Holocene Growth History and Evolution of the Scott Reef Carbonate Platform and Coral Reef

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Manuscript received November 2010; accepted April 2011

Abstract

As a prominent isolated oceanic atoll-like reef within the Oceanic Shoals Biozone to the west of the Kimberley coast, Scott Reef is a small carbonate platform located in a distal ramp setting on Australia's Northwest Shelf. Rising from depths of 400–700 m 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. Small differences in subsidence rates indicate differential subsidence between the paired platforms. Holocene (MIS 1, last 10 ka) reef initiation was at 11.3 ka, soon after Meltwater Pulse 1B thereby bracketing the Holocene growth phase to the subsequent deglaciation sea-level rise. The crest of southeast North Reef (and the rising sea-level) reached close to present sea level (-1.5m LAT) by 2.7 ka ago. There is no record of the southwest Australian sea level high stand of about +2m some 7 ka BP. The Holocene reef growth history record obtained for this long lived and resilient reef system is one of the most detailed yet for the western margin of Australia.

Keywords: Scott Reef, Kimberley, North West Shelf, Oceanic Shoals Biozone, global sea levels, marine isotope stages, subsidence, carbonate platform, cores, growth history, coral reef

Introduction

Coral reefs have long proved attractive for studies by biologists and geologists, the former focusing on their biodiversity values and the latter interested in longer term reef evolution, with the knowledge that coral reefs have been important in earth history. Since the recognition of subsidence as a control on coral reef formation (Darwin 1842) and the realisation of the role of glacial sea level low stands in reef development of the Quaternary (last 2 million years) time (Daly 1910), coral reefs have been prominent in marine geological research. Kimberley coral reefs first received attention through the pioneering studies of Fairbridge (1950), but have remained poorly known geologically since that time with some recent exceptions. Montaggioni (2005) and Montaggioni & Braithwaite (2009) summarised the history of geological research on Indo-Pacific reefs and described the last three decades of subsurface investigations of reef growth since the last glaciation (last 23 ka), recognizing four basic patterns of reef anatomy. Studies of Australian reefs have been dominated by work on the eastern seaboard and the Great Barrier Reef (see Hopley *et al.* 2007), but reefs of the western continental margin of Australia (with the exception of the Houtman Abrolhos and Ningaloo Reefs; Collins 2010) and its bordering Cretaceous-Tertiary carbonate ramps remain relatively poorly known. Coral reefs of Australia's western margin (Fig. 1) include isolated oceanic atoll-like reefs (Ashmore Reef, Seringapatam and Scott Reefs, Rowley Shoals); island-associated shelf reefs and fringing reefs of the Kimberley coast and Dampier Archipelago; Pilbara reefs (Barrow and Montebello Islands); Ningaloo Reef, a fringing reef adjacent to the North West Cape, and the outer shelf Houtman Abrolhos carbonate platforms and reefs, the southernmost coral reefs in the Indian Ocean.

This paper provides new insights into the growth history of Scott Reef (Fig. 1), one of the most prominent isolated oceanic atoll-like reefs within the Oceanic Shoals Biozone to the west of the Kimberley coast. As an isolated carbonate platform and coral reef Scott Reef is located in a distal ramp setting on Australia's Northwest Shelf (Collins 2002, 2010; this volume). Scott Reef rises from depths of 400–700 m and is a complex of two large isolated coral reefs separated by a deep channel; North Reef and South Reef (Berry & Marsh 1986).

Methods

Two generations of shallow seismic data were relevant to the study; the 2000 Curtin seismic survey, a shallow boomer survey conducted using RV *Franklin* and small vessels, which included reef margin and lagoon lines, and sampled surface sediments, and the shallow site test cores in reef and lagoon environments taken by Woodside Energy Ltd (WEL) in 2006/7 and these became available in 2008/9 for a study of reef architecture and growth history. Core logging and sampling were carried out to identify the major events and stages in reef development by recording sediment/rock types, primary, secondary and associated reef builders, coral

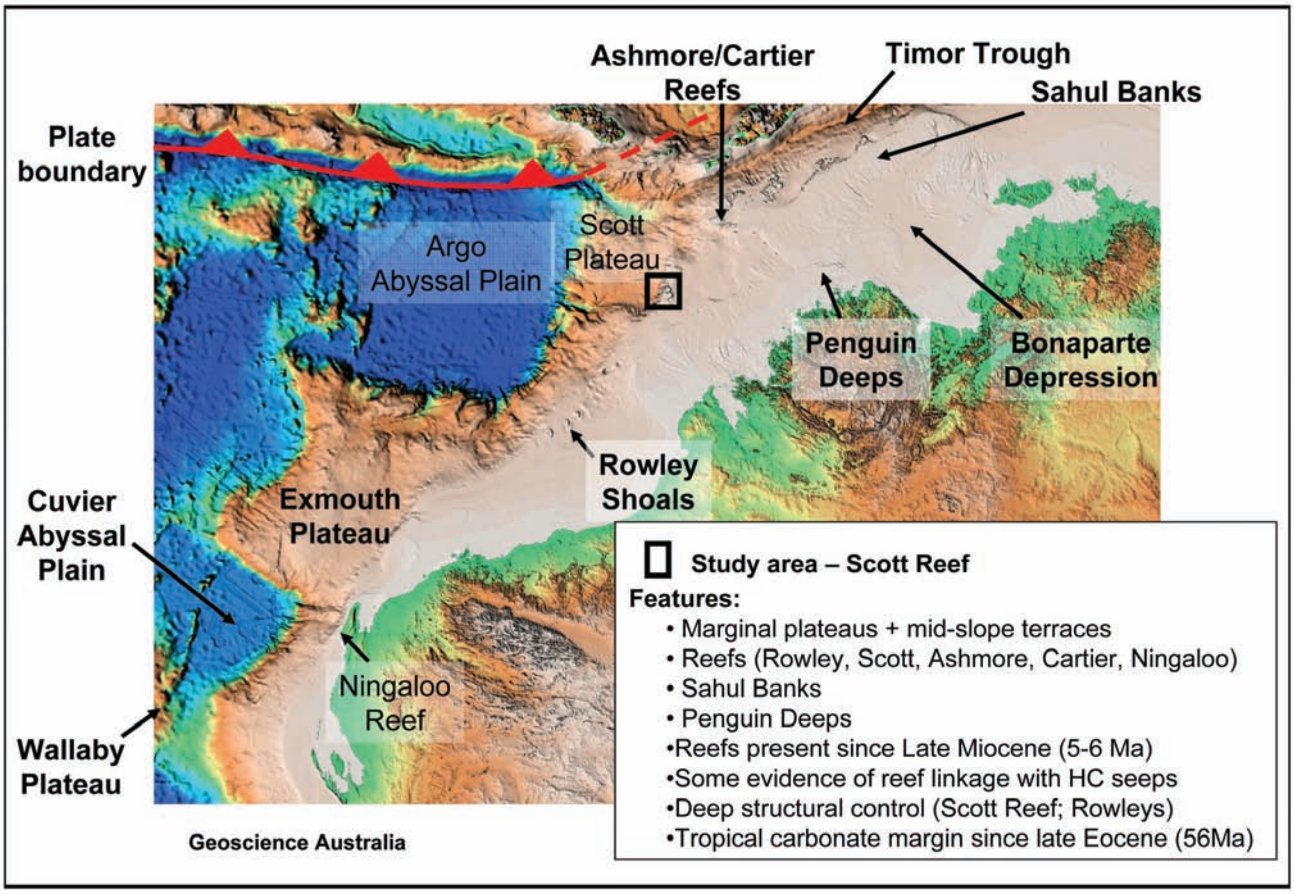

Figure 1. Regional setting of Scott Reef and northwest margin of Australia (after Geoscience Australia).

communities and morphologies, and hiatuses in reef growth. Cores were then correlated to interpreted seismic sections and significant seismic reflectors mapped. Selected sections were used for detailed microscopic study to better characterise the main rock types (lithologies), patterns of cementation, diagenetic changes, and porosity development. Of the logged cores a selection from the data base was made for the purposes of this paper.

Core/rock types were classified following the Expanded Dunham Classification (Embry & Clovan 1971) for depositional textures. For each rock facies (type) the related reef community was documented. Grain size classification followed Udden-Wentworth (1922). The full analysis of the reef framework itself followed the terminology suggested by Montaggioni (2005) which highlights the dominant coral growth forms, their role as reef builders and environment indicators. Additional terminology was introduced in order to manage the variability of the dataset presented in this work.

Least altered coral samples were selected for high-precision U-series dating using a VG Sector-54 Thermal Ionisation Mass Spectrometer (TIMS) at the University of Queensland (UQ) following the procedures described in Zhao *et al.* (2001) and Yu *et al.* (2006). ^{230}Th ages were calculated using Isoplot/Ex 3.0 Program of Ludwig (2003).

Setting and Oceanography

Scott Reef is under the influence of the Indonesian Throughflow, which modulates the exchange of waters and heat between the Pacific and Eastern Indian Ocean, and flows east-west through Scott Reef (Pandey *et al* 2007). It is a high hydrodynamic environment. Tidal currents seem to be dominant in influencing the sediment transport rather than oceanic swell (Harris *et al*. 1991).

The formation of internal waves was shown by Wolanski & Delleersnijder (1998) to be an interaction between tidal currents (tidal range of 4m, classified as high mesotidal *sensu* Hayes 1975) and overall morphology of Scott Reef. The proposed model suggests a counterclockwise rotation of the wave around the island, reaching with maximum amplitude along the island slopes, peak velocities of 0.7m/s, and showing an absence of eddies in the lee of the island. The hydrodynamic energy generated is partially transferred to the open ocean (Wolanski & Delleersnijder 1998). The possibility of flow separation due to the overall morphology may explain differences in reef development, although this was not depicted in their model. Importantly, the model suggests waves of 60 m peak to trough, which would promote major influences on the current patterns and distribution of temperature and salinity in the top 200 m of the water column. Wolanski & Delesalle (1995) suggested the potential of these waves bringing nutrients from below the pycnocline (located at 100 m depth) to within 40 m of the surface where other small-scale flow processes would occur. This would therefore promote reef development near the surface. Brinkman *et al*. (2008) have demonstrated that the Scott Reef environment is strongly thermally stratified and also demonstrated how the hydrodynamics can play an important role in larval dispersion and bleaching events. Scott Reef has semi-diurnal tides with a tidal range of 4.1m (National Tidal Centre 2009a, b; meso-high tidal range, *sensu* Hayes 1975). The region lies 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 is cyclone-influenced (average 3 per year, Lough 1998) and has southwest prevailing swell. The environmental importance of Scott Reef lies partly in the potential record it contains of the biological exchange between two oceans since its establishment in the Late Tertiary.

Regional Geology and Geomorphology

Scott Reef (Fig. 1) 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 197l a, 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) (Fig. 3.) 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) 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.

A section of Paleocene-Quaternary carbonates, 3,515m thick (mainly calcarenite, calcilutite 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, calcilutite and dolomite sections between 1,700–2,198m. Aquitanian calcarenite and marl sections at 2,198–2,379m unconformably overlie the Oligocene and Upper Eocene calcarenites, which continue down to 2,458m. Eocene and Upper Paleocene fine-grained carbonates and cherts continue from 2,458–3,484m. The remainder of the Upper Paleocene (claystones and marls) continues to 3,578m, and the Middle Paleocene rests unconformably on the Upper Cretaceous. The regional geological structure and the overlying carbonate sequence are shown in cross-section in Figure 2. The focus of this study has been to document the uppermost 30–40 m of cored reef section, the age of which ranges from present to some 10,000 years ago (Holocene; Marine Isotope Stage 1).

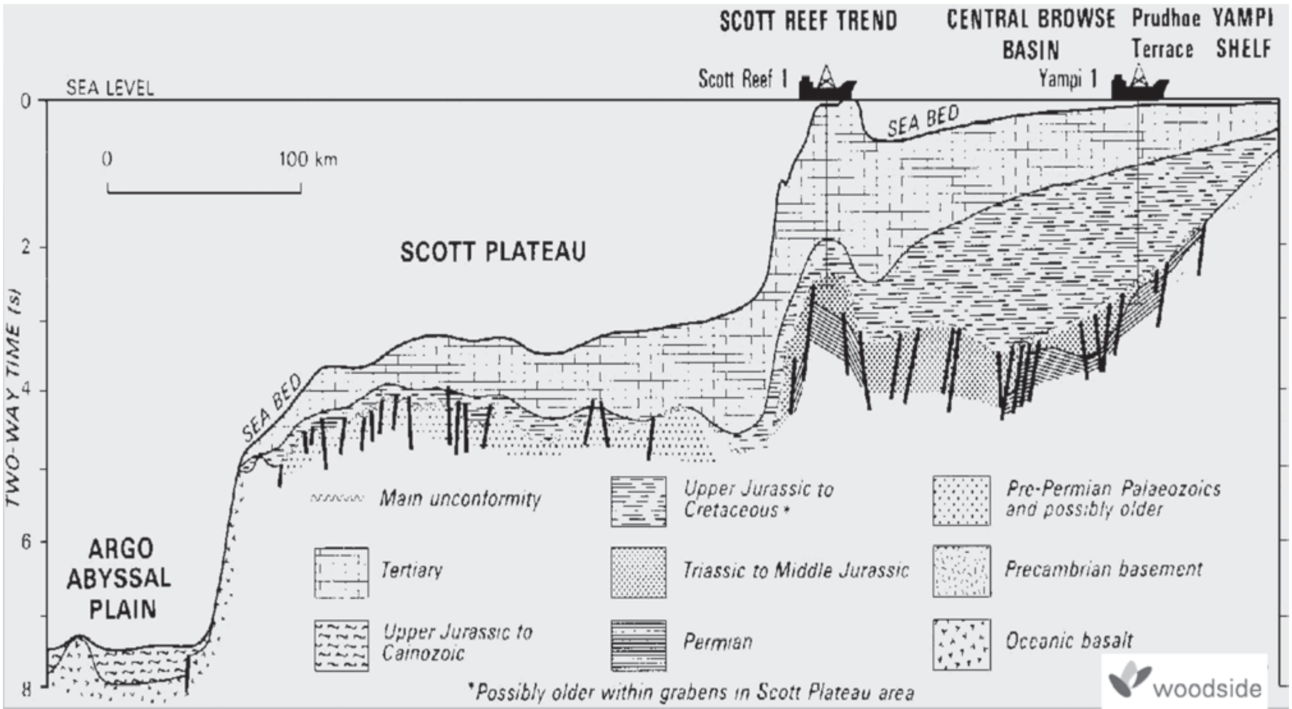

Figure 2. Schematic cross section of Central Browse Basin (from Woodside Energy Ltd). Note the position of Scott Reef, Scott Plateau and underlying geological structure. The Tertiary section consists of shelf and reef limestones.

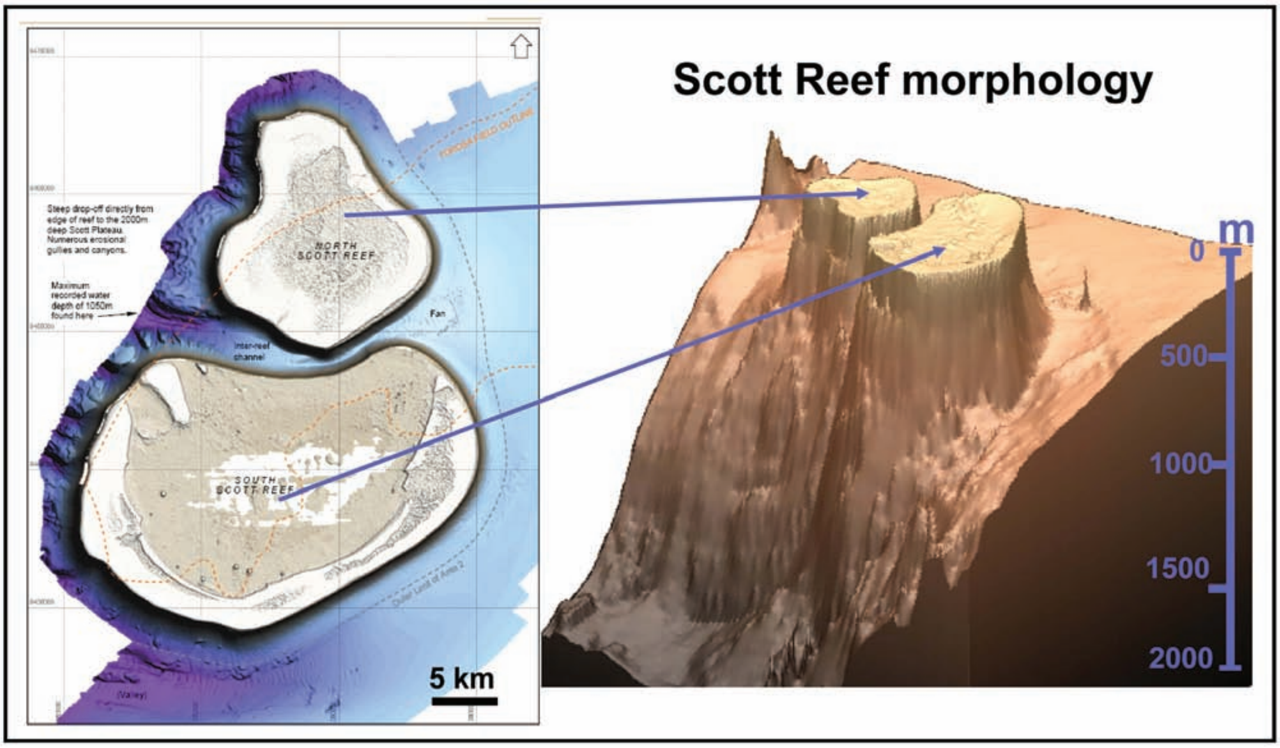

Figure 3. Scott Reef morphology, plan view and relief model. Note that Scott Reef rises from the continental shelf edge, enhancing the steepness of the slope. Talus deposits accumulate by downslope movement at the reef margin, whilst lagoon areas are scoured and reworked by strong hydrodynamic energy, generating mobile bedforms. (From Woodside Energy Ltd).

The geomorphology and digital elevation models of Scott Reef illustrate its proximity to the boundary of the Australian and Eurasian Plates, with marginal plateaux, mid-slope terraces and ocean deeps as shown in Figures 1 and 3. Scott Reef and related reef systems, such as Seringapatam to the north and the Rowley Shoals to the south, form a discontinuous reef rim which marks the position of a submerged, former continental margin, of probable Miocene (several millions of years) age. The North West Shelf is a carbonate ramp and the Scott Plateau forms part of its seaward margin (Fig. 3). Coral reef systems at the outer margin of the ramp such as the Rowley Shoals and Scott Reef were initiated and developed along (and mark the position of) an old continental margin formed some 5–6 million years ago (Late Miocene time) and have continued to grow through cycles of subsidence and sea level change throughout that time (Fig. 3).

Surficial Environments

Scott Reef rises from depths of 400–800 m on the distal portion of a carbonate ramp, and is similar in setting to 'downslope buildups' (*sensu* Read, 1985). 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 (Figs 3 and 4; Berry & Marsh, 1986). 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 scattered large boulders and occasional living corals. The outer reef gives way on its

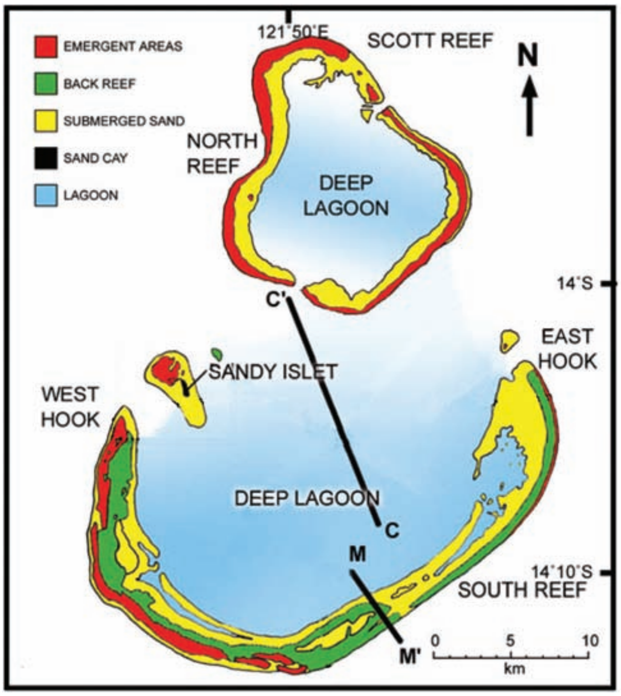

Figure 4. Scott Reef surface environments and position of selected shallow seismic lines showing lagoon and reef crest architecture.

seaward margin to a gentle slope followed by an irregular outer slope with surge channels extending to 30 m and steep gradient 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 (Done *et al*. 1994).

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 red 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 large *Porites* colonies, other corals and sparse seagrass. Lagoon depths inside South Scott Reef are 35–55 m (*ca.* 30 m in North Reef) and there are isolated coral knolls, sandy areas, and hard substrates with sponges and stunted coral communities (Done *et al*. 1994).

Only very limited portions of the reef crest of both reefs are exposed during low tide, leaving the majority of the reef structure submerged and prone to colonization by reef-related communities. Both reef crests and lagoons have prolific development of coral patch reefs and other reef communities in association with large amounts of reworked boulders to gravel size reef fragments, reworked by episodic cyclonic storms (Gilmour & Smith 2006) and the general high hydrodynamic energy of strong metre tides and swells.

Coral assemblages identified by Done *et al*. (1994) are: 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). For more recent data see discussions of the reef by Smith *et al.* (2008).

Seismic Architecture

The overall seismic architecture is a flat-topped platform bounded by platform margin reefs which flank steep marginal slopes, as reflected in the current day surface environments. There are distinct cycles of upward platform growth which resemble "stacked saucers" in shape, each mimicking the previous cycle. Cycle boundaries are marked by platform-wide seismic discontinuities (R1, R2, and R3) which rise under marginal reef crests before falling steeply at the platform margins (Fig. 5).

Lagoon seismic structure and morphology: The deepest two reflectors identified on lagoon profiles are at 64m and 68m below SL (R2 and R3) respectively (see Fig. 5A), and are also identified in the cores investigated. These surfaces mark the tops of Marine Isotope Stages 7 and 9 and are sub-parallel to and lie below the prominent R1 reflector which is present throughout the lagoon at 50–55 mbsl. 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) 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 known to be the last interglacial surface (Marine Isotope Stage 5e, or MIS 5e) 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 Holocene reef and intervening hard substrate, 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 show that the lagoon floor is a sediment-starved, mostly bedrock surface with a modern reefal community composed of encrusting coralline algae, corals and sponges, also with large boulders distributed apparently preferentially in the eastern side of the lagoon. 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 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 (Fig. 6).

South Reef margin structure and morphology: 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 (Fig. 5B). At the landward extremity of the platform margin reefs, the last interglacial surface has risen to 36 m below SL from the lagoon level of 60 m. A further rise to *ca*. 30 m below SL occurs beneath the Holocene crest (Fig. 5B; see profile 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, reflecting lowstand erosional modification and/or subsequent beveling of a pre-existing reef crest during transgressive drowning. Core data and geochronology confirm the seismic results.

Reef Architecture, Frame Builders, Holocene, Sea Levels and Cycles

Core analysis together with seismic data and geochronology provided the opportunity to determine the nature of reef-building cycles and the dominant reef communities in different settings, the time frame of reef development, sea level history and coral reef growth response, and the overall architecture of reef development. Core transects were studied from the South Reef southeast margin and North Reef southeast margin, with isolated Cores at ancillary locations recording the Holocene reef growth cycle (MIS 1, representing the last 10,000 years, or Holocene time). These are usually *ca.* 30 m thick reef growth events and are discussed below.

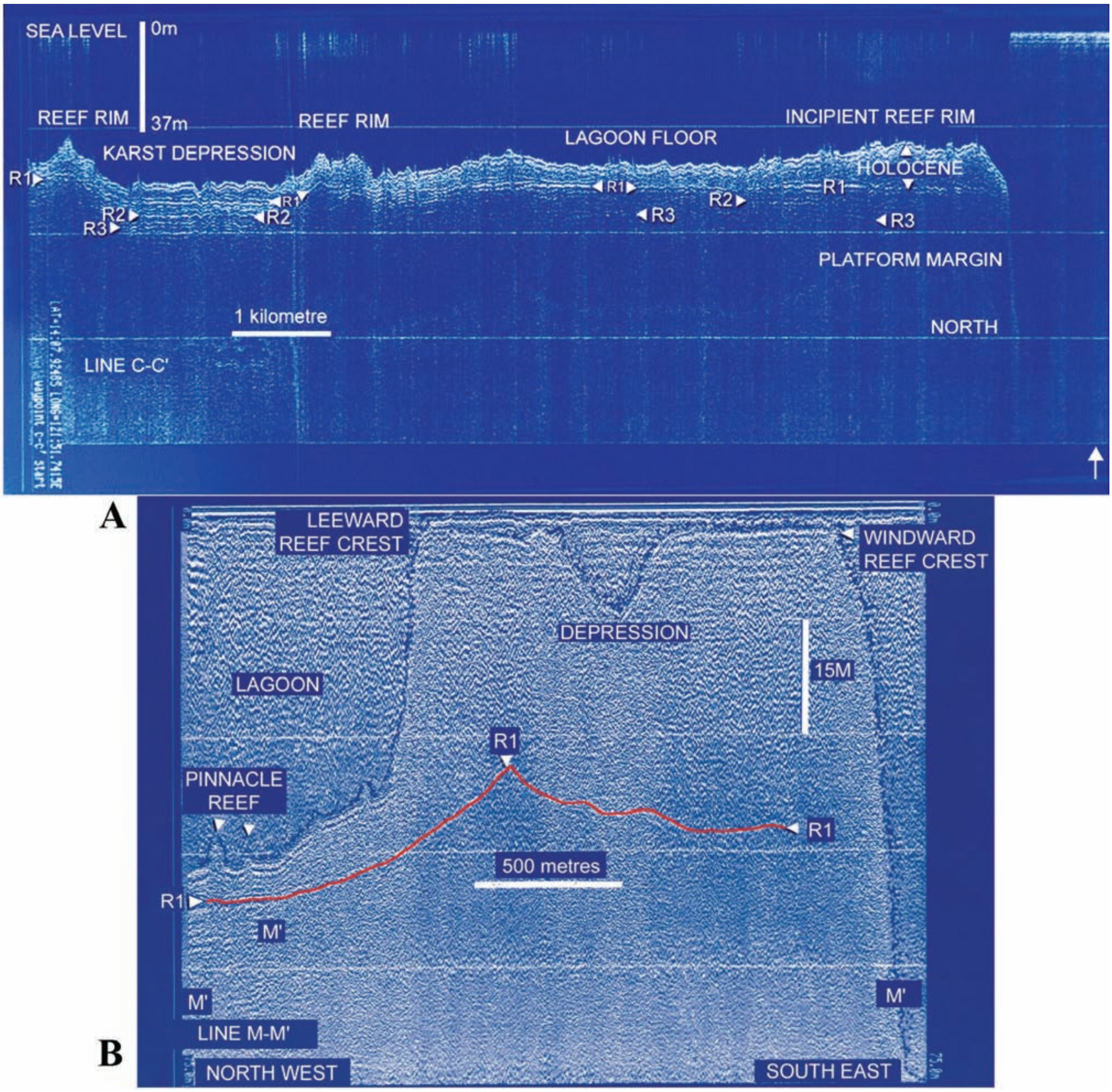

Figure 5. Seismic (boomer) architecture of Scott Reef platform (see Fig. 4 for location). **A)** Section C-C′ of South Reef lagoon showing seismic discontinuities and karst depression. Three unconformities can be identified: R1, R2 and R3. R1 corresponds to the Last Interglacial (top MIS 5e) surface, underlain by MIS 7 and 9. B) South Reef boomer profile M-M′ across reef crest (see Fig. 4 for location). Note presence and elevation of R1 beneath the Holocene reef crest (from Collins 2002).

Holocene Reefs, Characteristics, Sea Levels

Contemporary reef morphology results largely from Holocene reef growth (with antecedent influences) and the Holocene (MIS1) preserves a detailed sea level, chronological and growth history record at Scott Reef (Figs 6 and 7).

Global Sea-level during the Holocene (MIS1)

Since the Last Glacial Maximum, some 19 ka ago, deglaciation has been accompanied by a series of meltwater pulses which have influenced sea-level rise rates and reef growth responses, including drowning events. There was a prominent drowning gap in reef growth worldwide following Meltwater Pulse 1B. Subsequently during Holocene time some 40 m of vertical reef growth (*e.g.*, 35.9 m or 44.1m LAT; with reef initiation at 10.6 ka ago in SE BH6-J) has occurred at Scott Reef (Figs 6 and 7).

The Indo-Pacific reef growth phase (termed RG111) was characterised by moderate rates of sea level rise of 10 mm/year (generating "keep up" or "catch up" reefs) from 11 to about 7–6.5 ka BP until sea level stabilization at or 2 m above its present position (Pirazzoli 1996). However, short periods of rapid sea-level rise, such as the 6m jump at 7.5 ka of Blanchon *et al*. (2002), with accompanying pauses in reef growth, have been reported elsewhere. The dated Holocene cores at Scott Reef

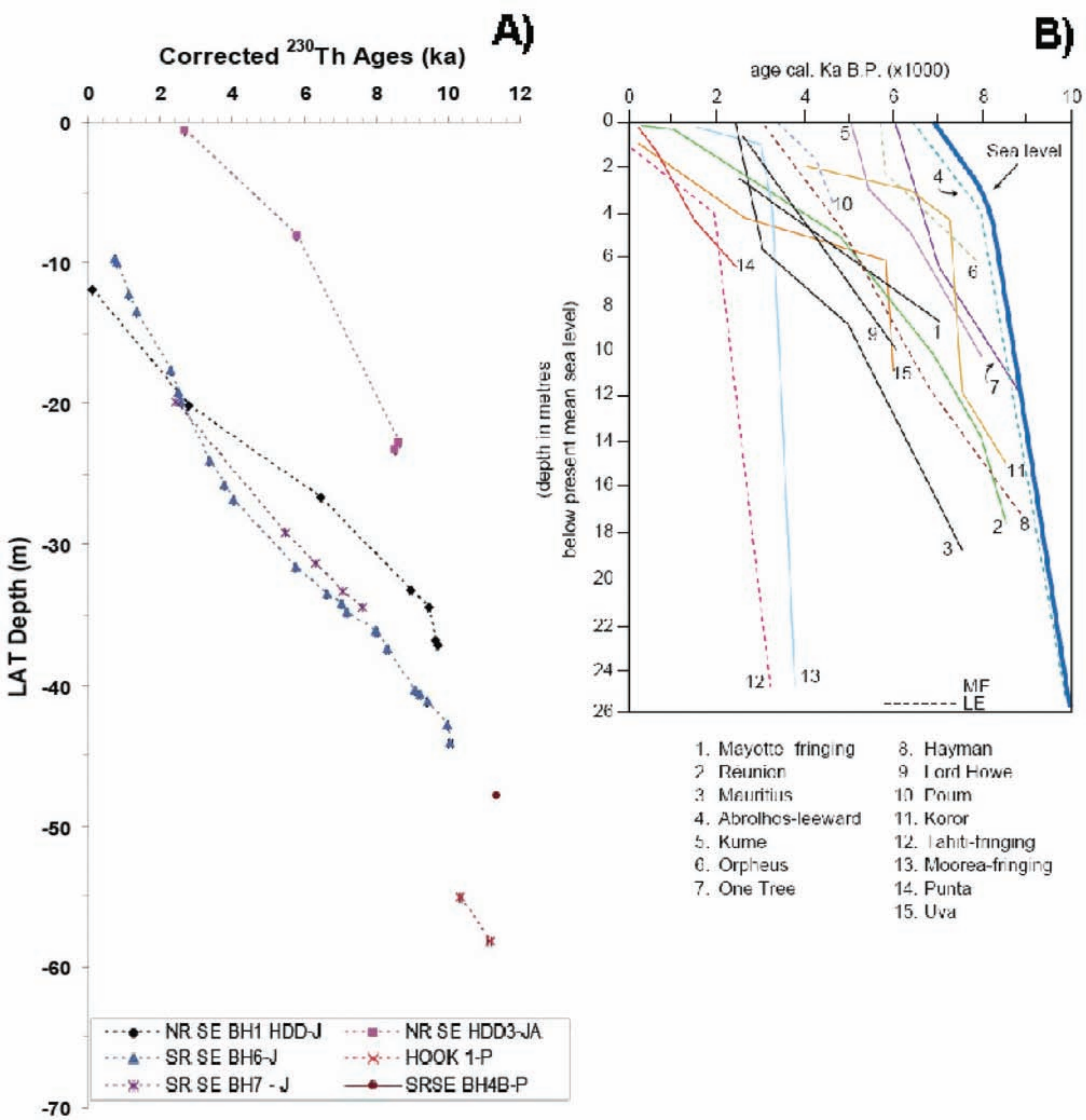

Figure 6. Comparative Holocene vertical accretion rates and curves related to Indo-Pacific reef development. A) Scott Reef dated cores. B) Selected growth histories of exposed Indo-Pacific reef crests/flats for the Holocene sea level rise (data from Montaggioni (2005, p.43), and references therein).

provide an opportunity to evaluate rates of sea level change and reef growth for reefs in different settings, both within Scott Reef, and between Scott Reef and reefs elsewhere (Figs 6 and 7).

Platform Morphology and Holocene Reef Initiation

The platform morphology that underlies the Holocene at Scott Reef is heterogeneous within and across North and South reefs. The irregularities generated during the erosional period that characterised the R1 hiatus are reflected in post glacial reef development as lower areas were inundated at the beginning of the event, whilst higher areas record younger ages. In Scott Reef, the earliest dated settlement of a reef building coral community was recorded for the borehole HOOK 1-P at 11.5 ka at -58m L.A.T. depth, and for SRSE BH4B-P, in the vicinity of the inner crest of the South Reef, reef initiation was at 11.3 ka, and at -47.9m LAT depth and SRSE BH6-J at 10.1 ka (Fig. 7). At North Reef, earliest colonization date is 9.7 ka for NRNE BH1- HDD-J. All these reef onset ages postdate the 11.5 ka assigned to Meltwater pulse 1B thereby bracketing the Holocene growth phase to this particular meltwater pulse and subsequent sea-level rise.

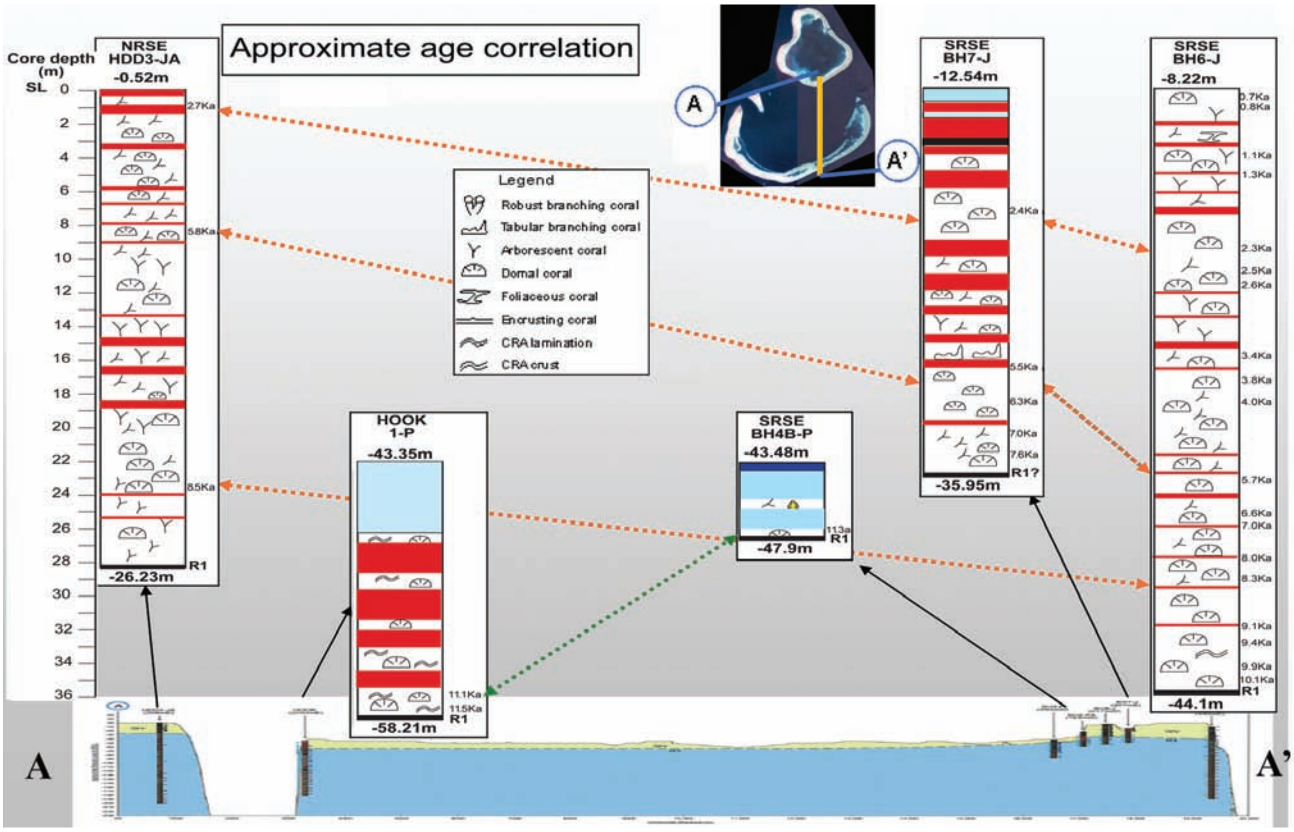

Figure 7. Summary of cored Holocene reef sections for Scott Reef showing major reef building communities. Note geochronology including Holocene reef initiation dates. All dates are expressed as U/Th ka (kiloyears) before present.

Rate of Holocene Reef Accretion

Accumulation rates were obtained using U-series dated material in relation to the thickness of the deposit. This necessarily included both original framework and reworked material. Accretion rates are expected to vary mainly related to three aspects: 1) regional occurrence of frame-building taxa; 2) primary frame building taxa related to the environment where the core is located; and 3) amount of reworked material locally generated (see Blanchon & Blakeway 2003, for discussion). This suggests that the nature of framework facies controls the accretion rates in reef environments (Montaggioni 2005). Rates and modes of reef growth vary greatly within the same reef system, according to the zone considered (Davies *et al.* 1985).

Most reefs investigated are frame-dominated structures, although reworked material is found in some sections. Reef accretion through the Holocene of Scott Reef varies from core to core. In frame-dominated reefs the accretion rate varied from a maximum of 3.57 m/ka recorded for SR SE BH6-J, to a minimum of 2.65 m/ka recorded for NR SE BH1 HDD-J. Most of the investigated cores with accretion rates within the same order of magnitude are formed by domal to arborescent coral facies.

Montaggioni (2005) suggested that domal and arborescent reefs appear to have similar growth rates, however higher accretion rates are found in cores containing a greater proportion of arborescent forms (see also Webster 1999). At Scott Reef the accretion rates are consistent with domal facies dominated reefs, i.e., smaller than 7 mm/y.

The changes in accretion rate observed in SRSE BH6-J during the Holocene (see Fig. 7) is faster in the beginning and end of the Holocene and slower during the mid-Holocene, and this may be attributed to the change from more domal to more arborescent dominated reef facies in the latter 3000 yrs. Therefore the reef developed as a keep-up to catch-up reef, finally returning to a keep-up mode of growth towards the end of the Holocene. This suggests that both catch-up and keep-up signatures can occur in framework as well as detritus, in ocean-facing and sheltered reef flats, in a given period of time.

In a regional assessment of core data from Indo-Pacific reefs, including the Houtman Abrolhos and Ningaloo Reefs (see Collins *et al.* 1993, 2001) a wide-ranging facies scheme was developed by Montaggioni (2005) and this provides the best reference framework available for evaluation of the Scott Reef communities and facies (rock) associations.

Framework facies are broadly grouped as high-hydrodynamic energy (calcareous red algae and robust-branching corals), moderate energy (domal, tabular-branching and arborescent corals), and sheltered areas (association of arborescent, foliaceous and encrusting corals).

Based on maximum rates of vertical accretion, the Indo-Pacific reefs can be classified into (1) fast-growing reefs, with rates up to 10 mm/year. Such rates can be sustained for 3–5 ka and may reach up to 20 mm/year for periods of about 500 years. They result commonly in expanded sequences up to 25 m thick; (2) moderate-growing reefs, with rates of 5–7 mm/year, which generally produce sequences 10–25 m thick; (3) slow-growing reefs, with rates of 1–4 mm/year which commonly form sections less than 10 m thick (Montaggionni (2005).

Reef margins have generally been considered to have lower accretion rates. The reasons why reef margins have developed slower vertically may be attributed to the settlement of slow growing corals or due to the higher hydrodynamic energy promoting lesser coral larval settlement. Accretion rates determined for Scott Reef are within slow-growing reefs, with rates of 1–4 mm/year, which commonly form sections less than 10 m thick. However the Scott Reef Holocene thickness approaches 40 metres.

Vertical accretion potential can be converted to net calcification (see Smith, 1983), a measure of carbonate production expressed in kg $CaCO_3$ m^{-2} $year^{-1}$, taking into account a value for the porosity of the original framework and detritus fabric (about 50%) and the density of an aragonite and calcite mixture (about 2.89 g/ cm^3). Thus, slow-growing reefs should range from 1–3 kg m^{-2} $year^{-1}$. To date no studies have been done of calcification rates at Scott Reef, however it would be interesting to pursue this line of research in the light of predictions of future climate change and increasing ocean acidity.

Reef Response to Holocene Sea-level Rise

Holocene reef growth history curves are presented in Figure 6A. The Scott Reef cores are unique in that they provide an uninterrupted history of reef growth throughout the rising deglacial sea-level of the last 10,000 years, with precise U-series dates and little ”noise” in the data. Four cores were documented fully and one (NRSE HDD3-JA) was dated on a reconnaissance basis. The 3 fully dated cores (NRSE BH1 HDD-J, SRSE BH6-J, SRSE BH7-J) “cluster” and have similar gradients, however NRSE HDD3-JA is distinctly older though less completely dated.

At -20 m LAT there is a “crossover” and thereafter the outer reef (SRSE BH6-J) grew more rapidly than the inner reef (SRSE BH7-J), probably due to changes in coral community, for southeast South Reef between -20 m and -10 m, where the data ends. The top 10 m of history is not recorded because the SRSE BH 6-J borehole was sited in 8m water depth, seaward of the reef crest, and BH7-J lies in a depression between the inner and outer reefs.

Core NRSE HDD3-JA represents a near-reef crest setting in southeast North Reef, and the data are recorded to close to sea-level. As a consequence this core provides the best data on reef crest growth rates, and most closely provides a proxy sea-level record. On this basis the crest of southeast North Reef (and the rising sea-level) reached close to present sea level (-1.5 m LAT) by 2.7 ka ago. Coral reef records in southwest Australia record a brief sea level highstand of about +2 m some 7 ka BP (Collins, 1993, 2003; Houtman Abrolhos and Ningaloo Reefs; both microtidal systems), followed by a decline to present sea-level, but there is no data at Scott Reef to support this.

A comparison between the Scott Reef data and growth history records for 15 documented reefs is shown in Figure 6B. Many growth history records lag behind sea-level, probably as a function of position of the core in the reef system, and the lag depth between sea-level and the particular reef community dated (for example *Acropora palmata*, which grows close to sea-level, is absent from Indo-Pacific reefs). The best sea level “fit” is curve 4 (Abrolhos reefs).

The dated onset of Holocene reef growth sheds some light on the relationship between the inner and outer reefs which form the “double reef” of the South Reef platform, though this information is incomplete. The shape of the antecedent surface (the R1 reflector; the eroded and possibly discontinuous, preceding reef crest of MIS 5) can be seen in seismic profiles (see Fig. 5). The elevation of this surface was an important control on reef initiation during sea-level rise. Because the outer reef had an early “start-up” date (10.1 ka) due to its position on the relatively deeper outer platform margin, and given the lag time of about 1000 years for reef “start-up” it is likely that the outer reef was well advanced before initiation of the inner reef occurred from shallow start-up depths. More U-series dating results will likely resolve this question.

Frame Builders of the Holocene Reef

The upper (Holocene) phase of reef growth, reef building communities, available U-series dates and core transect locations are shown in Figure 7. A range of reef settings, including reef front, west-facing, south-facing and east-facing reefs, back reef, and reef channel are represented. A data gap in Indo-Pacific reef studies is the lack of ocean-facing reef cores, so the presence of at least 6 such cores from Scott Reef provides a rare opportunity to address this deficit.

Most cores are composed of porous but relatively unaltered reef framework with lesser amounts of carbonate sediment; some intervals, particularly those of branching corals, are rubbley, partly as a result of disruption by rotary drilling, and partly as a result of accumulation of both “framework” and “fill” material.

The dominant frame builders are communities of arborescent (branching) corals, and domal (massive) corals (including *Porites*); these exist as end member communities as well as in mixed associations, as in cores SRSE-BH7-J; 6-J; NRNE-BH1-HDD-J; NRSE-HDD3-JA (Fig. 7). In SRSW-BH1-J there is a distinctive assemblage of robust branching corals and coralline algae, and in NRCH-BH1-J tabular branching corals, *Halimeda* and coralline algae are significant. In a regional assessment of 30 years of core data from Indo-Pacific reefs by Montaggioni (2005) framework facies are broadly grouped as high-hydrodynamic energy (calcareous red algae and robust-branching corals), moderate energy (domal, tabular-branching and arborescent corals), and sheltered areas (association of arborescent, foliaceous and encrusting corals). Scott Reef can be summarised as high energy; cyclone-influenced, swell-wave influenced and tidally dominated. Its 4 metre tidal range is at the high end of Indo-Pacific tidal energy conditions. Its cyclone exposure is significant, as illustrated by the boulder field that constitutes the outer reef flat surface, and surrounds the fore-reef slope.

Wave energy is also significant, largely from westerly approaching swell waves, but the arcuate to circular reef orientation combined with wave refraction provides a spectrum of reef front wave energies, from high to moderate to low.

The most common community and facies association is of arborescent (branching) corals, and domal (massive) corals (including *Porites*); both as end member communities as well as in mixed associations in vertical profiles, and found in cores taken immediately seaward of the reef crest on the forereef (Fig. 7). It represents, for the arborescent association, sheltered settings (at 0–20 metres) in lower to middle parts of the forereef, and for the domal association, a semi-exposed to sheltered, relatively deep environment of depth 10–15 m. This is the dominant reef building association in the South Reef southeast reef slope (SRSE-BH6-J), and the North Reef southeast reef slope (NRSE-HDD3-JA) which are relatively low-wave energy settings due to their southeast facing aspect. Core SRSE-BH7-J, situated on the inner reef slope at southeast South Reef, also has a similar assemblage, as does NRNE-BH1-HDD-J, (outer reef slope, relatively protected, northeast facing setting). In contrast, in SRSW-BH1-J an association of robust branching corals and encrusting coralline algae is significant (representing high hydrodynamic energy environments; Montaggioni, 2005) together with the assemblage of domal and arborescent corals of lower hydrodynamic energies. The outer reef flat to reef front of the southwesterly facing reef crest of South Reef has higher wave energies than more easterly facing settings, hence the presence of the high hydrodynamic energy indicator communities described.

The coral assemblage in NRCH BH1-J from the lagoon side portion of the tidal exchange channel which breaches the north facing reef of North Reef is relatively high in diversity, and includes tabular branching corals (open marine, moderate energy, depths <15 m), foliaceous corals, particularly in the lower part of the core, as well as domal and branching corals. Also present are *Halimeda* and calcareous red algae. Tidal channels are subject to high to very high tidal current velocities as part of the lagoon flushing process. Foliaceous corals are most prevalent in shallow back reef environments and this is also consistent with the setting of the core.

Core Hook 1-P was collected near the incipient reef rim which marks the northern most margin of the lagoon of South Reef (Figs 5A and 7). This reef is best characterised as a "give up" reef as it failed to grow to sea level. Analysis of the coral community, which apparently consists of domal coral and coralline algae, is limited by the very poor recovery in the core. Core loss intervals are likely to have consisted of unconsolidated sand and rubble, and this is consistent with the mixing of lagoon – derived sediment with the growing coral communities. Such an environment of high sediment supply and probably high turbidity may well have served to limit coral growth, and caused failure of the reef to keep pace with sea level rise. It is currently blanketed by carbonate sand and lacks modern recolonisation.

Scott Reef Holocene (compared with results from Indo-Pacific reefs) provides a record of reef front communities rarely obtained due to access problems. The dominant coral community and facies association of arborescent (branching) corals, and domal (massive) corals (including *Porites*), both as end member communities as well as in mixed associations in vertical profiles, from cores taken immediately seaward of the reef crest on the forereef, represents, for the arborescent association, sheltered settings (at 0–20 metres) in lower to middle parts of the forereef, and for the domal association, a semi-exposed to sheltered, relatively deep environment of depth 10–15 m.

The moderate hydrodynamic energy conditions represented by these frame builders, (Montaggioni & Braithwaite 2009) may be due to the fact that the community record is one that lagged somewhat behind the rising Holocene sea-level, thus representing relatively deeper conditions than would be experienced in the upper 10 metres of reef crest deposition. One factor here is that a number of key cores (NRNE BH1-HDD-J; SRSE BH6-J, for example) do not capture the uppermost 10 metres of the reef crest in their record where significant amounts of coralline algae might be expected. Records of the uppermost portion of the reef flat (NRCH BH1-J; core top at -3.09 m LAT; SRSW BH1-J; core top at -2.77 m LAT) have encrusting coralline algae in the upper few metres, indicating high hydrodynamic energies at the reef crest.

Discussion

Scott Reef rises from depths of 400–700 m on the distal portion of a carbonate ramp. 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. A cross section summarizing the relationships of reef building stages with the Scott reef platform is shown in Fig. 7.

The overall seismic architecture is a flat-topped platform bounded by platform margin reefs which flank steep marginal slopes, as reflected in the current day surface environments. There are distinct cycles of upward platform growth which resemble "stacked saucers" in shape, each mimicking the previous cycle. Cycle boundaries are marked by platform-wide seismic discontinuities (R1, R2, and R3) which rise under marginal reef crests before falling steeply at the platform margins.

The internal architecture of reef building phases in North Reef and South Reef are similar, with the exception that equivalent horizons are shallower in North Reef. Age/depth plots indicate the average subsidence rate for South Reef is 0.45 m/ka, and for North Reef is 0.29 m/ka, suggesting differential subsidence is occurring, with a higher subsidence rate for South Reef. This is consistent with the observation that equivalent subsurface horizons lie at shallower depths in the North Reef platform, however seismic data is lacking for North Reef restricting the information for comparison.

The Holocene reef profile preserves a detailed sea level and growth history record. During Holocene time (MIS1; last 10,000 years) 14 to 35 metres of vertical reef growth occurred. In the Indo-Pacific this reef growth phase (termed RG111) was characterised by moderate rates of sea level rise of 10 mm/year (generating "keep up" or "catch up" reefs) from 11 to about 7–6.5 ka BP until sea level stabilization. Core NRSE HDD3-JA represents a near-reef crest core in southeast North Reef, and the data is recorded until close to sea level. As a consequence this core provides the best data on reef crest growth rates, and most closely provides a proxy sea level record.

The most common Holocene community and facies association is of branching (arborescent) corals, and massive (domal) corals (including *Porites*); present in close association, both as end member communities as well as in mixed associations in vertical profiles, and found in cores taken immediately seaward of the reef crest on the forereef. Hydraulically this represents, for the arborescent association, sheltered settings (at 0–20 metres) in lower to middle parts of the forereef, and for the domal association, a semi-exposed to sheltered, relatively deep environment of depth 10–15m. This is the dominant reef building association in the South Reef southeast reef slope, and the North Reef southeast reef slope which are relatively low wave energy settings due to their southeast facing aspect. Robust corals and coralline algae are important constituents of the higher energy forereef of southwest Scott Reef, and these corals represent high hydrodynamic energies.

Scott Reef is an isolated system which is tide-dominated, cyclone influenced and wave-influenced. The combination of core data from a range of reef crest and lagoon settings, together with the availability of shallow seismic data has provided a unique opportunity to develop a Holocene model for reef growth which is geologically significant whilst informing biophysical analysis and environmental management.

Acknowledgements: Initial sampling and seismic surveys of Scott Reef in 2000 by RV Franklin provided reconnaissance data on Scott Reef. The Curtin project team thanks the Captain, Crew and support from Australian Research Council, and shipboard assistance from CSIRO and Geoscience Australia researchers. Site test cores collected by Woodside Energy Limited formed the basis of the Scott Reef study in 2009, and a Woodside grant to Collins (Curtin) to study the cores (with Viviane Testa, Curtin) made this project possible. Luke Smith (WEL) is thanked for assistance and advice throughout the study. U-series dating at University of Queensland was completed by Zhao and Qu in a timely way, and Dr Yue-xing Feng is thanked for analytical support in the UQ lab. Andrew Shuckstes and Michael Page (Worley Parsons) provided advice in the early stages of the core study. Ms Alexandra Stevens is thanked for assistance during the study and with compilation of the paper. The first author thanks co-authors for their enthusiasm and support in the successful completion of the study.

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