Geomorphic patterns, internal architecture and reef growth in a macrotidal, high-turbidity setting of coral reefs from the Kimberley bioregion

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Abstract

The coral reefs of the Kimberley bioregion are situated in an area that is considered a significant 'biodiversity hotspot' and are poorly known and of recognised international significance. This paper is a review of ongoing research as part of one of the first geoscientific reef studies of the Kimberley Biozone. Remote sensing, sub-bottom profiling and associated sedimentological work have been employed to produce a regional geodatabase of coral reefs and determine the Holocene internal architecture and growth history of the coral reefs. Satellite image analysis has revealed that fringing reefs in the Kimberley bioregion grow very well and differ geomorphologically from planar reefs both inshore and offshore. The acoustic profiles have depicted multiple reef build-ups, demonstrating the reefs' long-term resilience. This research has provided a better understanding of the Kimberley reefs and demonstrated their capacity to succeed in challenging environments and generate habitats characterised by high complexity and species diversity.

Introduction

The Kimberley region is located on the north-western continental margin of Australia (Figure 1) and is characterised by unique and complex geology and geomorphology, significantly influenced by the macrotidal system (up to 11 m), which result in expansive intertidal zones.[1] The Kimberley coastal region is a large-scale ria coast with a well-developed indented rocky shoreline and many offshore islands with unique geology and geomorphology.[2] Regional structure has determined much of the contemporary landforms and related ecosystem development, and controlled the architecture of the drowned landscapes over which coral reef systems have developed.[3] Thus, there are strong geomorphological controls on reef development. Coral reefs have developed over a broad shelf as shelf edge, inner shelf and coastal inshore reefs for over 800 km across a geomorphically complex coastal zone and, whilst the offshore reefs have been studied,[4] little is known about these inshore coastal reefs.[5]

It is not known whether Kimberley reef morphology conforms to the established geomorphic models, such as those identified from the Great Barrier Reef (GBR),[6] or has developed as distinctive morphologies driven by the extreme environmental conditions unique to the Kimberley. Here, regional reconnaissance mapping was used to assess reef morphology within the complex geophysical environments of the Kimberley coast. Questions such as the impact of extreme tides, high terrestrial sediment loads, exposure of the reefs for long periods during the tidal cycle, and relatively warm waters, all remain to be addressed.

While the offshore reefs have grown vertically as successive sea-level events drowned the shelf during the Quaternary, the inshore reefs have interacted with complex antecedent geomorphology during coastal inundation, as well as intermittent terrestrial inputs, developing around and over rocky islands, headlands and platforms. However, patterns of geomorphology and substrates are poorly understood and little documented regionally.[7] It is not known whether most Kimberley reefs are veneers over rock platforms or are long-lived features, recording processes and patterns of growth, community composition and structure, hiatuses, sea levels and climate changes through post-glacial time (see note 6). Access to such records is needed to determine long-term adaptive responses of Kimberley coral reefs to oceanographic and coastal processes that are near the environmental limits of coral growth.

The primary aim of this project is to understand the past history of coral reef growth for several Kimberley reef types, using a combination of remote sensing, sub-bottom profiling (SBP) and, where possible, reef stratigraphy in order to provide the first geomorphological analysis of the inshore reefs. The analysis will add value to the many Western Australian Marine Science Institution (WAMSI) biological studies being carried out in parallel to this geological investigation. This paper reviews ongoing research in WAMSI Project 1.3.1 on Coral Reef Geo- morphology and Growth History of Kimberley Reefs.

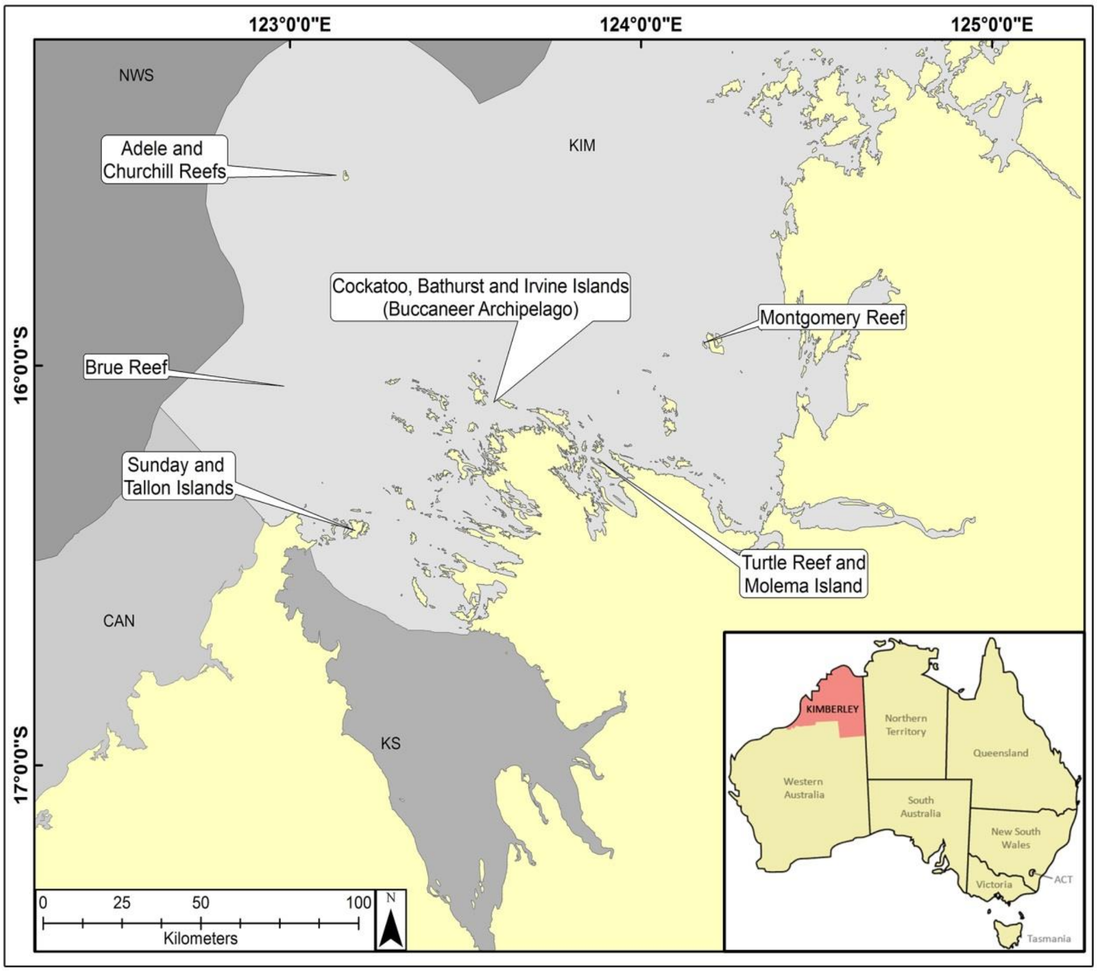

Figure 1. Map of the Southern Kimberley region. The marine bioregions (Commonwealth of Australia*, A Guide to the Integrated Marine and Coastal Regionalisation of Australia Version 4.0,* Department of the Environment and Heritage, Canberra, Australia, 2006) are shown in grey (NWS: North West Shelf; CAN: Canning; KS: King Sound; KIM: Kimberley). The main reefs studied in this study are labelled, Cock- atoo Reef is in the Buccaneer Archipelago.

Materials and methods

In the absence of any previous chronological, stratigraphic and geomorphic data for the inshore Kimberley reefs, three approaches were attempted in related and interactive sub-projects in this study. These were a remote sensing approach used to regionally map the many island and hinterland associated reefs, to analyse geomorphic patterns of reef growth and to determine the living communities and substrates; a targeted stratigraphic and chronologic study of reef growth, using one of the rare reef exposures in a mine pit at Cockatoo Island; and a seismic study to determine reef thickness, the number of stages of reef growth, and an attempt to analyse the regional growth pattern using available chronologic data from the Cockatoo Reef study. These objectives were determined in consultation with agencies responsible for marine park management in the area. The work in this paper is preliminary in nature and ongoing.

Remote sensing data

Coral reefs occur extensively in the Kimberley Bioregion (KIM), forming major geomorphic features fringing both islands and mainland coasts. Here remotely-sensed images were used to map the spatial distribution of reef habitats and to characterise reef geomorphology. Multiple data sources (see Table 1) were integrated using ESRI's ArcGIS to validate results, which were then verified against ground truth control points in order to produce consistent, accurate habitat and geomorphic maps. Remote sensing data were mainly from Landsat 7 and aerial photography, using unsupervised classification, supported by ground truth whenever available.

Table 1. Data sources.

Data sets	Source of data	Representation
Kimberley coastline	Satellite images (USGS), Aerial photography (WAMSI)	Polyline
Islands	Satellite images (USGS), Aerial photography (DPaW), Bathymetric charts (AHS), Geological maps (GSWA)	Polygon
Coral reef	Satellite images (USGS), Aerial photography (DPaW), Bathymetric charts (AHS), Geological maps (GSWA)	
	Western Australian Museum Woodside Collection Project (Kimberley) 2008–2011, Brooke, 1995, 1997 and Wilson 2009, 2010	Polygon, points
Seabed geomorphology	Geoscience Australia	Polygon
Sea surface temp	NOAA	Polyline
Bathymetric map	Geoscience Australia, AHS	Polyline
Sub-bottom profiles	Applied Geology Department, CU	Seismic Profiling
Weather	Australian Bureau of Meteorology	Vary

Notes: USGS, U.S. Geological Survey; WAMSI, Western Australian Marine Science Institution; DPaW, Department of Parks and Wildlife; AHS, Australian Hydrographical Service; GSWA, Geological Survey of Western Australia; NOAA, National Oceanic and Atmospheric Administration; AHO, Australian Hydrographic Office; CU, Curtin University.

Reef and mine pit mapping

The two main iron ore pits on Cockatoo Island have been excavated to a depth of approximately 50 m below sea level and extend out onto the island's modern reef flat. The fringing reef and the pre-existing substrate have been exposed in a complete vertical section along the face of the pit. Stratigraphic logging, sampling and photographing of the section were completed by Solihuddin, Blakeway, Collins and O'Leary.[8] In order to establish a geochronology of the reef growth, *in situ* coral samples were collected at selected levels and dated using accelerator mass spectrometry radiocarbon dating methods. Dating was recalibrated using CALIB Version 5.0.2, calibration curve Marine04 and calibrated in years Before Present (cal yBP) with 2 σ (68.2%) probability range.

The coral distribution along stratigraphic horizons within the mine pit was compared and correlated with the distribution of living coral communities along the adjacent reef flat and fore-reef slope, using towed camera transects during high tide and on foot during spring low tides (see note 8).

Sub-bottom profiling

A total of 300km of high-resolution shallow sub-seafloor imaging data was acquired during a sub-bottom profiling (SBP) study, using an AA201 boomer SBP system (Applied Acoustic Engineering Limited, Great Yarmouth, UK). A dual frequency Differential Global Positioning System (DGPS) Fugro SeaSTAR 8200 XP/HP with Trimble Antenna was used to obtain an accurate position (decimetric accuracy). Data were digitally recorded in SegY format (Rev 1), using SonarWiz 5 (Chesapeake Technology Inc., Mountain View, CA) as acquisition and post-processing software.

Results

Kimberley reef classification scheme

Before providing an integrated analysis of remotely sensed, stratigraphic and seismic results, it is necessary to propose an organised classification framework for the specialised, macrotidal Kim- berley reefs, which are diverse, and which have unique characteristics.

Previous studies have attempted to apply reef classification schemes developed for the GBR to Kimberley reefs.[9] Although their applicability has been noted, the greater diversity of Kimberley reefs made their use limited. In more recent geoscientific studies,[10] including new reef core data, radiocarbon dating and seismic profiles as well as GIS data allowed the proposal of a new modified classification scheme for the reefs in the Kimberley bioregion (Figure 2).

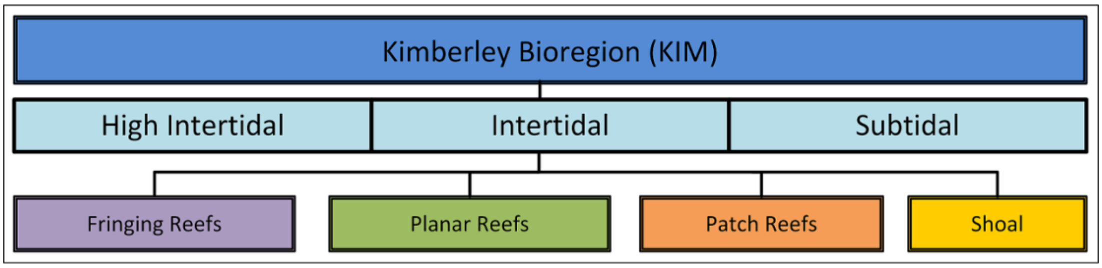

Figure 2 (previous page). Preliminary reef classification scheme based on adaptation of previous studies and geoscientific data from this study. Modified after Bufarale et al and Kordi et al (see note 10).

Geomorphology, habitats and substrates

Preliminary analysis using unsupervised classification of Landsat data, and ground truth observations, of substrate types for the reefs studied to date has shown distinctions between high inter- tidal, fringing, planar and patch reefs. The most striking features of these reefs are the dominance of sand and coral rubble on their reef flat. They are also characterised by a widespread distribution of rhodolith-rich substrates, present as terraces and also near the reef crest. For example, at Montgomery Reef, the reef flat is approximately 30% sand and coral rubble while the reef terraces and crest are about 6% rhodolith dominated substrates (Figure 3).

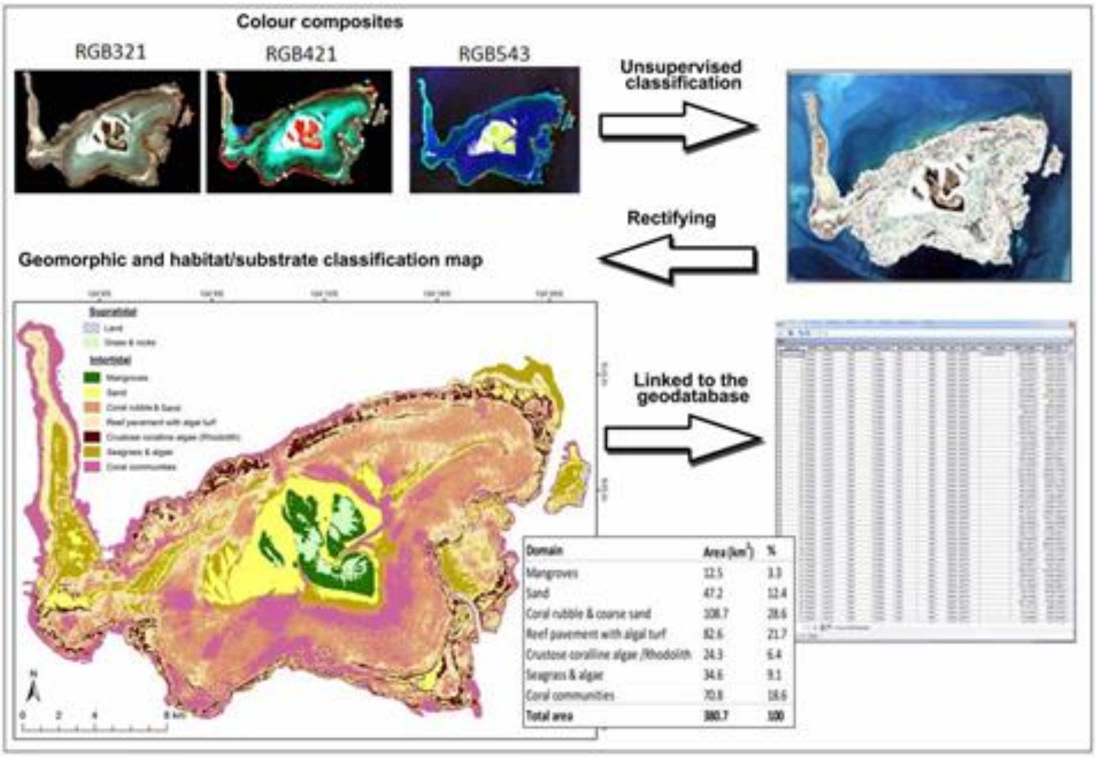

Figure 3. Example of processing of satellite imagery, for Montgomery Reef (see Figure 1 for location), modified after Kordi et al (see note 10).

The satellite image analysis has demonstrated that the geomorphic and associated habitats of the inner- to mid-shelf platform reefs have similarities with high intertidal reefs such as the abundance of rhodoliths and coral rubble over the reef platform and the presence of terraced reef flat. The low-gradient fore-reef slope zones in inner- to mid-shelf platform reefs are predominantly colonised by soft and encrusting flat coral and bryozoans, with domal and plate corals becoming significant. This can be seen clearly at Adele Island (see Figure 1 for location), where the coral communities colonising the reef slope represent about 31% of substrates on the platform surface (Figure 4).

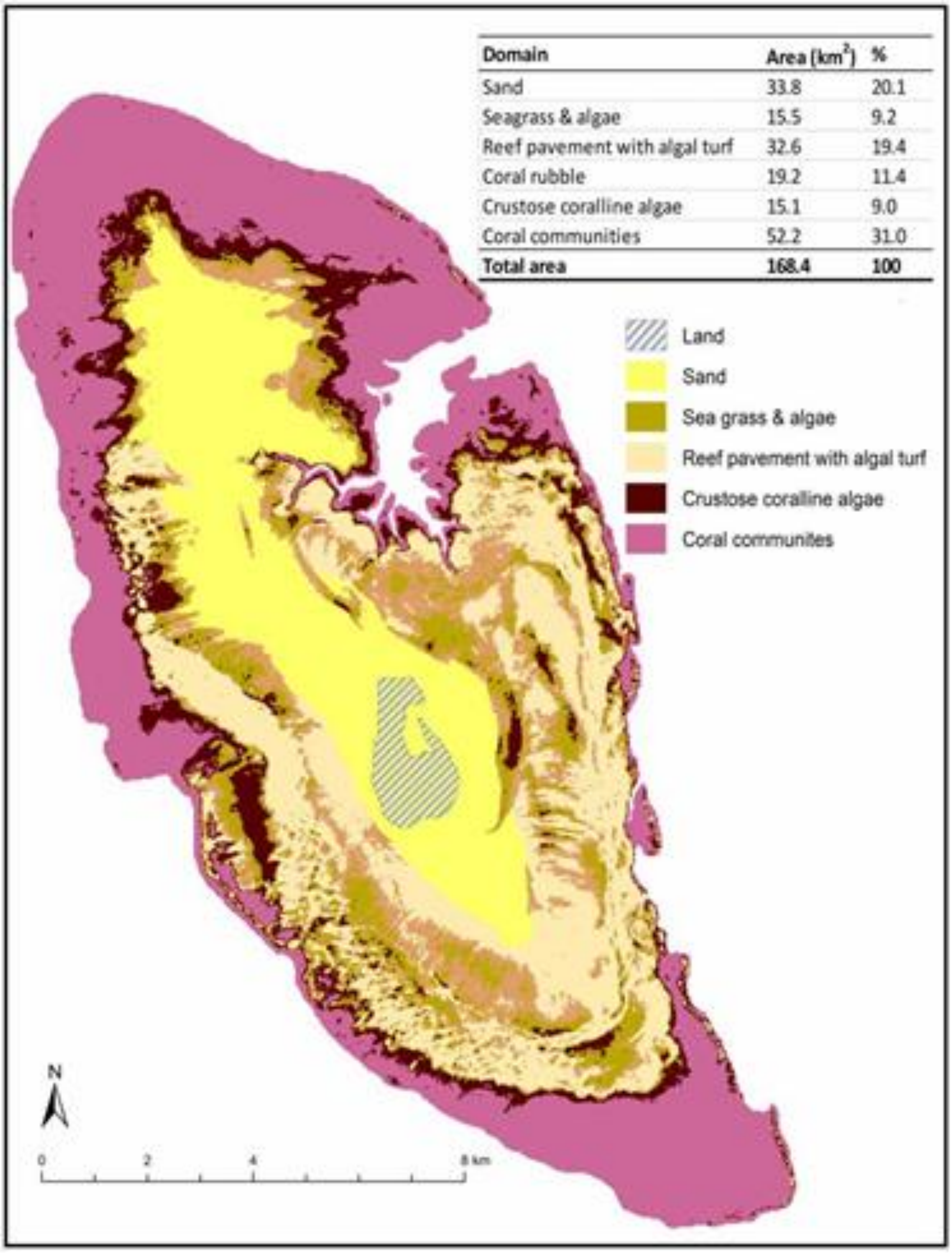

Figure 4. A preliminarily geomorphic, substrates and habitat map of Adele Reef, surrounding Adele Island. Sample data provided by the REEFKIM database, modified after Kordi et al (see note 10). Coral communities dominate the fore-reef slope. For location, see Figure 1.

Stratigraphy and geochronology

Solihuddin, Blakeway, Collins and O'Leary documented stratigraphy and geochronology of mine pits at Cockatoo Island.[11] The following section is based on their results.

Stratigraphic and palaeoecological data, combined with radiometric dates (Figure 5), have revealed that the lower section of the mine pit is Proterozoic basement (Figure 6). A thin layer (1–2 m) of thick sedimentary talus breccia containing haematite boulders separates the basement from a younger coral-rich unit, containing mainly domal corals with minor encrusting and branching forms, dated as belonging to the last interglacial (LIG) (Figure 5). On top of this reef sequence, a second, thinner, haematite boulder breccia layer is present which is overlain by Holocene reef (see note 11). The Holocene reef unit is up to ~13 m thick (Figure 5) and two distinct facies dominate the unit: muddy domal and branching coral framestone. Coral clasts are visually dominated by branching corals mainly of the genus *Acropora* and massive corals including *Porites*; diverse molluscan fauna is also present. Towed camera observations highlighted a few differences between the Holocene and the living reef (see note 11). *Porites* and *Faviids* are the most abundant genus, along with *Sargassum* which sparsely colonises the intertidal coral zone, whilst branching *Millepora* and *Porites cylindrica,* which increase seaward and are not present in the fossil record, have a medium density (see note 11). The contemporary live corals are uncommon in the measured Holocene sections, suggesting that the Holocene reef communities lack reef flat habitat. The Holocene reflects mostly subtidal growth, whereas the present reef is largely intertidal or very shallow subtidal (see note 11).

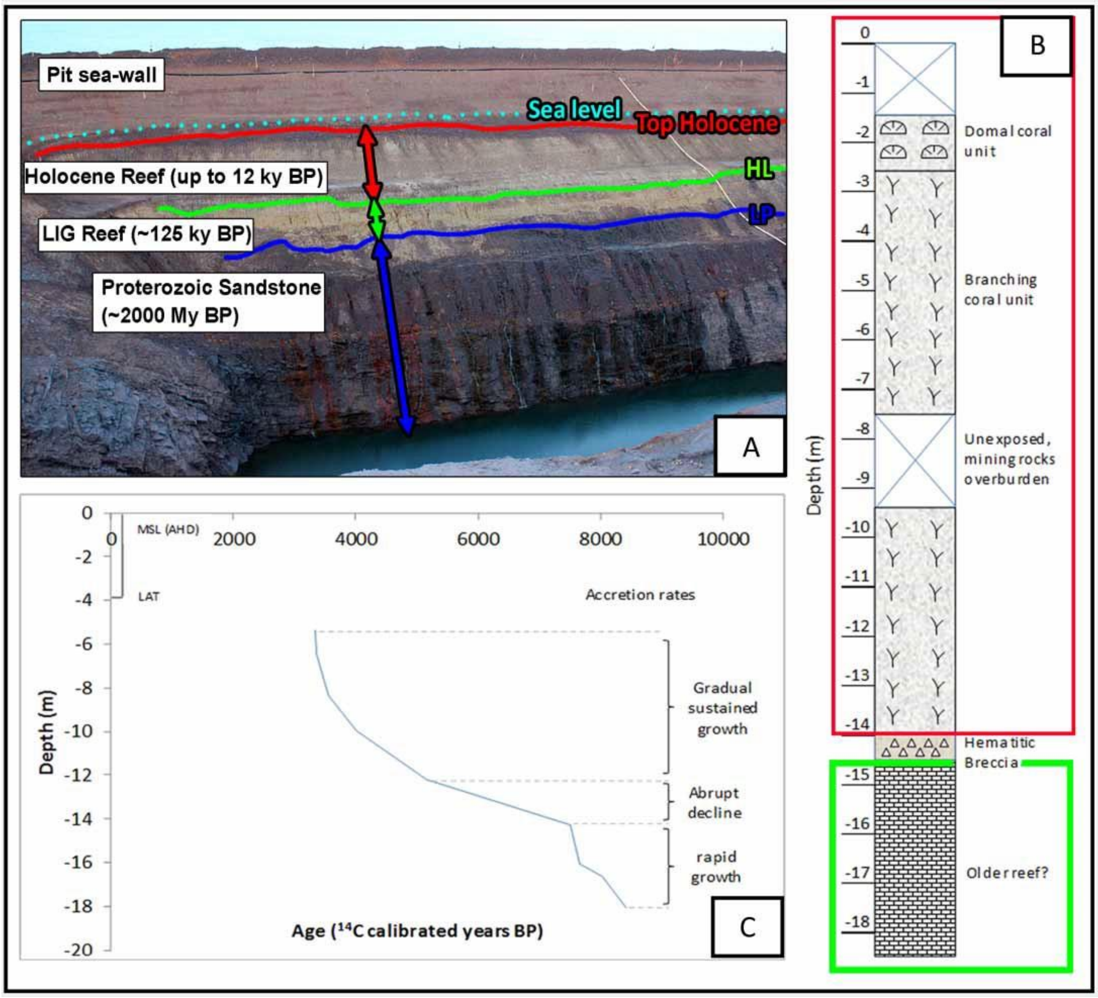

Figure 5 (previous page). (a) Cockatoo mine pit section, looking SW (refer to Figure 1 for the location). (b) Idealised reef stratigraphic column. (c) Idealised vertical accretion rates. Haematitic breccia marks base of Holocene reef. Older reef is presumed LIG reef. Modified after Solihuddin et al (see note 11).

Radiocarbon results (see note 11) have indicated that the earliest Holocene reef growth started on the pre-transgressive haematitic breccias, at a depth of ~18 m below mean sea level (bmsl) by approximately nine thousand years before present (ky BP). Vertical accretion rates show initial rapid reef growth after the initial flooding (at 9–8 ky BP), followed by an abrupt decline after about 8ky BP, until about 5ky BP when the accretion rate was low (see note 11). In the following period, the coral accretion showed gradual but sustained growth following sea-level rise closely (Figure 5(c)) (see note 11).

Seismic facies

New data on Holocene reef growth and its relationship to antecedent foundations of the Kimberley reefs were obtained through a shallow seismic survey. Selected reef sites (Figure 1) were chosen in order to evaluate most of the Kimberley reef morphotypes described in the reef classification scheme (Figure 2). During the post-processing and interpretation of the acoustic data sets, two major acoustic horizons, HL and LP, were recognised based on their relative position, appearance and internal architecture. In mid-ramp reefs (Adele Island), two further deeper seismic reflectors were described. The seismic profiles were calibrated using, for the inner shelf reefs, the mine pit mapping stratigraphy of the proximal part of Cockatoo Island (see note 11)[12] (Figure 6), and for the mid-shelf reefs, palynological and well completion reports for a well drilled in 1982 on the northern tip of Adele Island.[13]

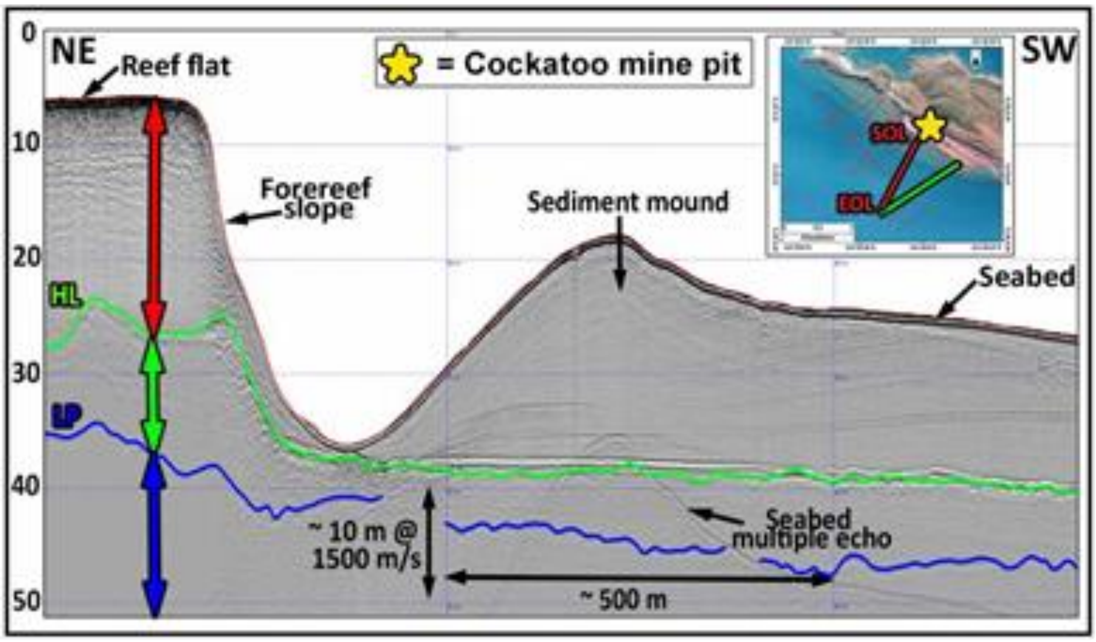

Figure 6. Seismic profile adjacent to Cockatoo mine pit section (Figure 5(a)) mapped by Solihuddin et al (see note 10) showing the position of Proterozoic (LP, blue), LIG (HL, green) and overlying Holocene reef intervals across the fringing reef (see inset for location of sections. SOL: start of line; EOL: end of line). Note the sediment mound in front of the reef flat. Depth values are in metres, below the sea level. Landgate aerial photography provided by DPaW (modified after Bufarale et al (see note 14)). Note significant subsidence of LIG surface (HL, green).

The first 150 m of the Adele Island well consists of multiple stacked limestone sequences. Within the equipment range, the seismic profiles (see Figure 7) reveal the presence of four stages of reef build-up, identified as Holocene (Marine Isotope Stage 1 MIS 1, last 12ky BP), LIG (MIS 5e, ~125ky BP), Penultimate Interglacial (MIS 7, ~200 ky BP) and MIS 9 (~300 ky BP), as comparable to the Marine Isotope Curve (Figure 8).

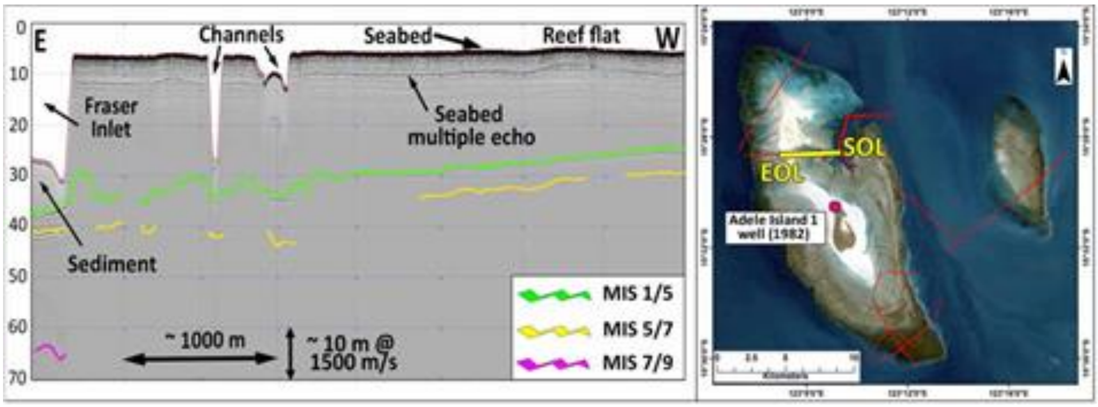

Figure 7. Left: Profile showing multiple stages of reef build up (MIS 1, 5, 7, 9, respectively) in the northern portion of Adele Reef. Depth values are in metres, below the sea level. Right: Location of the profile (in yellow) and track plot of all the seismic profiles performed in Adele and Churchill reef (in red). Landgate aerial photography provided by DPaW (modified after Bufarale et al (see note 14)).

Holocene and Pleistocene reef thicknesses vary respectively between 10 and 22 m and 10 and 15 m, in relation to the accommodation locally available (see Bufarale et al[14]): where the Proterozoic rock foundation is shallower, the reef is thinner due to a limited capacity to vertically grow, relative to ultimate sea level (e.g. in Sunday Island). Vice versa, wherever the antecedent substrate is profound, the colonisation could benefit from a greater amount of accommodation (i.e. Montgomery Reef and Cockatoo Reef, Figure 6 and see note 14).

Conclusion

The Kimberley Coral Reef Geomorphology and Growth History Project researchers are using information and experience gained from participation in WAMSI 1 within the current WAMSI 2 project research. Our data and newly generated products reflect the three areas of activity in the study: remote sensing, SBP and associated sedimentological work.

The work in this paper is preliminary in nature and ongoing. Fringing reefs in the Kimberley bioregion grow very well, despite the inshore Kimberley environment being extremely turbid. Preliminary study using Landsat satellite images reveals that the fringing reefs in the Kimberley bioregion differ geomorphologically from planar reefs both inshore and offshore. The most noticeable distinction is the absence of rhodolith banks and coral rubble over the reef platform as well as reef terraces. The reef flat which slopes gently seaward consists of intertidal coral, macroalgae and sediment deposits.

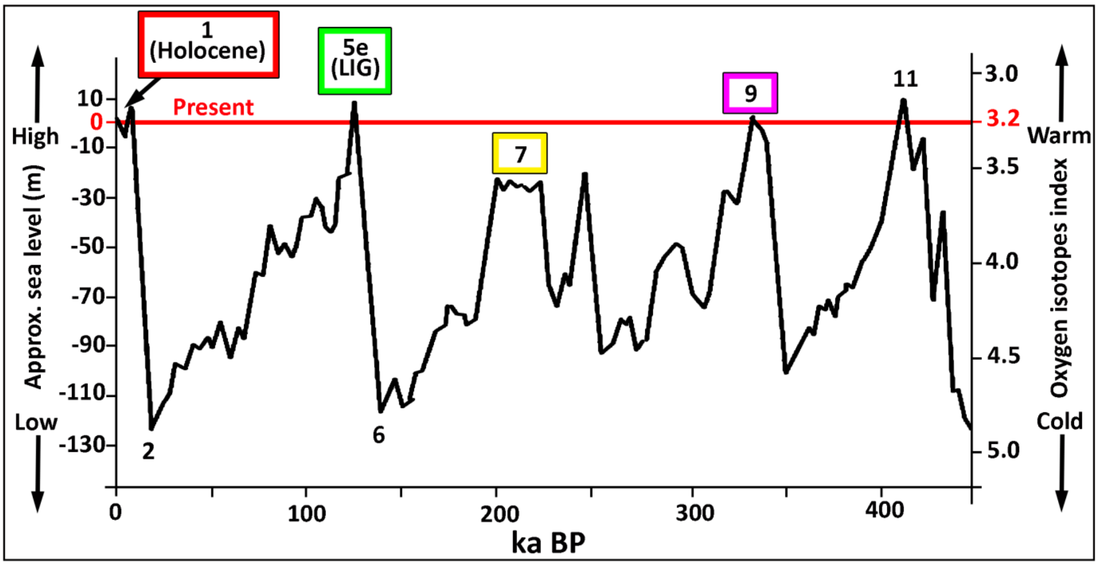

Figure 8. Marine oxygen isotope index and sea-level changes for the last 500 ky BP (after).15 Inner shelf reefs: Holocene reef (last 12ky BP), LIG reef (~125 ky, MIS 5e) have grown on Proterozoic rock foundation. Mid-shelf reefs: two additional older reef units are identified (~19 ky BP, MIS 7 and ~300 ky, MIS 9).

The acoustic profiles have depicted two acoustic reflectors across the inner shelf reefs, marking the boundaries between Holocene reef (Marine Isotope Stage 1, MIS1, last 12,000 years) and MIS 5 (last 125,000 years) and an ancient Neoproterozoic rock foundation over which Quaternary reef growth occurred. In the mid-shelf reefs (Adele complex), three acoustic horizons can be characterised. Correlating the seismic data with the reef chronology determined in Cockatoo and Adele Island, it has been possible to highlight the evolution of multiple stages of reef building, stacked by repeated high sea levels (Adele, 3 stages, at least; Sundays Group, Buccaneer Archipelago and Montgomery Reef, 2 stages; some patch reefs, 1 stage). The foundation over which reef growth occurred is the two-billion-year-old land surface seen in many Kimberley islands composed of Neoproterozoic rocks. Thus, Kimberley reefs are not thin growths over bedrock as sometimes postulated recently.

These new data sets have provided a better understanding of reef growth and have demonstrated the reefs' long-term resilience, with multiple reef build-ups, and their capacity to succeed in challenging environments through the late Quaternary. The interaction between complex pre-existing topography, subsidence of the LIG substrates and global sea-level fluctuations, controlled by ice-age fluctuation events, have influenced the successive reef morphology, controlling the available accommodation for reef growth. Simultaneously with these long-term mechanisms, short-term processes such as macrotidal conditions, terrigenous inputs from inland (resulting in high turbidity) and warm ocean temperatures, have contributed to generating a coral-dominated habitat characterised by high complexity and species diversity.

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Funding

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Notes

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