Session 34

Coral reef records of sea level, climatic and environmental changes: a tribute to Lucien Montaggioni

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Geomorphology and Holocene evolution of Kimberley coral reefs

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Abstract The Kimberley Bioregion (NW Australia) is characterised by the largest macrotides of any tropical region in the world (about 11 m), frequent tropical cyclones and high-turbidity. Despite these challenging environmental conditions, the region is also known for extensive and diverse intertidal coral reef habitats. While the area has been recognised as an international biodiversity hotspot, it is still poorly investigated compared to other reefal ecosystems in Australia, primarily due to its extreme remoteness and lack of infrastructure. A combination of remote sensing, sub-bottom profiling and associated sedimentological work produced a geodatabase of coral reefs, providing the first detailed geospatial study of coral reefs within the bioregion. More than 800 reefs have been documented and a regional reef geomorphic classification scheme, which includes a new "high intertidal" geomorphic class of reef, was developed. Reef coring shows that reef growth began soon after the post-glacial flooding of the antecedent substrate. High-resolution seismic data, acquired along selected reefs, showed that pre-existing substrate has influenced the successive reef morphology. Global sea-level changes, controlled by ice age fluctuation events, are recorded as successive stages of the reef growth, separated by growth hiatuses. Two seismic reflectors can be distinguished, marking the boundaries between Holocene (Marine Isotope Stage 1, last 12,000, 10-20 m thick) and Last Interglacial (MIS5, 125,000 BP, 12 m thick) reefs and an ancient Neoproterozoic rock foundation.

Keywords: reef geomorphology, Holocene reef growth history, sea level change, reef mapping, internal reef architecture

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Introduction

The Kimberley region is located on the north-west of Australia (Fig. 1) and is characterised by unique coastal and marine habitats, rich in biodiversity (Wilson 2013; Collins et al. 2015; Kordi et al. 2016), which endure macrotidal conditions of up to 11 m in range (Cresswell and Badcock 2000), high turbidity and frequent high-energy cyclonic events (Brocx and Semeniuk 2011). The geology and geomorphology of the Kimberley is also very complex, influenced by ancient folded and faulted Proterozoic metasedimentary and igneous rocks, resulting in an extremely irregular and indented ria coastline (Tyler et al. 2012). During the Quaternary, tectonism in terms of subsidence has been significant (around 0.11 m/ky during the last 18 ky. Solihuddin et al. 2015), determining much of the modern landforms and shore marine biota (Sandiford 2007). The progressive drowning of the inner shelf of the region has determined, in particular, the development of coral reef systems. The sea level oscillations during the Last Interglacial and Holocene have also conditioned the reef growth (Wilson 2013; Collins et al. 2015; Bufarale et al. 2016).

Despite been recognised as one of the most important biodiversity hotspots worldwide (Wilson 2013), the extensive onshore coral reef systems remained very poorly studied until 2013, when the Western Australian Marine Science Institution (WAMSI) developed the Kimberley Marine Research Program (KMRP) Science Plan. This research plan aimed to improve the understanding of the marine environment of the Kimberley and close the gap in the scientific knowledge of this area. Since then, a total of 26 projects have been studying different aspects of the biology, geology and ecology in the Kimberley coastal region (WAMSI 2012). This paper summarises the research that was undertaken to investigate the stratigraphic and geomorphic evolution and distribution of several Kimberley reefs and determine their interaction with different substrates, morphological patterns and coastal processes (WAMSI Project 1.3.1).

Materials and methods

The research used a combination of three different methods. *Remote sensing data* were used to map the geomorphological surface cover of the Kimberley Reef and evaluate their extension, in order to create a geodatabase of the main reefs, together with a new reef classification scheme specific for this area. *Geomorphic surveys* aimed to study the

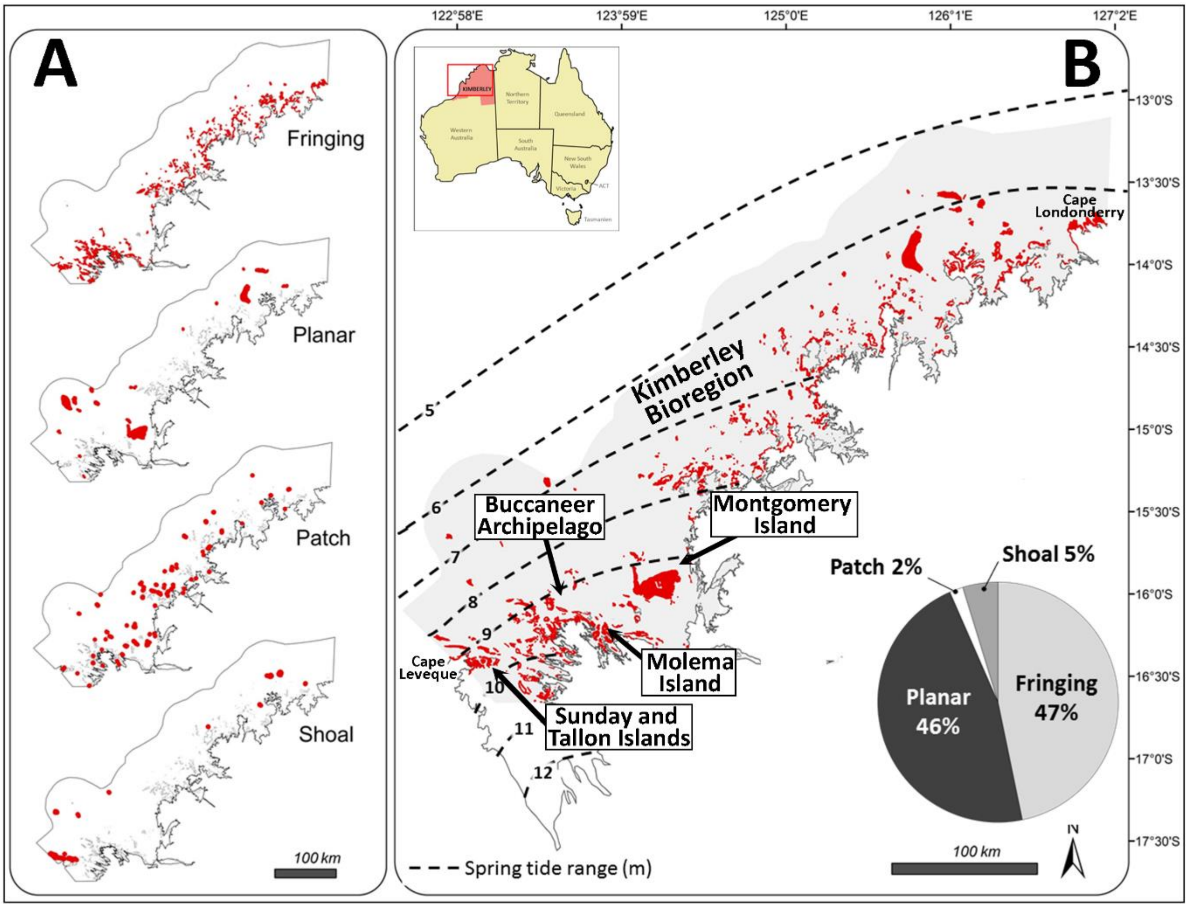

Fig. 1 A) Reef distribution in the Kimberley Bioregion by type: fringing; planar; patch; and shoals. B) Distribution map of reefs with spring tidal range contours (modified after Kordi and O'Leary 2016b). The reefs seismically surveyed in this study are labelled. The inset shows the percentage of each reef type

geomorphology, elevation, composition and age of selected reefs. *Coring and seismic surveys* determined the reef architecture and thickness and determined the growth pattern and stages of reef buildups.

Remote sensing analysis

Aerial and satellite images were used to produce classification maps of the reef flat geomorphology and substrates and spatial distribution maps of the Kimberley reefs and islands (Kordi and O'Leary 2016a; 2016b). Using GIS Software (Geographic Information System; ArcGIS® by Esri) and ENVI 4.3 Software, unsupervised classification was performed in order to produce consistent data. Existing literature on Kimberley reefs (particularly from Wilson et al. 2011; Richards et al. 2013 and WA Museum Woodside

Collection 2008 – 2012), combined with the information collected during this research project, provided the necessary ground truth information (Kordi et al. 2016).

Geomorphic surveys

Access to a complete record of coral growth was possible thanks to two large iron ore pits on Cockatoo Island (Buccaneer Archipelago. See location in Fig. 1), which have left exposed the whole coral reef stratigraphy and pre-existing substrate to depth of approximately 50 m below sea level. Solihuddin et al. (2015) logged, sampled and recorded the main stratigraphic information (reef framework / matrix ratio, texture, coral identification, matrix carbonate content) of two complete vertical and horizontal sections. These data were compared and correlated with the coral distribution along the reef flat and fore-reef slope of the fringing reef that rims the island, using towed camera and visual observations.

Samples for radiocarbon dating were also collected, in order to establish a geochronology of the reef growth.

Reef elevation was measured using an Odom ES3 multibeam echo sounder combined with a Valeport sound velocimeter, a TSS 355B motion sensor and an iX Blue Octans gyro compass. A Differential Global Positioning System (DGPS) Trimble Net R9 provided accurate positioning (±2 cm).

Seismic and coring surveys

About 300 km of high-resolution shallow seismic data were acquired, using an AA201 boomer SBP system (Applied Acoustic Engineering Limited, Great Yarmouth, UK), combined with a DGPS Fugro SeaSTAR 8200 XP/HP. The seismic profiles were digitally recorded using SonarWiz 5 (Chesapeake Technology Inc., Mountain View, CA) as acquisition and post-processing software.

The information provided by the Cockatoo Reef study (from Solihuddin et al. 2015) provided a calibration for the acoustic datasets. The reef proximal to the mine pits of Cockatoo Island was examined in detail, serving as a base for the seismic correlation. Within the Buccaneer Archipelago, the neighbouring reefs of Irvine and Bathurst Islands were also surveyed to verify the consistency of the seismic correlation. Montgomery Island was selected as special type of planar reef. Molema, Sunday and Tallon Islands were targeted because of their variety of fringing reef types (see location in Fig. 1). The survey lines were planned to target the orientation, internal architecture and morphology of the reefs.

A total of 42 cores, along the seismic lines and up to 6.5 m long, were obtained by percussion coring and rotary drilling. The sediments were logged and dated using the same parameters adopted for the mine pit samples (from Solihuddin et al. 2016).

Results

Classification and distribution maps

High-resolution images, combined with other relevant data (such as bathymetric charts and ground-truth information) were used by Kordi et al. (2016) to map the extent of the Kimberley coastline and quantify the distribution of reefs and islands. More than 800 nearshore reefs and 2400 islands were recorded, along 5300 km of coastline (Fig. 1), between Cape Leveque and Cape Londonderry. A total of 30 reefs were mapped in detail, producing as many geomorphic maps. In each map five reef geomorphologic zones were

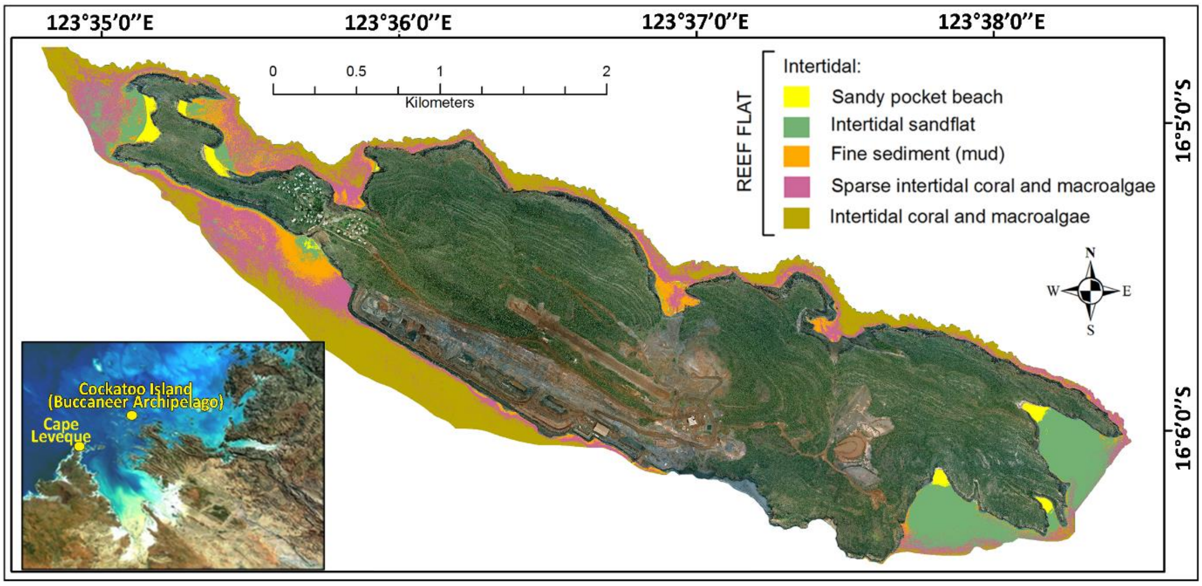

Fig. 2 Map showing Cockatoo Island geomorphic and substrate classification, based on aerial photography interpretation (modified after Solihuddin et al. 2015). Inset: Landgate photography provided by the Department of Parks and Wildlife (DPaW

defined (land, reef flat, lagoon, reef crest and fore-reef slope, see example in Fig. 2). Habitats and substrates maps were also drawn, recording up to seven feature classes (mangroves, sand, seagrass and algae, coral rubble, reef pavement with algal turf, crustose coralline algae and coral communities).

Geomorphology and geochronology

Solihuddin et al. (2015) documented the lithostratigraphic and chronostratigraphic history of a coral reef exposed in mine pits at Cockatoo Island.

Stratigraphic and palaeoecological data, combined with radiometric dates revealed that the lower section of the mine pit is composed of Proterozoic Elgee Siltstone, which represents the basal substrate for the successive reef deposits (Solihuddin et al. 2015). Atop the basement, a thin layer (1–2 m) of sedimentary talus breccia and haematite boulders is present. Overlying the haematitic breccia, a sandy coral-rich unit, up to 7 m thick, can be recognised. Dating revealed that the growth of this buildup (mainly composes of Faviids domal corals) initiated during the Last Interglacial highstand (Solihuddin et al. 2015). Above this ancient reef formation, a second, thinner, haematite boulder breccia layer divides this unit from an additional reef unit. This shallower reef buildup is at least 9-13 m thick and characterised by muddy domal and branching coral framestone (mainly coral clasts of *Acropora* and *Porites*), with several fragments and whole molluscs (Solihuddin et al. 2015). Results from radiocarbon dating indicated that these are Holocene corals that started colonising the pre-existing topography approximately between 9070 and 8840 years ago.

Towed camera observations provided information about the living reef. Similarly to the mine pit findings, *Porites* and *Faviids* are the most abundant genus, along with *Sargassum* and *Millepora* which are not present in the fossil record.

Coring surveys conducted on the reefs of Tallon Island, Sunday Island and Irvine/Bathurst islands extended the study on reef flat habitats undertaken at Cockatoo Island (Solihuddin et al. 2016). Multibeam echo sounding surveys recorded and measured the seabed elevation, providing further information about these reefs. Low intertidal reefs, where reef flat elevation is approximately mean low water spring, are largely composed of coral colonies and coral fragments in a muddy to sandy matrix. High intertidal reefs, which have a reef flat elevation between mean low water neap and mean high water neap, are dominated by coralline algae terraces.

Internal reef architecture

The post-processing of the seismic profiles showed that the stratigraphy underneath the modern reef flats is characterised by two main units (U1, U2), overlaying the rock foundation (RF). During the analysis and interpretation of the seismic datasets, the seismic reflectors that define U1 and U2 were considered on the basis of their relative vertical and lateral position and reflection characteristics. The distinctive features of each main reflector can be recognised across the study area and be identified through the correlation with the Cockatoo mine pit sections (Table 1).

Table 1 Facies identified in the seismic profiles

Seismic unit	Limits	Thickness	Internal structure	Correlation with mine pit stratigraphy
U1	Seafloor to R1	Variable: 7-22 m	*Under the reef platform*: hard and locally moderately layered (sub-reflectors H1, H2 and H3), locally chaotic.	*Under the reef platform*: Holocene reef
			Elsewhere: very well-layered, with parallel to subparallel continuous laminations	*Elsewhere*: sediment bodies
U2	R1 to RF	Variable: 7-12 m	Mainly without internal structure; locally with discontinuous, sub-parallel minor reflectors	LIG reef
Basement	RF-NA	NA	Laminated to massive, locally chaotic. Valley-like depressions and ridges recognisable	Proterozoic metasediments

Discussion

These new datasets provided a better understanding of Quaternary reef growth in the Kimberley region of Western Australia. Some of the key interacting factors in coral reef classification and growth include morphology, physical processes, antecedent topography and sea level change. By developing an understanding of seismostratigraphic events, it has been possible to document the subsurface evolution and growth history of diverse reefs in the Kimberley, at the scale of multiple reef building stages correlated to the Marine Isotope Curve. The seismic unit U1 bounded by the seafloor and reflector R1 represents the Holocene reef/sediment buildup (Fig. 3). Between the Proterozoic rock foundation (RF) and the

Holocene reef buildup, the Pleistocene calcretised reef unit, related to the Last Interglacial (LIG, MIS 5e, ~ 125 ky BP) sea level highstand, is present (Bufarale et al. 2015; Collins et al. 2015; Bufarale et al. 2016).

A comprehensive geodatabase (*ReefKIM*) was proposed to organise and integrate the results obtained through the remote sensing analysis and stratigraphic and seismic surveys, together with a new reef classification scheme specific for the Kimberley Bioregion.

ReefKIM Geodatabase

All the project' findings about the spatial distribution of reefs and islands, the habitat/substrate classification maps and the geological and biological datasets available for the Kimberley reefs were georeferenced and integrated together to create ReefKIM, a data fusion geodatabase (Kordi et al. 2016). This GIS-based database can be considered a significant conservation and decision-support method under several aspects. For instance, it provides researchers with an overview of essential information on many Kimberley reefs, especially those considered "atypical" and it can be used as a main platform for further reef census data. ReefKIM can also be updated with a variety of types of marine environment-related information, sourced from different studies and works in the Kimberley Bioregion including crowdsourcing (Kordi et al. 2016).

Kimberley reef classification scheme

A number of reef classifications based on geomorphic attributes are present in literature (i.e. Fairbridge 1950; Hopley et al. 2007; Wilson 2013) but they all lack the information to enumerate the high intertidal reefs, which are a unique feature of macrotidal reefs and

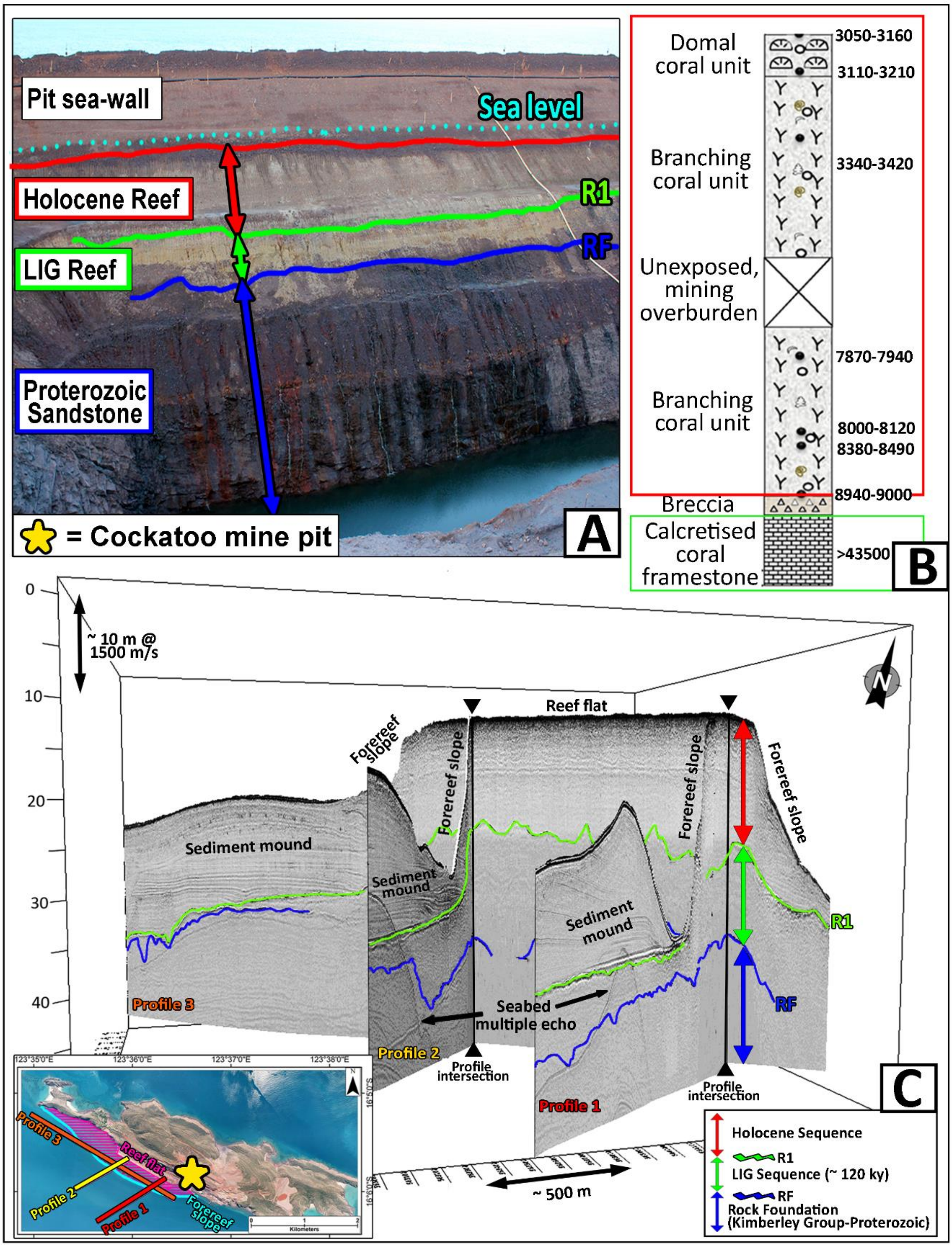

Fig. 3 A) Cockatoo mine pit section looking south west (Photograph credit: Solihuddin T., 2013). The marked lines represent: top of the Holocene reef (red), top of Last Interglacial reef (green) and top of Proterozoic rock (blue). Modified after Collins et al. 2015 and Bufarale et al. 2016. B) Reef lithostratigraphic column, with radiocarbon ages (Solihuddin et al. 2015). C) Intersecting cross-sections (Profiles 1 and 2) and distal longitudinal section (Profile 3) of seismic profiles adjacent to the mine pit. Depth values are in metres, below the sea level. Inset: Landgate aerial photography provided by DPaW

characteristic of the Kimberley. In order to include this highly-specialised type of reef recognised by Wilson (2013) and confirmed by Solihuddin et al. (2016), a revised reef geomorphic classification scheme, specific for this project, was proposed by Bufarale et al. (2016). The classification comprises a hierarchical subdivision of the reefs. In the first order the reefs are divided into high intertidal, intertidal and subtidal on the basis of their elevation. The second rank is based on reef geomorphology and comprises fringing reefs, planar reefs, patch reefs and shoals. The third level further subdivides each reef type according to their configuration in relation to the shoreline and architecture. In this level, five main types of fringing reef are described (bay head, interisland, circum island, headland and narrow beach base) and two for each other reef (planar reefs: sand lagoon or coralgal; patch reefs: irregular or unbroken margins; shoal: sand or coral. Bufarale et al. 2015).

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