls) continues to 3,578 m, and the Middle Paleocene rests unconformably on the Upper Cretaceous.

#### Platform and reef morphology

Scott Reef (Fig. 12) rises from depths of 400-700 m on the distal portion of a carbonate ramp, and is similar in setting to "downslope buildups" described from the geological record (Read, 1984). It is a complex of two large isolated coral reefs separated by a deep channel; the pear-shaped North Reef and the crescent-shaped South Reef (Berry & Marsh, 1986) (see Fig. 11). North Scott Reef is continuous except for two narrow passages, one in the southwest, and one in the northeast, with similar reef flat dimensions throughout. The outer reef flat is a mixture of algal turf, with scattered large boulders and occasional living corals. The outer reef gives way on its seaward margin to a gentle slope followed by an irregular outer slope with surge channels extending to 30 mwd. There are steep gradients to seaward. The inner reef has low coral cover, some algal turf, and lacks a distinct boulder zone. The back reef is deeper, with a more diverse coral fauna, and the lagoon is sandy with scattered corals.

South Reef is open to the north, and is 27 km wide (east-west) and 20 km from north to south. The distance between the reefs is 5 km and the intervening channel is 400-700 m deep. The reef flat of the western part of South Scott Reef is over 2 km wide, and 600 m of reef flat is emergent at low water. Sandy Islet is a small, unvegetated sand cay situated atop a detached northwesterly portion of the reef. The eastern part of the reef is similar in morphology to the west reef, also with a detached sand cay, which is the only portion emergent at low water. The outer reef generally has encrusting coralline algae and minor corals, and the reef flat includes boulder rubble, sand flats, algal turf and minor amounts of coral. The back reef is sandy with scattered *Porites* "bombies", other corals and sparse seagrass. Lagoon depths inside South Scott Reef are 35-55 m, and there are isolated coral knolls, sandy areas, and hard substrates with sponges and stunted coral communities.

Coral assemblages identified by Done et al. (1994) were: Staghorn *Acropora* thickets, with moderate diversity of massive and branching corals (deep inner reef flats), *Goniastrea retiformis*/*Porites* massive community (sheltered reef flats and lagoon slopes), *Acropora brueggemanni* thickets (areas with moderate water motion), Faviid, pocilloporid and *Acropora palifera* assemblage (areas with moderate-strong water motion), and the 'Staghorn plus' assemblage (lagoon floors). Coral cover, diversity and median coral sizes were high, and levels of injury and death, low at that time consistent with an absence of physical disturbances. Coral predators, present in low numbers, represent a potential threat to coral communities.



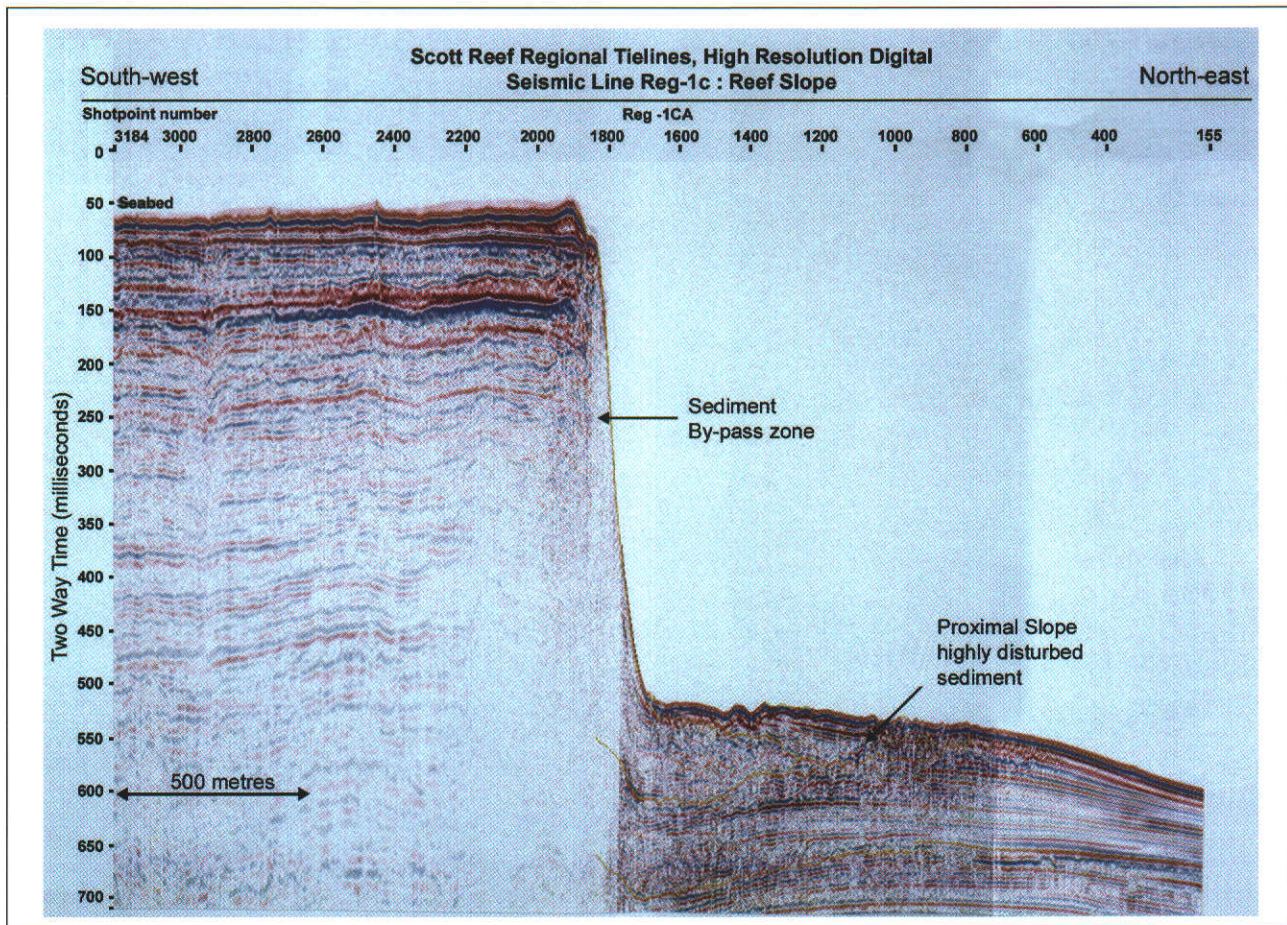


Figure 12: Shallow seismic profile of South Scott Reef from NE to SW (see Fig. 13a line A-B for location). Note slump deposits at the foot of the steep platform margin, overlying Tertiary carbonates, and shallow Tertiary-Quaternary reflectors within the platform. Data provided by Woodside.

### Seismic structure of Scott Reef

Little is known of the Quaternary geology and reef growth history, and there is a lack of surface and subsurface data. Shallow seismic investigations of the South Scott Reef region were designed to investigate reef morphology, age structure and growth patterns.

#### Late Quaternary geology

There is no outcrop available for assessment, other than boulders thrown onto the reef flat from the reef front by storms, and small sand cays at East and West Hook. Sandy Island, the West Hook sand cay, was investigated by shallow (31 m) site test borings in 1974 (Fig. 13). An upper and lower reef unit were encountered, separated by a discontinuity at 21 m below groundwater level. The upper unit consists of coral sand and coral fragments, and probably represents Holocene reef growth. The lower unit has similar lithology but has many hard bands (presumably due to calcretization) and the penetration rate ("blowcounts/ft" on the drill log, Fig. 13d) decreased abruptly at the discontinuity. This unit is likely to represent the Last Interglacial reef, immediately below the

Holocene, a stratigraphy documented from most coral reefs. Whilst no material is available for dating, the lithostratigraphy, interpreted chronostratigraphy, and the elevation of the discontinuity can be used to calibrate the seismic data.

#### Calibration of seismic data to subsurface geology

Sandy Island is a topographic high near the northwestern margin of the South Scott Reef platform. Seismic profile B-B' passes close to Sandy Island, and the topographic high is clearly visible near B' (Fig. 13). The prominent seismic reflector, R1, identified on all seismic profiles as the first reflector beneath Holocene reef growth, is present beneath the high, and rises to trace out a palaeo-high beneath the contemporary topography. The maximum elevation of R1 beneath the high is 34 m below sea level (bsl), and the crest of the high on B-B' is 9 m bsl. Thus it is likely that the elevation of R1 and the palaeo-high beneath Sandy Island, which is just emergent, may be 9 m shallower, or about 25 m bsl. This estimate agrees well with the borehole estimate for the discontinuity, ie. 21 m below GWL (groundwater level), considering that the values are uncorrected for tides (tidal range is 4 m), so it is highly likely that R1 represents the Last Interglacial surface.



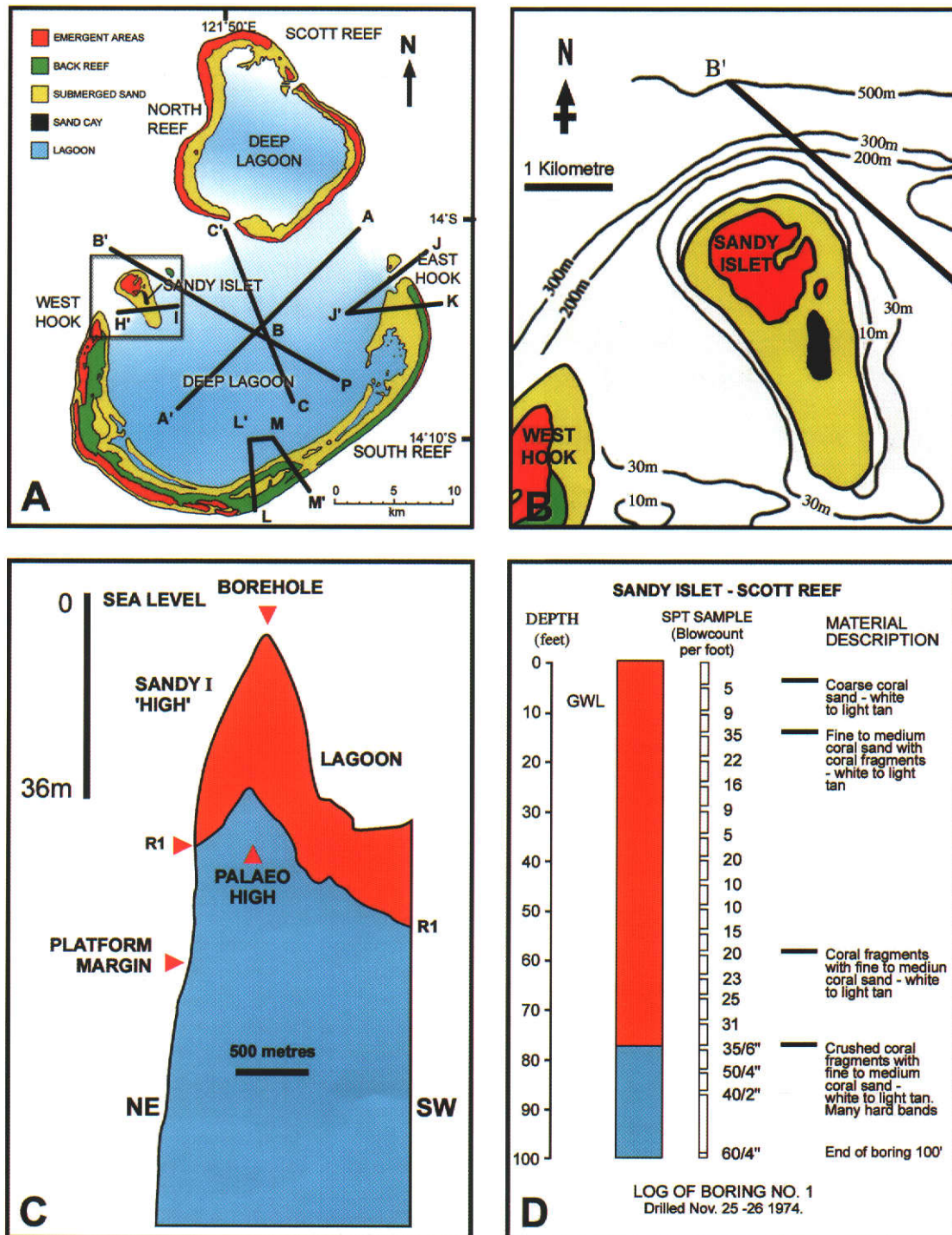


Figure 13: Subsurface geology of Sandy Island, Scott Reef and relationship between topography, seismic reflectors and Late Quaternary geology at south Scott Reef.

- Location map of South Reef seismic lines. Note line B-B' passes just to the north of Sandy Islet.
- Bathymetric map of the northwest platform margin near Sandy Islet. Seismic line B-B' extends SE from B, passing from depths of 500 m to the platform just to the NE of Sandy Islet, and from there across the lagoon.
- Diagram of part of seismic line B-B' (near B', see Fig. 13b) shows the steep platform margin, the Sandy Islet 'high' and the lagoon. Reflector R1 traces out a "palaeo-high" beneath Sandy Islet. The approximate position of the Sandy Islet borehole is shown.
- The Sandy Islet borehole shows a 25 m thick unit of coral and coral sand (Holocene reef growth) overlain by a similar but highly indurated unit below 25 m (the Last Interglacial reef). This lithologic discontinuity appears to coincide with seismic reflector R1 (see C). (Borehole data provided by Woodside).



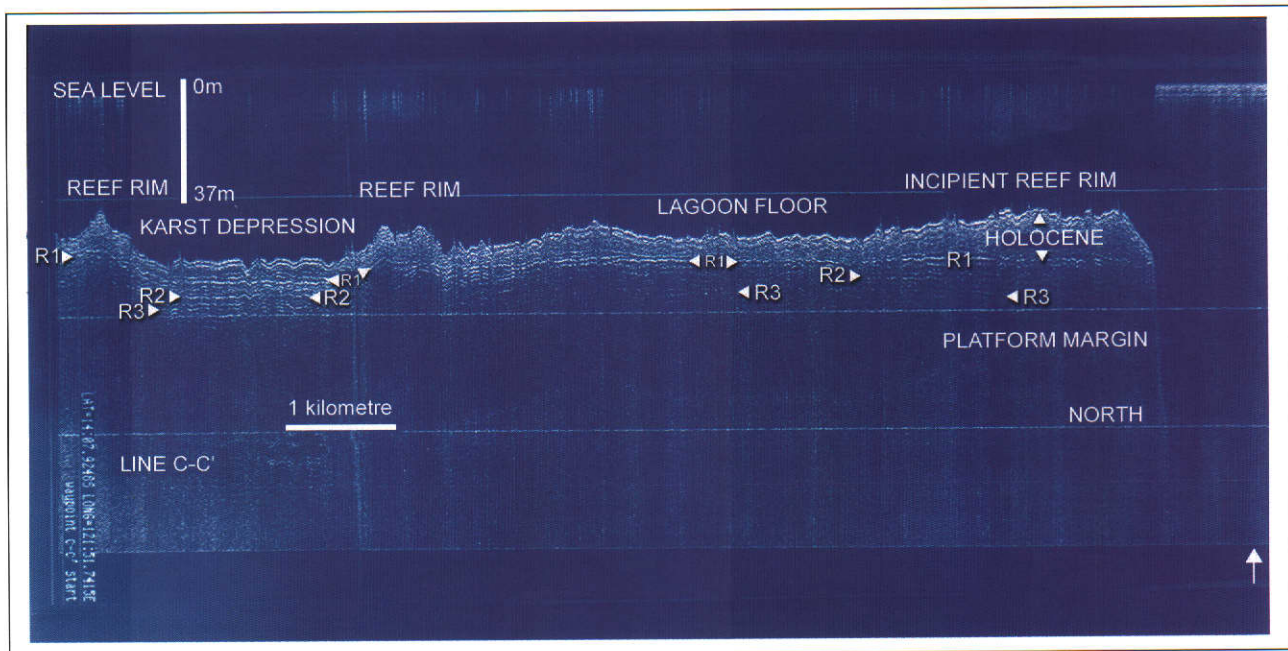


Figure 14: Seismic profile C-C' of South Scott Reef lagoon, showing the Last Interglacial surface (=R1), and morphology of Holocene reefs (for location see Fig. 13). Line C-C' is a N-S profile of lagoon floor, south lagoon of Scott Reef. A steep slope terminates the platform to the north near C', where an incipient Holocene reef is present. The lagoon floor is relatively flat with well developed pinnacle reefs, of relief 5-7 m. Three subparallel reflectors occur at 56m bsl (R1), 64 m bsl (R2) and 68 m bsl (R3). Reflector R1, the Last Interglacial reflector provides an antecedent surface of highs (53 bsl) and lows (56 m bsl) which are reflected by the Holocene reef growth pattern. The Holocene reef thickness ranges from 10 to 17 m. Reflectors R1 & R2 are flatter and less distinct than R1. A prominent flat-floored depression near C is 1.3km across and is 7 m below the general lagoon floor level, and is rimmed by Holocene reef growth. The Holocene above R1 is here only 7 m thick, with a smooth surface. R1 is at 64 m bsl on the depression floor, up to 10 m lower than elsewhere in the profile. Reflectors R2 and R3 are also present as flat surfaces beneath the depression at levels lower than elsewhere in the profile. This feature is interpreted as antecedent karst, which dates from R3 time and continues to be expressed in the Holocene topography.

#### Seismic investigations

Seismic profiles of the South Scott Reef lagoon and reef crests were conducted during 2000 to assess the Quaternary reef growth pattern. At least two stages of reef growth (Last Interglacial and Holocene) were anticipated, both with the potential to be exposed, but the absence of outcrop data ensured that seismic methods afforded the best opportunity of mapping reef geometry. The nature of the Last Interglacial platform, its substrate and topography, including the position and elevation of any palaeo-lagoon and reefs, were expected potentially to exert antecedent controls on Holocene reef growth. The type and pattern of Holocene reef growth, and the amounts and location of Holocene reef building in the lagoon and at the marginal reef crests were assessed. The contemporary reef is double-crested over much of its arcuate distribution, with active pinnacle reefs interspersed with sandy depressions between inner and outer crests; intervening areas are single-crested.

#### Lagoon seismic structure and morphology

The deepest two reflectors identified on lagoon profiles are at 64 m and 68 m bsl respectively (see Figs 13a & 14, profile C-C'). These surfaces are sub-parallel to and lie below a

prominent reflector which is present throughout the lagoon at 50-55 m bsl. This surface is flat to hummocky, and rises at the lagoon margins by as much as 10 m, towards the contemporary reef crests. There are two probable karst depressions in the reflector which are ca.10 m deep (rim elevation: 50-53 m; floor 64 m bsl) and up to 1.3 km across, steep sided and flat floored, with a younger reefal infill whose elevation lies distinctly below that of contemporary lagoon-floor pinnacle reefs. The reflector R1 is interpreted to be the Last Interglacial surface based on its apparent karstification and relatively uniform elevation as the substrate to Holocene accretion in the lagoon. It is consistently overlain by 10 m of accretion, interpreted to be Holocene reef and intervening hard substrate (based on seismic character and seafloor photography), the upper surface of which is the contemporary lagoon floor, composed of pinnacle reefs of 4-8 m elevation above a more flat, intervening substrate. Benthic sampling and seafloor video recordings collected by Franklin show that the lagoon floor is a sediment-starved, hardground surface with a high cover of encrusting coralline algae, corals and sponges. There is a strong correlation between the growth positions of Holocene lagoon reefs and antecedent topography, in that most reef initiation took place upon highs in the Last Interglacial surface. In addition, reefs growing from the floors



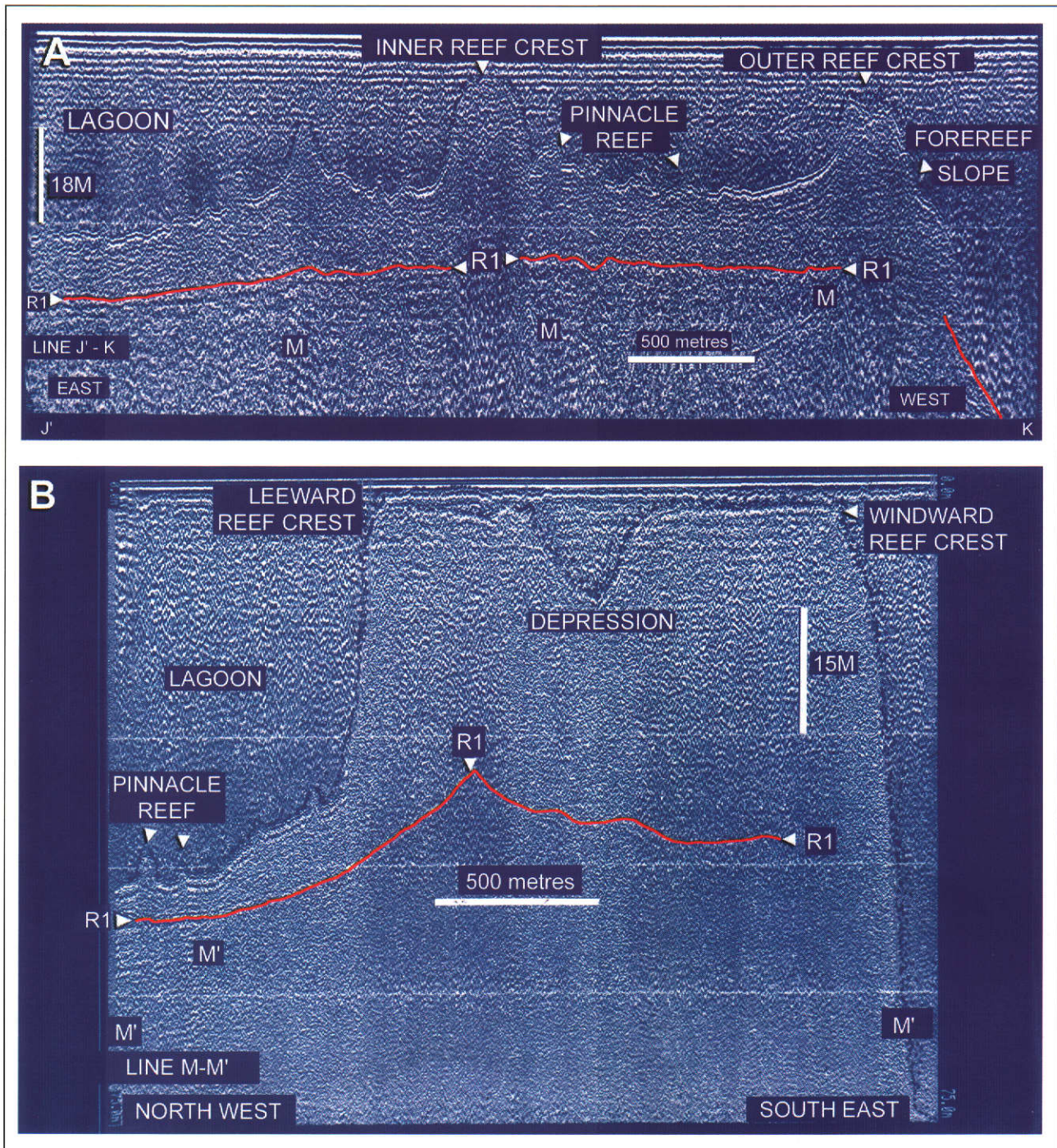


Figure 15: Seismic profiles J'-K and M-M' of platform margin reefs of South Scott Reef (for locations see Fig. 13).

- Profile (J'-K) across reef crest, SE portion of southern Scott Reef. The lagoon near J is ca 38 m deep and has well developed pinnacle reefs, which increase in height from 3-4m to 5-6m approaching the inner reef crest. The Holocene section is 14m thick, above reflector R1 (shown in red). The reef is distinctly double-crested, with a intervening depression ca 25 m depth which has active reef growth in the form of small (3-6 m) pinnacles. The inner and outer reef crest have 30m of relief but have not completely grown to sea level, with crests ca 10 m bsl. The forereef slope descends steeply to 75 m bsl near K. The prominent reflector R1 (the interpreted Last Interglacial reflector) is 52 m bsl beneath the lagoon at J and rises to 44 m bsl beneath the inner reef crest and maintains this elevation to the leeward side of the outer reef crest, where it becomes difficult to trace, (M= multiple).
- Profile (M-M') of reef crest, south reef of Scott Reef. The reef rises from lagoon depths of 15 m to LW Springs. A central depression is sand-floored and 15 m deep. Reflector R1 (the interpreted last Interglacial reflector) is 52 m bsl below the lagoon floor, rises to 35 m bsl beneath the leeward reef crest, then falls in elevation to ca 40 m beneath the windward reef crest, where it becomes indistinct, (M = multiple).



of karst depressions fill the depressions but grow to a level significantly below that of other lagoon reefs, whilst reefs on the depression rims rise above those of the general lagoon level.

#### Platform margin reefs

Profiles of the arcuate, single- to double- crested reef, which rims the lagoon, show that the Last Interglacial reflector rises beneath reef crests and falls beneath inter-crest depressions, exerting an antecedent influence on younger (Holocene) reef growth. At the landward extremity of the platform margin reefs, the Last Interglacial surface has risen to 36 m bsl from the lagoon level of 60 m. A further rise to ca. 30 m bsl occurs beneath the Holocene crest (Fig. 15, see profiles J'-K and M-M') before the reflector falls towards the seaward face of the Holocene reefs. Though the reflector is difficult to trace in its entirety to a seaward-sloping termination at the platform margin, it is clear that the Last Interglacial "rim" is a relatively low relief feature, perhaps reflecting lowstand erosional modification and/or subsequent bevelling of a pre-existing reef crest during transgressive drowning.

Reefs at the platform margin have active coral growth and are interpreted to be Holocene features, with crestral thicknesses of 24-32 m overlying the Last Interglacial surface. These buildups are uniformly present above the Last Interglacial reflector in all profiles collected, and have a steep, seaward face which has been traced on seismic profiles to 150m bsl as it descends at the fore-reef slope of the platform margin.

The northern platform margin is open, and has a weakly-developed, incipient reef rim adjacent to the deep trench between North and South reefs. The Holocene thickness is 15m, and the Last Interglacial reflector descends from -55 m to -68 m with a significant foreslope, terminating on the foreslope of the platform margin.

#### Scott Reef: discussion

The inferred history of Late Quaternary platform evolution is based upon the interpreted seismic structure, supported by dating of corals to confirm the timing of events, and using known sea level histories derived from dating of reef growth in tectonically stable environments. The most detailed and regionally applicable chronology of reef growth has been derived from the Houtman Abrolhos carbonate platforms, which are shelf-edge reefs on the tectonically stable western margin of Australia, at latitude 27°S (compared with the latitude of 14°S for Scott Reef). Though these microtidal reefs are in a significantly different (and distant) tectonic environment, they provide, in the absence of dated cores at Scott Reef, reference growth history and sea level chronology for comparative purposes (Eisenhauer et al., 1993; Collins et al., 1993, 1997, 1998; Zhu et al., 1994). Over 100 km of shallow seismic profiles were collected, with lines tied to 8 fully cored holes, and radiometric dating was performed both on the cores and island reef outcrops of the 25 km wide Easter Platform. The data available constrain the ages and elevations

of both Last Interglacial and Holocene transgressions and reef growth histories, and agree with established global sea level history (see Collins et al., 1993). In applying these data to Scott Reef, the critical questions are: 1) the lack of emergent Last Interglacial reefs (emergent by 2-5 m at 125 ka at the Abrolhos and Ningaloo Reefs; highest elevation at Scott Reef is 30 m below sea level), and 2) the lack of Holocene emergence (1 m above sea level at the Abrolhos at 5000 years B.P., but no evidence of emergence at Scott Reef). The significant difference in Last Interglacial reef level could be attributed to Late Pleistocene tectonism, involving relative subsidence (by 30 m; ca. 1 m/4000 y) in the Scott Reef area, and this is assumed to be the case, though little supporting evidence is available. Further, if this process was assumed linear since 125 ka, the Holocene component would be of the order of 3 m, which could also account for the lack of Holocene emergent reefs. This mechanism is assumed for the tentative reconstruction of events proposed, as follows:

**Stage 1:** Last Interglacial (Stage 5e) reef growth, ca 140,000 to 110,000 ky: the seismic data do not reveal the thickness of Last Interglacial reefs, but there is up to 30 m elevation difference between the lagoon and reef crest, so this elevation difference in the Last Interglacial reflector approximates the relief and thickness of this phase of reef growth, which reached a highstand at 125,000 ky. A saucer-shaped platform with a central lagoon and platform-edge reefs, similar in morphology to the present-day reef, existed at this time.

**Stage 2:** Regression following Stage 5e reef growth: this stage saw emergence of the Last Interglacial platform, and development of karst morphology in the lagoon, as recorded in at least two locations on seismic profiles. It is likely that emergence was continuous or was interrupted by brief inundations (Stages 5c and 5a) through to and beyond the Last Glacial Maximum (sea level at -130 m; 18,000 y B.P.).

**Stage 3:** Early Holocene transgressive drowning of Last Interglacial platform: the rising Holocene transgression reached ca. 30 m bsl, the elevation of much of the Last Interglacial reef rim, by 10,000 y B.P., and rapid drowning of the platform commenced at about this time. After a startup lag of about 1,000 y, Holocene reef growth built upon the antecedent topography and tracked sea level rise through the Holocene.

**Stage 4:** Holocene sea level maximum of 1-2 m asl; 5,000 y ago: it is likely that Holocene reefs grew to sea level by this time, based on data from other reef systems. However, there is no local evidence to support this. Holocene reefs are up to 30 m thick at the circum- platform reef crests, and over 10 m thick buildups occur in the lagoon, where small patch reefs of ca. 5 m thickness are also common. The East Hook area is the only location at which reef growth has not fully reached sea level.

**Stage 5:** Late Holocene regression to present sea level: this phase, usually evident as emergence of reefs and islands, is not evident at Scott Reef, where there is only one small sand cay which is present and permanently exposed near West Hook.



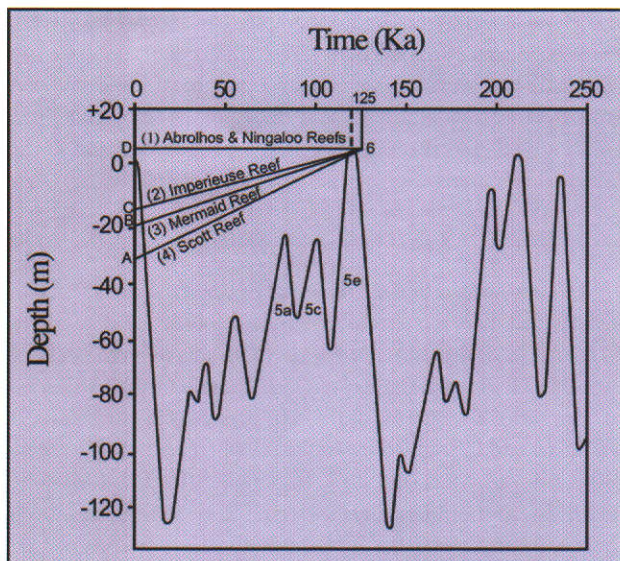


Figure 16: Estimated subsidence of Last Interglacial reefs (based on seismic data) compared with global eustatic sea level curve of Chappell and Shackleton (1986). Oxygen isotope stages (eg. 5a) are labelled on the curve.

The 4 m tidal range ensures that emergence of much of the reef occurs at spring tides, but complicates determination of subtle isostatic reef emergence.

The most striking feature of the seismic structure of South Scott Reef is the relationship between Holocene and Last Interglacial reef development. The saucer-shaped morphology of the Last Interglacial reef provided a template for Holocene reef growth, which duplicates the preceding reef and its morphology, and has grown in the accommodation space provided by subsidence of the Last Interglacial reef. This subsidence, up to 30 m at Scott Reef (see Fig. 16), is in contrast to the tectonic stability of the Last Interglacial in the Carnarvon and Perth Basins (Ningaloo and Houtman Abrolhos Reefs) where the Last Interglacial reef remains emergent by 2-5 m above sea level along 1000 km of coast (Collins et al., 2002) in these proximal shelf settings. Though local Quaternary subsidence data are lacking, the position of Scott Reef at the distal margin of the North West Shelf would ensure that subsidence due to hydro-isostatic loading of the shelf by transgressive drowning would be at a maximum there, and the calculated subsidence rate since the Last Interglacial is 4 m/1000 y, based on coral reef dates from the southern North West Shelf. This subsidence, along with global eustasy, has been a key control on the morphology of Scott Reef in the Late Quaternary.

### Rowley Shoals: regional setting and Tertiary foundations

The Rowley Shoals (Figs 1, 2 and 17) are emergent annular reefs situated 260 km west of Broome, and rise from water depths in excess of 230 m. They are within the Rowley Sub-

basin of the Roebuck Basin, which is dominated by a seaward-thickening wedge of mainly Triassic and Jurassic sediments that reaches a maximum thickness of about 10 km at the lower continental slope (Colwell & Stagg, 1994). This wedge overlies Palaeozoic strata, which in turn overlie faulted Precambrian basement.

East Mermaid 1, drilled 25 km northeast of Mermaid Reef, is dominated by clastics prior to the mid-Cretaceous; these are overlain by 1200 m of calcarenites, calcilutites and claystones, including a Tertiary prograding carbonate wedge of shallow shelf to lagoonal deposition. During the Miocene the Scott Reef/Rowley Shoals platform formed a narrow continental shelf, and the reefs have persisted despite rapid subsidence of the shelf edge since the mid-Miocene, with one drowned reef reported south of the Rowley Shoals (Jones, 1973).

### Reef morphology

The Rowley Shoals (Fig. 17; Mermaid, Clerke and Imperieuse Reefs) have been described as the most perfect morphological examples of shelf atolls in Australian waters (Fairbridge, 1950). The three shoals have similar dimensions, shape, orientation and distance apart, and all rise from the distal ramp of the North West Shelf at latitudes 15-17°35'S. From northeast to southwest the reefs rise from progressively shallower depths on their landward sides; Mermaid Reef from

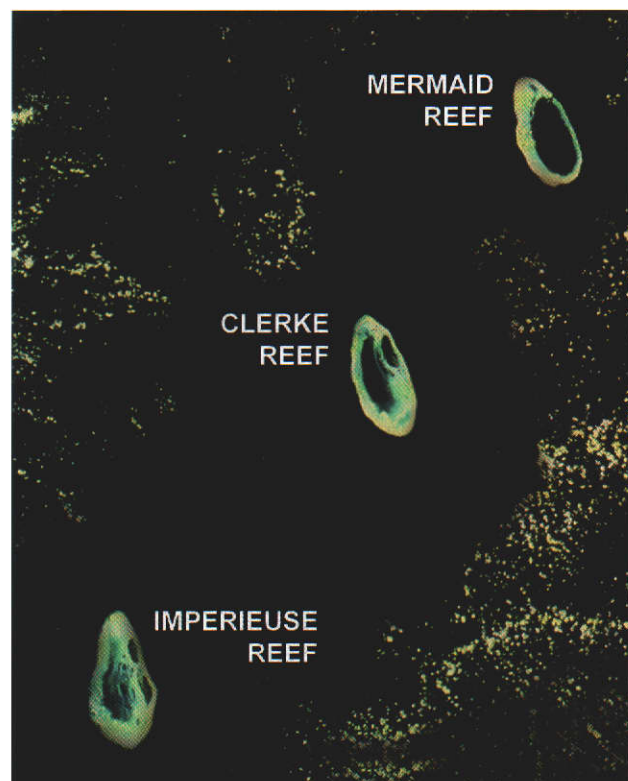


Figure 17: Landsat image of Rowley Shoals: Mermaid, Clerke and Imperieuse Reefs (width of each platform is approximately 5 km). Note the increasing degree of lagoon infill from northeast to southwest.



440m, Clerke Reef from 390 m, and Imperieuse Reef from 230m. The reefs were described morphologically from LANDSAT images and diver traverses by Berry & Marsh (1986), but this study provides the first geological information.

Each atoll (length range 15-17 km, width range 7-9 km) has north-south orientation, is pear-shaped with the narrower end to the north (Fig. 17), and has a reef which encloses a single central lagoon which is ovoid and relatively deep in Mermaid Reef, but becomes increasingly shallow and segmented in Clerke and Imperieuse Reefs. About two thirds of the way up its eastern side, each system has a narrow passage (or passages), through which tidal flushing and sediment exchange occur.

Mermaid Reef has, on its western side, an outer reef flat (0.5 km is exposed at low tide), and a back reef of similar width, backed by a 1 km wide sand flat. The eastern reef is only 0.6 km wide and the sand flat is absent. The western outer reef slope has well-developed spur and groove, the outer reef has coralline algae and slow-growing corals, while the back reef flat has a cover of living and dead coral and algal turf (Berry & Marsh, 1986).

Clerke Reef was not visited during this study, but LANDSAT images (Fig. 17) show the shallow (<10 m) lagoon is segmented into three parts by sand sheet development. Imperieuse Reef has a lagoon partitioned into three basins by sand sheet development. The two along the eastern edge are deeper than the larger, central basin which is extensively infilled by a meshwork of coral growth, composed of flat-topped coalescent reef with intervening sand-floored depressions.

The coral assemblages described for Scott Reef by Done et al., (1994) were also recorded at Rowley Shoals. Differences in reef morphology, hydrodynamic exposure and ponding were reflected in the assemblages.

Jones (1973) reported the presence of a drowned shoal 50 km south of Imperieuse Reef. The position of this shoal was verified; it rises from a flat plain at 370 mwd to its flat surface at 260-280 m, and has a N-S length of over 20 km. The northern margin is steep, and resembles a fault scarp, with ca. 50m vertical relief; the southern margin was not profiled. The western margin has a "double step" of relief 50 m, and the substrate is assumed to be hard, based on successive failed sampling attempts and strong Precision Depth Recorder echo character.

### Seismic structure of Rowley Shoals

Seismic profiles of the Mermaid and Imperieuse Reefs, particularly their lagoons and reef crests, were conducted to assess the Quaternary reef growth pattern, and the style of platform sedimentation. At least two stages of reef growth (Last Interglacial and Holocene) were anticipated, both with the potential to be exposed, but the absence of outcrop ensured that seismic methods afforded the best opportunity of mapping reef geometry. The nature of the Last Interglacial reef platform, its substrate and topography, including the geometry

and elevation of any palaeotopography (eg. lagoon and reefs), were expected potentially to exert antecedent controls on Holocene reef growth. The type and pattern of Holocene reef growth, and the amounts and location of Holocene reef building and sand sheet development in the lagoon and at the marginal reef crests were assessed.

### Late Quaternary geology

Little is known of the Quaternary geology and reef growth history, and there is a lack of surface and subsurface data. Berry & Marsh (1986) reported what they considered were stacks of probable Pleistocene (Last Interglacial) reef remnants rising up to 3m above contemporary Holocene reef surfaces, at Mermaid and Clerke Reefs. However, wherever such sites were inspected, at Mermaid and Imperieuse Reefs, they were identified as boulders of Holocene Reef which had been thrown onto the reef flat by storms, and no outcrops of Last Interglacial reef could be located or identified during this study.

### Calibration of seismic data to subsurface geology

There are no shallow subsurface data available for Rowley Shoals. However, in the Boomer profiles collected during the Houtman Abrolhos, Ningaloo and Scott Reef studies (some 200 line kilometres of profiles), the first strong reflector beneath the Holocene reef has been confirmed from core data as the Last Interglacial reflector in all cases. In the Rowley Shoals seismic interpretations the Last Interglacial reflector has been identified using this approach.

### Mermaid Reef seismic investigations

#### Lagoon morphology

A prominent reflector is present below the northern and central lagoon, at a depth of 36 m bsl, and as the first reflector beneath the modern lagoon floor, this is considered to be the Last Interglacial reflector. The reflector is generally smooth with occasional small elevations of 2-4 m relief. The reflector shallows gently toward the lagoon margins. The lagoon is commonly 20 m deep, shallowing to 10 m at the east and west margins as the windward and leeward reef crests are approached. Pinnacle reefs 5-10 m high rise from an irregular lagoon floor, where the Holocene section is 15 m thick, exclusive of pinnacle reefs (see Fig. 18, profiles MA-MA' and MC'-MC). Based on reflector character, thin (1-3 m) sediment drapes are present in depressions between lagoon pinnacle reefs, but are less well-developed on the steeply sloping margins of these reefs.

#### Platform margin reefs

There are distinct windward (western) and leeward (eastern) reefs, which rise above the lagoon floor to become emergent at low water. Due to wave conditions, only the leeward reef was fully profiled from the lagoon to the outer reef slope, but profiles of the lagoon side of the windward reef were



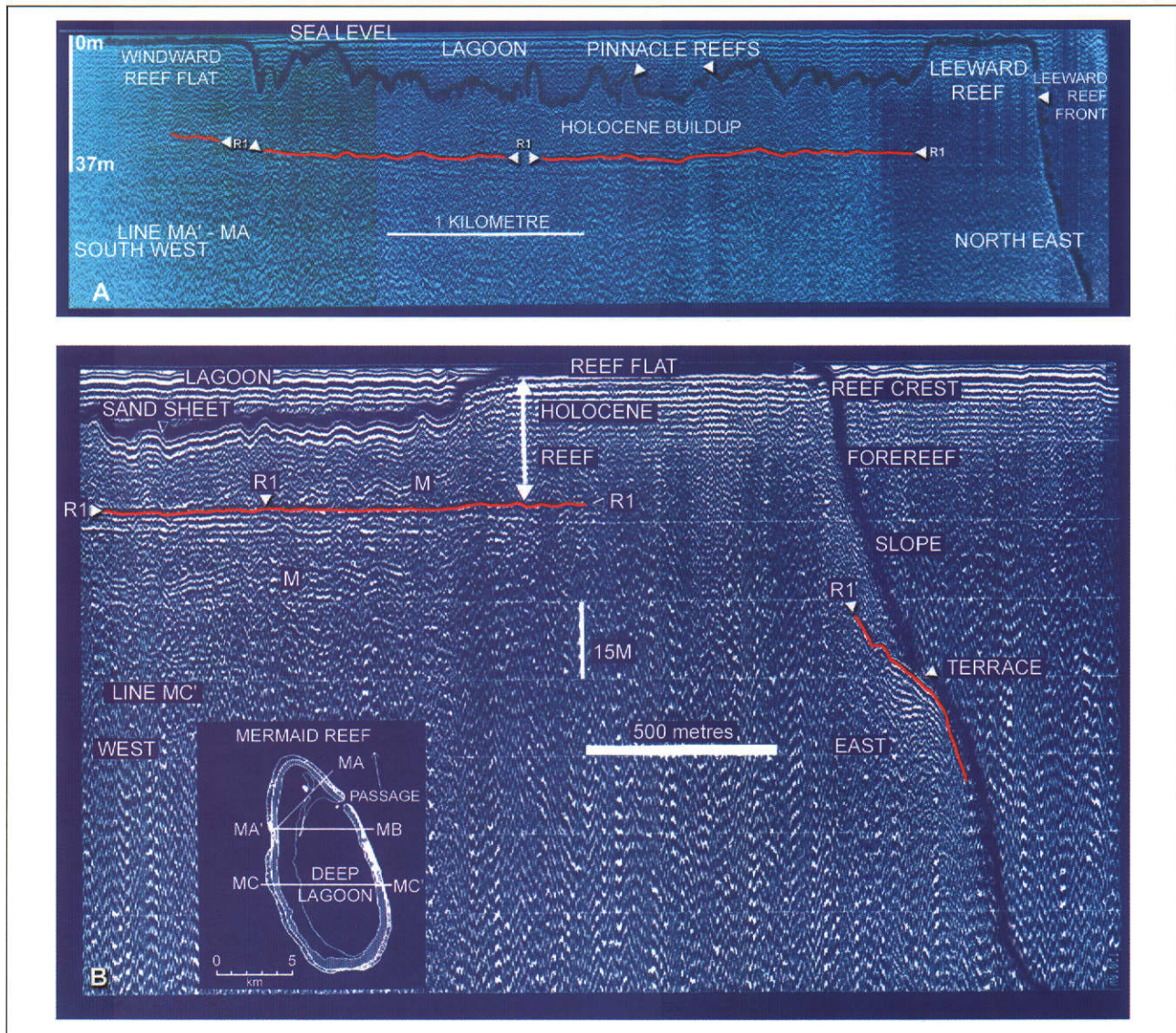


Figure 18: Mermaid Reef seismic profiles.

- a). Profile MA-MA' across Mermaid Reef lacks the foreslope of the windward (western) reef, but is otherwise a complete cross-section. The flat-topped reefs rim irregular topography within the lagoon. The reflector R1 (shown in red), present as a flat lying surface, 36 m bsl, is interpreted to be the Last Interglacial surface. It rises only slightly beneath the reef crests, which are interpreted to be Holocene growth features at least 30 m thick. Maximum lagoon depth is 20 m, and Holocene reefs rise 5-15 m above the irregular lagoon floor, overlying ca 20 m of Holocene accumulation.
- b). Profile MC-MC' across leeward reef and lagoon. The leeward reef front is steep with a break in slope at 70m bsl. The wide shallow reef flat is backed by an irregularly surfaced lagoon (at 18 m bsl), where a sand sheet is interrupted by coral heads. Reflector R1 (interpreted to be the Last Interglacial surface) underlies the lagoon at 36 m bsl, rising only slightly beneath the reef flat. This surface cannot be fully traced beneath the leeward reef, but it apparently reappears as a steeply inclined surface between 54 and 70 m bsl which emerges on the reef front at 70 m and is expressed as a terrace.

also obtained. The Last Interglacial reflector rises gently from lagoon depths and shallows beneath both reef crests, indicating significant Holocene growth in these reefs.

Beneath the leeward reef the reflector rises from 36 to 29 m bsl by the midpoint of the reef, becomes indistinct, but reappears on the windward reef slope at 72 m bsl, then rises steeply toward the lagoon to an elevation of 50 m bsl, before again becoming indistinct. The maximum elevation attributed to this surface below the leeward reef is 20 m, leaving a

maximum of 20 m of Holocene reef accretion above the Last Interglacial (see profile MA'). The measured Holocene reef thickness on profiles is 18 m.

Beneath the windward reef the Last Interglacial reflector rises from a lagoon depth of 36 m to reach 20 m bsl by the central portion of the reef. Though the westward emergence of the Last Interglacial reflector to depths closer to sea level than -20 m cannot be ruled out on the data available, it seems likely that there is up to 20 m of Holocene reef accretion in the



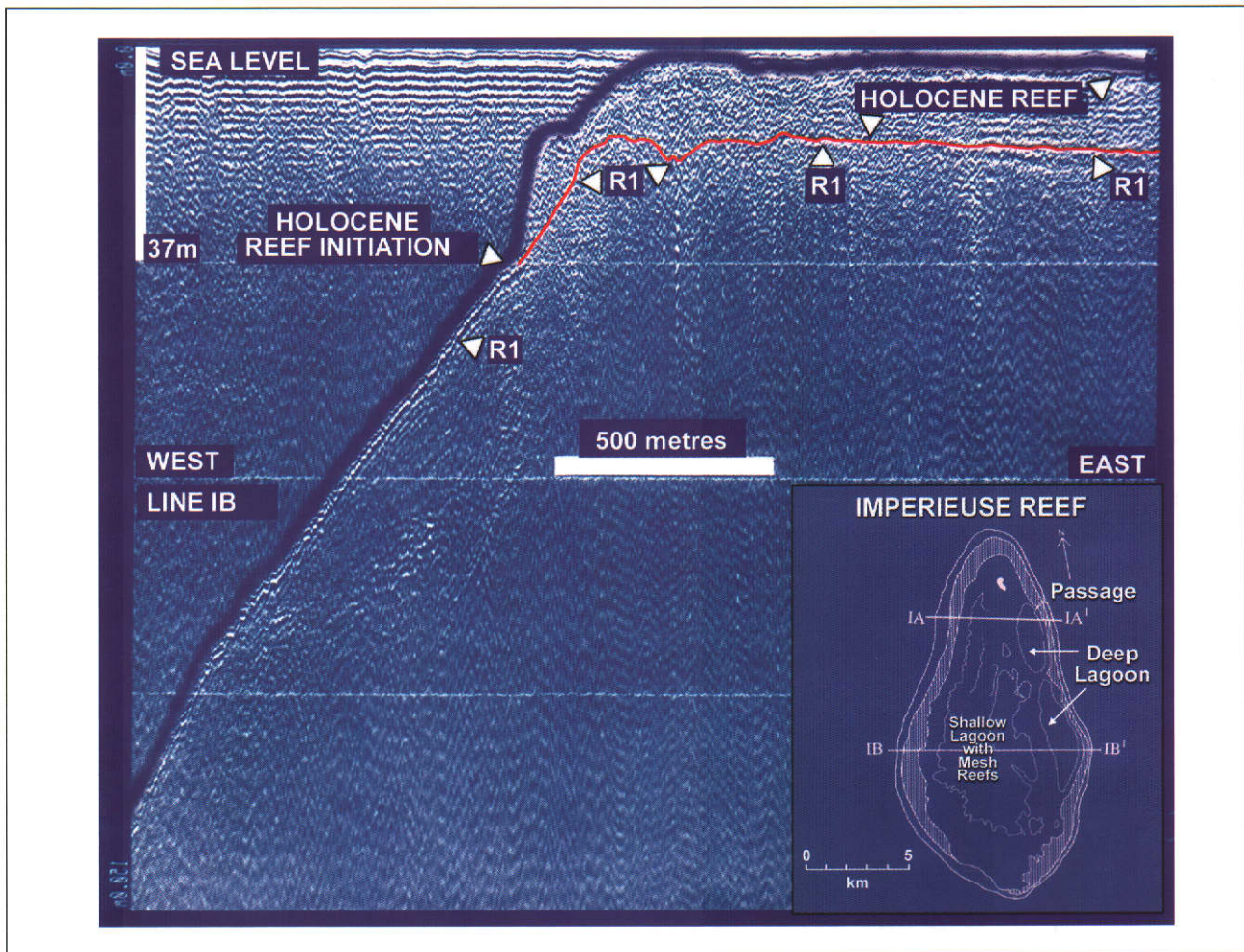


Figure 19: Imperieuse Reef, windward reef in part of seismic profile IB-IB'. Foreslope of the reef rises from ca 150 m to 37 m bsl. Thereafter the correlative surface (R1, the Last Interglacial surface, shown in red) is overlain by Holocene reef growth, initially as an inclined surface which rises to 18 m bsl, where irregular topography indicates an old reef crest, then as an essentially horizontal surface extending eastward beneath an 18 m thick section of Holocene reef. The "backstepping" Holocene reef development in response to transgression is expressed by reef initiation at 37 m bsl and vertical growth to 18 m bsl (the level of the Last Interglacial platform), at which time the platform was drowned, then regional platform buildup (above R1) to present SL. (M= multiple).

windward reef crest. This interpretation is based on a comparison with the leeward reef and the east-west symmetry shown on the seismic cross-sections.

#### Clerke Reef

Clerke reef was not seismically profiled, so no firm conclusions can be reached about its Pleistocene to Holocene growth history. The geomorphological similarity between Mermaid and Clerke reefs is strong, but the amount of lagoon sediment infill is significantly greater in Clerke Reef. Whether or not their subsurface structure is as similar as their surface expression must await future investigation. Clerke Reef represents an intermediate stage of development between Mermaid and Imperieuse Reefs. When compared to Mermaid Reef, Clerke Reef has shallower and smaller lagoons, and more fully developed sand sheets and active coral growth as lagoon infill.

#### Imperieuse Reef seismic investigations

##### Lagoon morphology

A prominent reflector is present below the northern and central lagoon (Fig. 19, profile IB-IB'), at a depth of 18 m bsl, and as the first reflector beneath the modern lagoon floor, this is considered to be the Last Interglacial reflector. The reflector is generally smooth with occasional small elevations of 2-4 m relief. The reflector shallows gently toward the lagoon margins. The lagoon is partitioned into segments of differing depth. Deep lagoons are commonly 10 m deep, shallowing to 2-5 m at their margins; longitudinal sand ridges are 1-2 m high, and the southwestern lagoon segment with well developed mesh reefs varies from 1-2 m deep over reef surfaces, dropping nearly vertically to 5-7 m in intervening sandy depressions. Pinnacle reefs and mesh reefs are ca. 5 m high and rise from the lagoon floor. The Holocene section is 10 m thick, exclusive of



pinnacle reefs (see profile IB-IB'). Based on reflector character, thin (1-3 m) sediment drapes are present in depressions between lagoon pinnacle reefs. Sand sheets of thickness ca. 3 m are developed on the lagoon-side of both the windward and leeward reef flats.

### Platform margin reefs

There are distinct windward (western) and leeward (eastern) reefs which rise above the lagoon floor to become emergent at low water. Profiles of the windward and leeward reefs were obtained. The Last Interglacial reflector rises gently from lagoon depths and shallows beneath both reef crests, indicating significant Holocene growth in these reefs. Beneath the leeward reef the reflector rises from 18 to 14 m bsl by the midpoint of the reef, becomes indistinct, but reappears on the windward reef slope at 65 m bsl, then rises steeply toward the lagoon to an elevation of 45 m bsl. The maximum elevation attributed to this surface below the leeward reef is 15 m, leaving a minimum of 15 m of Holocene reef accretion above the Last Interglacial. The Holocene reef has a distinct double crest with a foreslope depression between the crests.

Beneath the windward reef the Last Interglacial reflector rises from a lagoon depth of 18 m to reach 15 m bsl by the central portion of the Holocene reef. The Last Interglacial reef crest has a central depression, 3 m deep, and the appearance of subdued (eroded?) double-crested morphology. It has a foreslope which emerges at the seaward platform slope at 36 m bsl. The Holocene windward reef appears to "backstep" from an initial crest, which grew from 65 to 15 m bsl by vertical and lateral growth at the steeply sloping flank of the Last Interglacial platform, before colonising and laterally expanding across the upper surface of the Last Interglacial reef crest, of elevation 15 m bsl. This reef, which has reached close to sea level, has a thickness of 12 m (Fig. 19, profile IB').

### Rowley Shoals: Discussion

The Rowley Shoals are characterised both by striking similarities and by significant differences. They are similar in gross morphology (ovoid shape, with annular reef and central lagoon; similar length and width) and similar in their down-ramp setting, except that they rise from increasing depths to the northeast, from 230 m at Imperieuse reef to 440 m at Mermaid Reef. Their oceanographic and physical process setting is similar, in terms of wind, wave and tidal regimes. The difference between the reefs lies in the morphological series manifested by an increasing degree of lagoon infill from northeast to the southwest, from the open, ovoid and 20 m deep Mermaid lagoon, through the partially infilled and partitioned Clerke lagoon, to the shallow, more fully infilled Imperieuse lagoon (Fig. 17).

The concept of the coral reef as a "leaky bucket", in terms of the amount of lagoon sediment retained or alternatively, permanently lost to the system by sediment transport, has had a long history. This principle could be invoked to explain the

series of differential lagoon infill referred to, and indeed Mermaid Reef (with the deepest and most open lagoon) has a 60 m wide leeward channel through which active sediment transport is occurring, and a plume of expelled lagoon sediment was detected in nearby seafloor samples collected at 400 m depth. Similar northeasterly leeward channels at Clerke and Imperieuse Reefs are poorly developed, only a few metres wide, and transport much smaller sediment loads. These lagoons apparently retain far more sediment than Mermaid Reef.

A comparison of the seismic results for Mermaid and Imperieuse Reefs provides additional information (Fig. 20). Firstly, the pattern of reef growth in both cases is similar to that of Scott Reef, with the Holocene reef growing in the accommodation space provided by a saucer-shaped, subsided, Last Interglacial reef. The calculated subsidence rate since the Last Interglacial (Fig. 16) is 1 m/6000 y, comparable to that of Scott Reef. However, there is a striking difference in the depth of the Last Interglacial reflector in the lagoon, which is uniformly 36 m below sea level in Mermaid Reef, but only 18 m below sea level in Imperieuse Reef (Fig. 20). Aside from indicating differential tectonic movement since the Last Interglacial (assuming the lagoon floor elevations were initially similar) these data indicate that the accommodation space available for Holocene lagoon infill at Imperieuse Reef was only 50% of that available at Mermaid Reef, and this is an important control on the differential amounts of lagoon infill observed between the two reefs.

A similar five stage history of global eustatic events to that summarised above for Scott Reef can be applied to Rowley Shoals, but elevation differences in the Last Interglacial substrate will result in changes to the timing of platform drowning events. The identification of a "backstepping reef" in the windward reef profile for Imperieuse Reef (see Fig. 19) provides an example of the interaction of the colonising Holocene reef with the morphology and elevation of the pre-existing Last Interglacial substrate, which exerts an important control on the pattern of reef growth.

### Conclusions

This paper has outlined the geological controls on a few of the many North West Shelf reefs (one fringing reef and two isolated reef systems). The detailed sea level records previously obtained from the Houtman Abrolhos Reefs to the south (Collins et al., 1998) provide useful reference data for the reefs described here. The results obtained demonstrate the importance of the interaction of the local subsidence regime with global sea level change in determining reef growth patterns and morphology. Aside from the information that coral reefs provide about their ancient reservoir counterparts, glacio-eustatic sea levels and past climates, there are several related issues of interest to exploration geologists. These include the location of exploration targets, drilling in sensitive reef environments, and development projects in reef terrains.



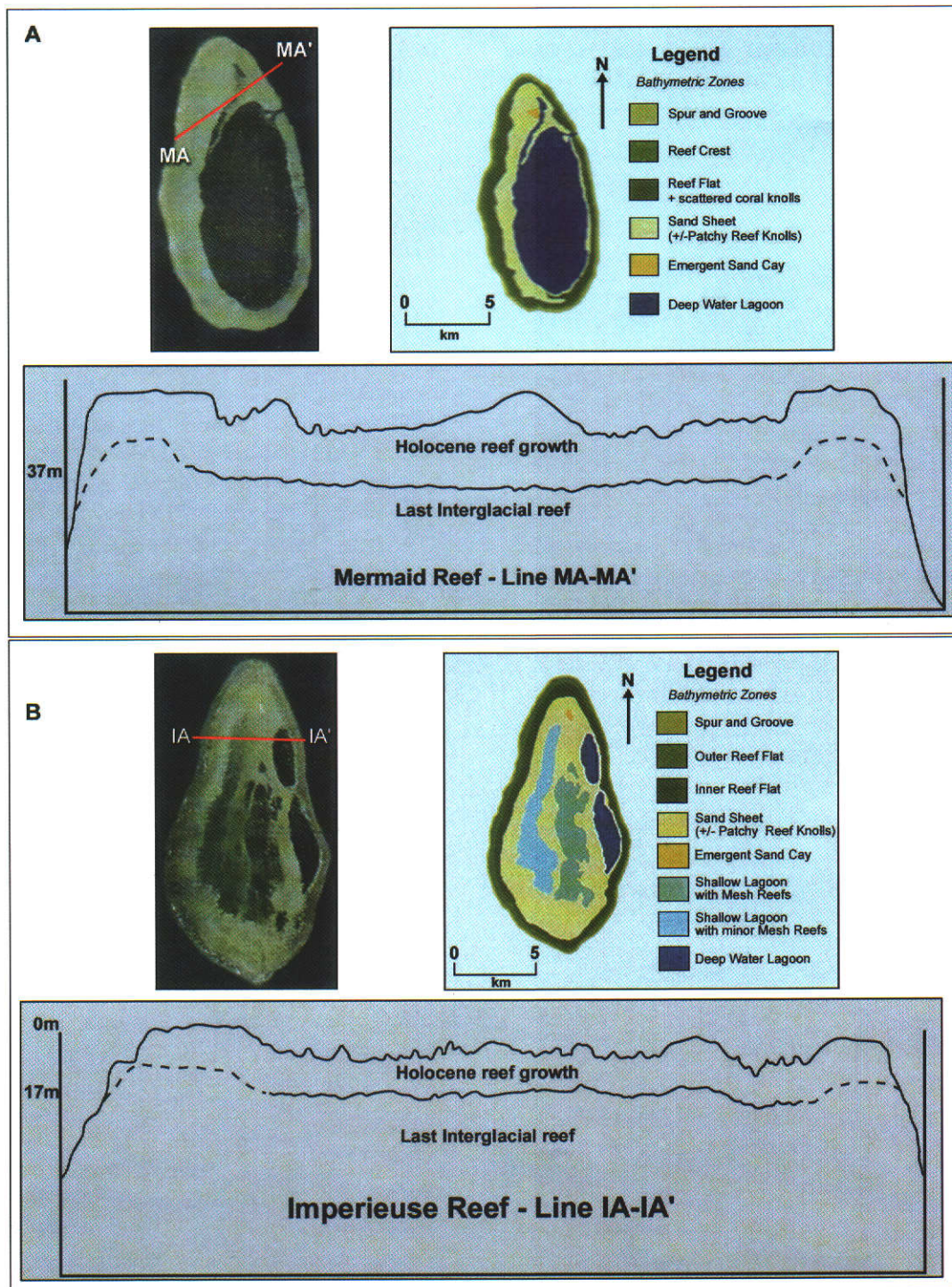


Figure 20: Comparison of morphology, sub-environments and seismic structure of Mermaid Reef and Imperieuse reef. Note differing elevation of Last Interglacial surface and differential accommodation space filled by Holocene buildups.

Remote sensing studies (synthetic aperture radar, geochemical sniffer, airborne laser fluorosensor and seismic data) and sediment sampling have indicated that some reefs and buildups are associated spatially with active and palaeo-hydrocarbon seeps in the northern North West Shelf, and that hydrocarbon seeps may localise buildup communities (Bishop and O'Brien, 1998; O'Brien et al., 1999). This continuing

work may provide added impetus to future reef studies.

Drilling in and around sensitive reef environments such as Ningaloo Reef has been previously carried out, and is continuing. However, environmental constraints continue to change and become more restrictive. In developing management plans for coral reefs and similar marine protected areas it is important that geological controls, obtained from



studies such as those outlined here, are considered alongside biological variables by planning agencies.

Future development projects in coral reef terrains are also reliant on environmental and geological data. For example, the lagoon of South Scott Reef is wide, open to the north, and has strong wind-driven and macrotidal circulation, providing strong flushing characteristics compared to other more sensitive coral reef lagoons. However, in such areas it is also important to understand other potential impacts (eg. from fishing and tourism) and natural processes of change such as cyclone damage and coral bleaching. An understanding of the geological process framework in which such changes occur is also necessary for sound management of the reef system.

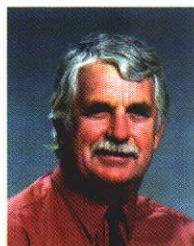
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## Biography



**Lindsay Collins** gained his PhD in sedimentology from UWA in 1984. He subsequently worked with WMC on the reservoirs of the South Pepper, North Herald, Chervil and Basil Fields. He was involved in reservoir studies of the North West Shelf in the 1980s and 90s, and subsequently specialised in cool water carbonate shelf and coral reef sedimentology; this research continues using the CSIRO research ship *Franklin*. Lindsay is currently Associate Professor and Head, Department of Applied Geology, at Curtin University. He is a former PESA Committee Member, and has contributed to PESA's Canning Basin and North West Shelf Symposia, WABS 2 and 3.



# Stratigraphy and Palaeontology

