Article Title:

Geomorphic Classification of Coral Reefs in the North Western Australian Shelf.

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Abstract

Coral reefs occur extensively along the northwest Australian continental shelf in the Kimberley Bioregion (KIM), forming major geomorphic features along and just off the coast. These reefs have not been studied in as much detail as the offshore reefs and are poorly known due to the coastal conditions, including extremely high tide regimes, high turbidity and complex coastline morphology. This study aims to establish a regional-scale distribution map of exposed and intertidal reefs of the KIM and to classify the Kimberley reefs into types, adopting widely recognised reef classification and typology schemes. Remote sensing and Geographic Information Systems (GIS) were used in this study to process and produce digital maps as well as to provide some of the first detailed spatial analysis of reef distribution. Outcomes of this study showed that the Kimberley reefs possess strong morphological complexity and clear regional patterns. The study revealed that the number of Kimberley reefs and their area are considerably (60%) greater than previously thought; the total combined reefal area is approximately 1,950 km^2. Fringing reefs have been identified as the dominant reef type and are widely distributed throughout the KIM. It was also found that tidal range affected the distribution of reef geomorphologies. The outcomes of this study will contribute to a better understanding of the Kimberley reefs, and provide marine park managers with essential and quality scientific information so that better management decisions can be made in this area.

Keywords
Kimberley Bioregion; coastal management; continental shelf; reef mapping; remote sensing; GIS

1 Introduction

1.1 Reef Mapping and Classification

Coral reefs are widely distributed through the world's tropical oceans and commonly rise abruptly from relatively deep water creating a major navigational hazard, but can also provide a safe anchorage. There are many famous examples of ships running aground on coral reefs, the wrecks of the VOC ship Batavia in 1629 and the HMS Pandora in 1779 being just two notable Australian examples (Green, 1975; Edwards *et al*., 2003). The increase in international shipping during the 18th and 19th century saw maritime nations and international trading companies seek ways to reduce shipping losses through improved charting, but also sought a scientific understanding of where reefs are likely to be encountered and how they form. In fact few questions in 19th century science aroused more controversy than the origin of coral reefs. So when HMS Beagle departed in 1831 on its 5-year journey of discovery around the world, it not only carried a young Charles Darwin but also secret instructions from the Admiralty requiring a detailed geological investigation on how coral reefs formed.

The result was that in 1842 Darwin published *The Structure and Distribution of Coral Reefs,* the first of three major monographs arising from observations and data he collected during his voyage on the Beagle. This monograph put forth the theory of atoll formation through island subsidence and included the first detailed map of the distribution of different kinds of coral reefs through the Indo-Pacific and Caribbean region. This map represents the first global census of coral reefs and presented the first geomorphic reef classification scheme which is still in use today. Joubin (1912) expanded Darwin's original reef census by producing a series of five 1:10,000,000 scale reef maps covering the entire globe. His work combined existing survey charts as well as observations and voyage reports from a range of sources.

Following Joubin's work, there was almost no other attempt to systematically map coral reefs on a global scale until the launch of the Landsat series of satellites in the 1970's, which for the first time allowed the detection of coral reefs using moderate-resolution satellite imagery (Jupp *et al*., 1985), and the opportunity to map reefs globally. Most recently, the United Nations Environment Program (UNEP) funded the Global Reef Monitoring Network (GRMN) and the International Coral Reef Action Network (ICRAN) to build and maintain a global reef GIS database *ReefBase*, which provides a repository for available knowledge about coral reefs. The Millennium Coral Reef Mapping Project is using a suite of high-resolution spaceborne remotely sensed imagery systematically map and classify coral reefs worldwide (IMaRS-USF and IR, 2005; ReefBase, 2015).

The development of a geomorphic classification of coral reefs has been closely linked to the improvement of reef mapping techniques (Kordi *et al*., 2016). For instance, the three basic classes of reef include fringing, barrier, and atoll were identified by Darwin (1842) and formed the basis for his global map of coral reefs. In the 1920s, the advent of aerial photography allowed coral reefs to be viewed in plan view, allowing for a more detailed analysis of spatial characteristics of reefs and mapping their features in greater detail. The pioneering geoscientific work on Australian reef classification was conducted by Fairbridge (1950, 1967), who recognised the role of antecedent topography, eustasy, and physical processes in generating reef morphology, first working on the Great Barrier Reef (GBR) and later on the reefs of northern Australia, including the Kimberley coast (Finkl, 2011). Subsequently, as knowledge of reefal processes increased, Hopley (1982) was able to develop an evolutionary reef classification scheme for the GBR. Accordingly, reef classification and reef typology at the global, regional and reefal scales have been dramatically improved (Andréfouët *et al*., 2006; Hopley *et al*., 2007; Leon, and Woodroffe, 2013; Madden, et al., 2013; Roelfsema et al., 2013; Rowlands *et al*. 2014).

There are still many reef regions of the world where the accurate numbers and extent of coral reefs are underestimated or unknown. One such area is the Kimberley bioregion of north-west Australia where there have only been a limited number of global scale mapping efforts that have advanced our understanding of reef formation and growth, as well as providing information for monitoring of coral reef health and to support informed decisions about coral reef use and management in this region (Spalding, 2001; Wilkinson, 2008), but they still lack the resolution required to provide realistic reef census data at regional and local scales. Despite efforts that have been made to fill this gap, no significant spatial map detailing the size and distribution of the Kimberley reefs and their attributes exists.

1.2 North west Australian reef systems

The Reefs of North West Australia occur within two distinct bioregions, the shelf edge Oceanic Shoals bioregion (OSS) and the inner shelf Kimberley bioregion (KIM) (Figure 1). The OSS, which includes the Rowley Shoals and Scott Reef have seen significant scientific investigations, due in part to their proximity to the Browse Gas Fields. In particular, the morphology and growth history of these reefs have been examined using a number of methodologies such as coring, U-series dating and vertical seismic profiling (Collins, 2011; Collins *et al*., 2011).

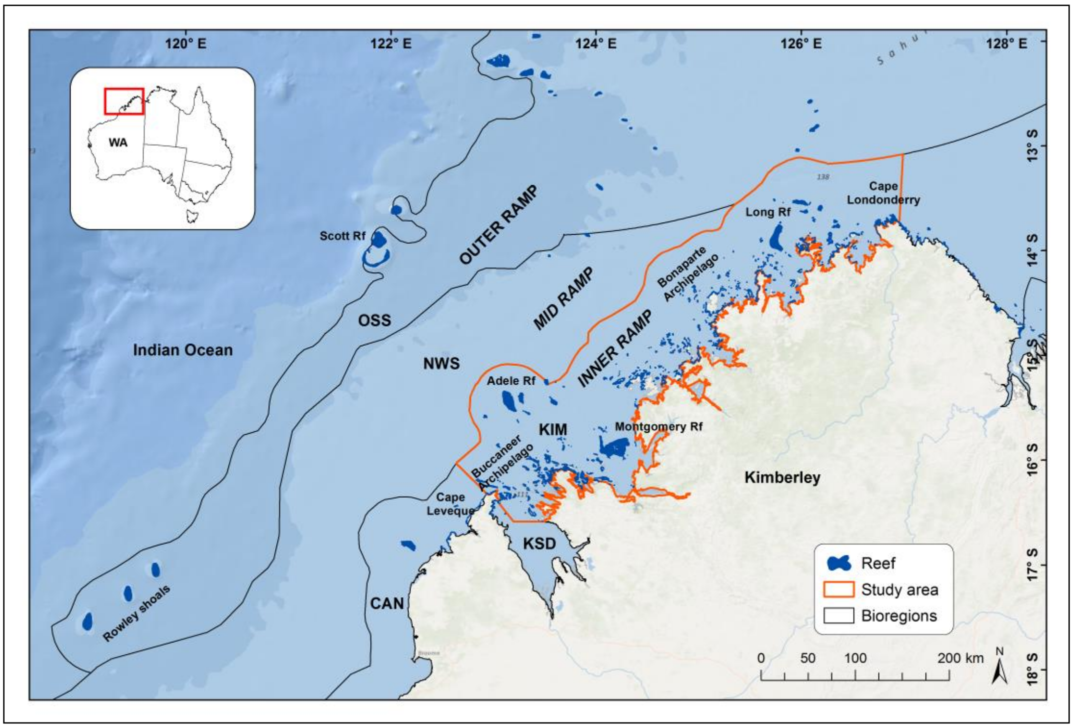

Figure 1. Map of the North West Shelf (NWS) showing the spatial distribution of reefs, bioregion boundaries and the continental shelves (ramp) subdivision. Boundaries of the study area, the Kimberley bioregion (KIM), is highlighted with red lines. The Oceanic Shoals bioregion (OSS) and the North West Shelf bioregion are at the seaward margin of the KIM. The King Sound bioregion (KSD) and Canning bioregion (CAN) are at the south of the KIM.

The inner shelf reefs of the Kimberley have seen limited scientific study due in part to the geographic remoteness of the region and limited infrastructure. Early investigations by Teichert and Fairbridge (1948) noted that fringing reefs exist around the margins of many islands in the region, despite the normally unsuitable environment for coral build-up, including high sediment input, macrotidal regimes, highly turbid water and raised sea surface temperatures. Wilson (1972) and O'Conner (1989) observed reefs in the intertidal zone between shallow rocky shoals, along muddy shores, and in some bays. Geographic and geomorphic estimation of reef location, thickness, and reef area was provided by Brooke (1997), who demonstrated that fringing reefs were widespread along the Kimberley coast and could be classified into three reef forms: fringing reefs adjacent to a cliffed shore; reefs developing on bedrock edges; and large reef complexes. Latest studies of Montgomery Reef and Talbot Bay by Wilson (2011) and Wilson *et al*. (2011) revealed the unique nature of these reefs and their habitats and substrates and documented the relationship between the unique physical processes and reef geomorphology. Despite these studies, there are still many unknowns in our understanding of the Kimberley reefs.

This study intends to provide a spatial analysis of fringing and nearshore reefs along the Kimberley coast. The spatial approach is expected to lead to an analysis of the reefs' geomorphologic patterns, new information about reef statistics, and to a description of reef classification and distribution by type. The resulting data will provide a reliable, spatially constrained dataset for biodiversity assessment and reef structure comparisons. It will also provide stakeholders and beneficiaries, such as marine park authorities, universities, Traditional Owners, and non-governmental organization (NGOs) with quality information relevant to the monitoring, conservation, and management of these vital natural resources. Furthermore, it will pave the way for future studies in various disciplines beyond the scope of this study

2 Methodology

2.1 Study area

The KIM covers a massive area 60,000 km^2, stretching from Cape Londonderry (13˚S) in the north to Cape Leveque in the south (16°S). The KIM coast is characterised by deep inlets, capes and archipelagos forming a very complex coastline (Figure 1). It has extensive fringing coral reefs that exceed the Ningaloo Reef in their biological diversity and it supports a huge range of marine habitats (DEC, 2011). In some parts of the Kimberley coast the spring tide reaches more than 11m, making it the highest tidal range of any coral reef system in the world and the second largest tide after Fundy Bay in Canada (Purcell, 2002; Wolanski and Spagnol, 2003). Kimberley coral reefs are the main geomorphic feature along the continental shelf between the latitudes of 12°S and 18°S (Collins, 2011). Currently, activities such as oil and gas extraction, mining, and tourism are increasing in this region, necessitating timely management to protect the marine environment (Wood and Mills, 2008).

2.2 Datasets

There are two groups of datasets that have been utilised in this study: input datasets and derived datasets. The input datasets, including satellite images, orthophotographs and bathymetric charts, were acquired from different sources, whereas the derived datasets were extracted mainly from these input datasets (Table 1). All input datasets were assembled, georeferenced and projected to the coordinate system of Australia (Geocentric Datum of Australia GDA94) using ESRI’s ArcGIS 10.

Table 1. Datasets and their sources that have been used in this study.

	Datasets (raster)	**Sources**	**Resolution**
Input datasets	*a)* Satellite images		
	- Landsat 5 (TM)	The United States Geological Survey (USGS)	30 m
	- Landsat 7 (ETM+)	The United States Geological Survey (USGS)	30 m
	- Landsat 8 (OLI)	The United States Geological Survey (USGS)	30 m
	b) Orthophotographs	Landgate, Western Australia	0.6 m
	c) Bathymetric maps	Geoscience Australia (GA),	vary

		Australian Hydrographical Office (AHO)
	Datasets (feature classes)	**Description**
Derived datasets	Reefs	Major reefs occurred along the KIM including reefs size, shape and types.
	Coastline	Land-water boundary mapped using the Mean Low Water Neap (MLWN) level to ensure that mangroves and reef flats are not included on the land.
	Islands	Islands, islets, exposed rocks and cays of the KIM as defined by the Geoscience Australia.

2.3 Field surveys

Ground-truth data, which included field surveys, observations and georeferenced field photographs for more than 2,500 points, were collected between 2009 and 2014 from primary and secondary sources using handheld GPS devices (WA Museum Woodside Collection Kimberley Project, 2009–2012; Wilson and Blake, 2011; Wilson *et al*., 2011, WAMSI 1.3.1 Reef Geomorphology Project, 2012 - 2015; Solihuddin *et al*., 2015) These observations, were made on various dates, encompassed descriptive geomorphological information, habitats and substrates, and were used as reference data for validation purposes.

2.4 Geomorphic classification of the Kimberley reefs

A reef evolutionary or genesis model developed by Hopley (2007) has not been incorporated in this study, due to the simple fact that unlike the Great Barrier Reef, Kimberley reefs have not received the same level of geological and geomorphological investigation. Instead a geomorphological typology classification scheme using a simple hierarchy (*i.e.* primary, secondary and tertiary) of geometric criteria (Figure 7) has been developed for the Kimberley reefs, using the same categories as in Hopley, 1982 and Hopley *et al*., 2007.

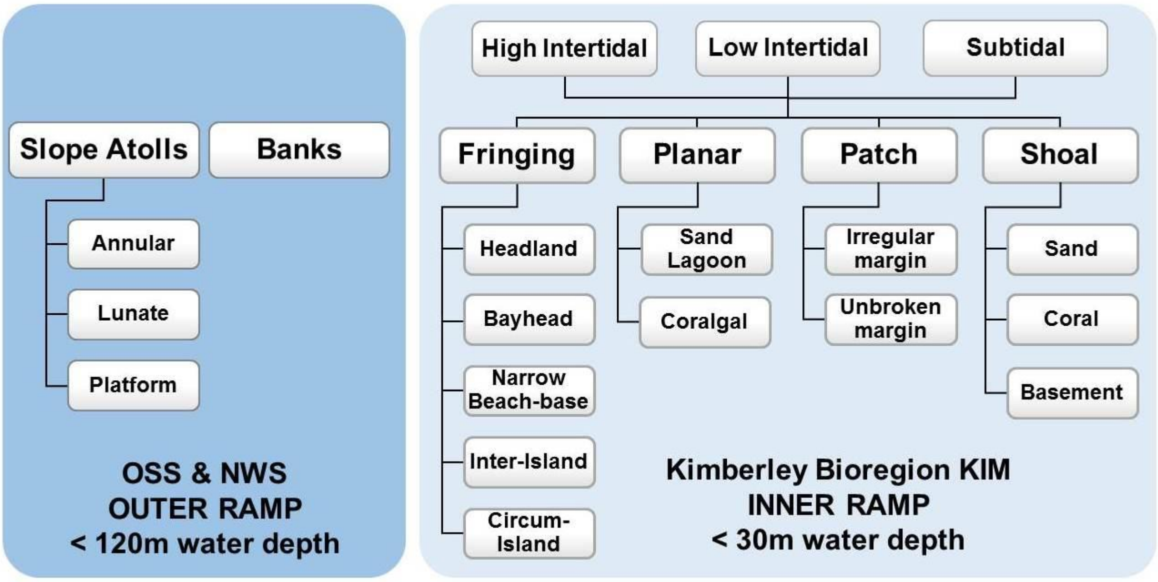

Figure 2. A geomorphological typology classification scheme of the North West Shelf. The left section represents reefs from mainly the Oceanic Shoal bioregions (OSS) and partially from the North West Shelf bioregion (NWS). The right section represents reefs of the Kimberley bioregion (KIM).

2.4.1 Oceanic shoals bioregion

The continental margin of the Kimberley has a ramp-like profile that can be subdivided bathymetrically into an outer, mid and inner ramp (James *et al*., 2004). The outer ramp (>120m water depth) has a relatively steep seaward slope and corresponds to the OSS bioregion. Reefs here are tower-like, rising from an old Miocene shoreline, with heights of 200–400 m above the seafloor, and consist of multiple stages of Pleistocene to Holocene reef growth stages separated by hiatuses (Collins *et al*., 2011). Termed 'slope atolls' by Wilson (2013), their morphologies include annular (*e.g.* Mermaid Reef at Rowley Shoals (Figure 8b)), lunate (*e.g.* south Scott Reef (Figure 8a)), and platform (*e.g.* Ashmore Reef (Figure 8c)) types. Similar submerged forms, in which *Halimeda* is a significant sediment contributor, are termed 'banks' by Heyward *et al.* (1997) and Wilson (2013); these occur to the north on the Sahul Shelf. The OSS bioregion is included here for comparative purposes, but the focus of this study is on the KIM.

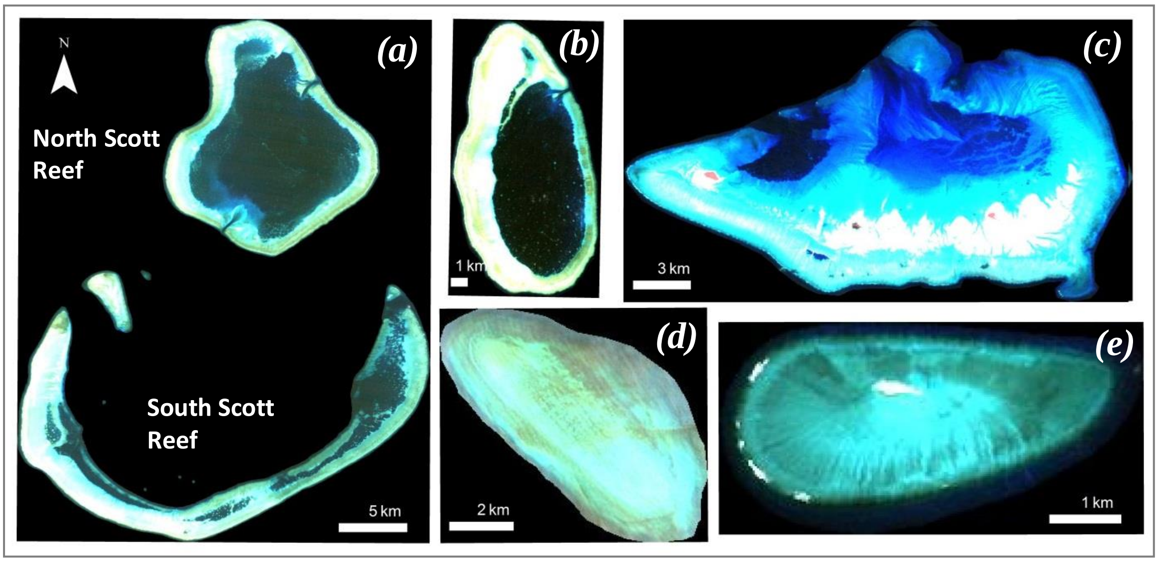

Figure 3. Morphology of slope atolls of the outer ramp and OSS bioregion. Examples of slope atolls are: annular reefs *(a)* North Scott Reef and *(b)* Mermaid Reef; lunate reefs *(a)* South Scott Reef; platform reefs *(c)* Ashmore Reef and *(e)* Cartier Reef; banks *(d)* Heywood Shoal.

2.4.2 Kimberley bioregion

The primary level of the geomorphological classification scheme shown in Figure 7 represents reef flat elevations against a tidal datum. The first category is *high intertidal reef*, where the reef flats are situated above the mean low water neap (MLWN) tidal level. The second category is *low intertidal reef*, where the reefs flats are situated between the level of the mean low water spring (MLWS) and MLWN tidal levels. The third category is *subtidal reef*, which is situated below the MLWS level. The secondary level is based on descriptive morphological characteristics and include fringing, planar, patch and shoal reefs. The tertiary level divides each reef type into subclasses based on more detailed reef geometry and substrate type, these reef classes are described below.

Fringing reefs

Fringing reefs are well developed and widespread throughout the Kimberley and vary in shape and size, and can be found along both the mainland and islands coasts. The majority of fringing reefs in the KIM can be further classified into five subclasses which include: (1) Headland, (2) Bayhead, (3) Narrow Beach Base, (4) Inter-Island and, (5) Circum-Island. Several of these classes, resemble the fringing reefs of the GBR that were identified by (Hopley *et al*.) 2007 with some modifications (Figure 9).

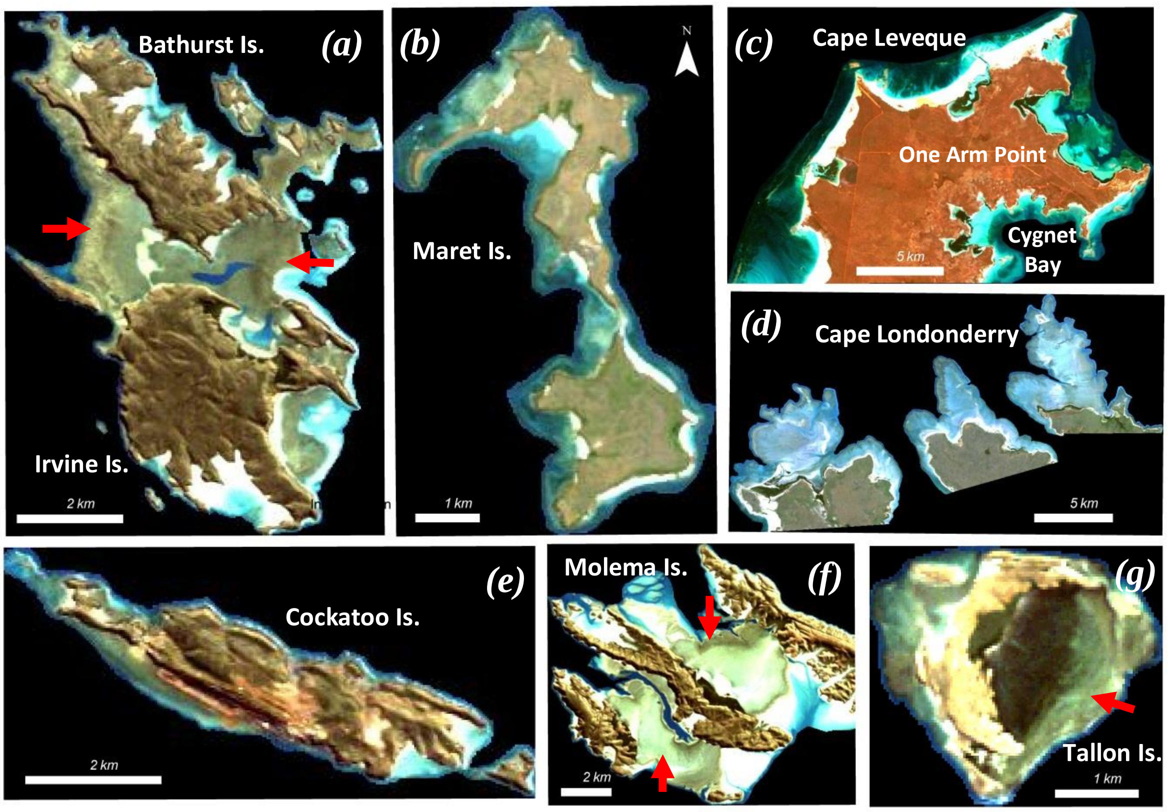

Figure 4. Morphology of fringing reefs of the KIM bioregion. Examples of fringing reefs: **(1)** high intertidal fringing reefs (reefs are indicated by red arrows) *(a)* reef between Bathurst and Irvine Islands, *(f)* Turtle reef north and south Molema Island and *(g)* reef on the eastern side of Tallon Island; **(2)** low intertidal headland fringing reefs *(b)* reefs on NW Maret Island and *(d)* Cape Londonderry; low intertidal bayhead fringing reefs *(a)* reefs on SE Irvine Island and *(c)* reefs on Cygnet Bay S One Arm Point; low intertidal headland fringing reefs on narrow beach base *(c)* reefs on sandy beach N One Arm Point; and low intertidal circum-island fringing reefs *(e)* reef around Cockatoo Island.

1. *Headland* fringing reefs are found on many islands and mainland coasts. They are mainly developed on rocky intertidal shores that are often exposed to prevailing ocean swells and waves generated by passage of cyclones (*e.g.* reefs on NW Maret Island (Figure 9b)) and reefs on Cape Londonderry (Figure 9d)).

2. *Bayhead* fringing reefs also occur on many islands and mainland coasts. They are developed in embayments and advance toward the head of the bay (*e.g.* reef on SE Irvine Island (Figure 9a); reef on Cygnet Bay (Figure 9c; and reef on E Tallon Island (Figure 9g)).

3. *Narrow beach-based* fringing reefs are frequently found on island shores and occasionally on mainland shores. They are developed along extended sandy coasts (*e.g.* reefs on E Maret Island (Figure 9b); and reef on N One Arm Point (figure 9c)).

4. *Inter-Island* fringing reefs are developed between two or more high islands and/or a peninsula. These islands are connected together by their fringing reefs. This type of fringing reef is largely found toward the southern end of the KIM (*e.g.* reef between Bathurst and Irvine Islands (Figure 9a); and Turtle reef which connects Molema Island and other Islands to the south; and northward, Molema Island to a peninsula (Figure 9f)).

5. *Circum-Island* fringing reefs are the most common type in the KIM. They are developed around high islands (*e.g.* Cockatoo Island (Figure 9e)).

Additionally, there are distinctive features of high intertidal fringing reefs that are common across these five subclasses. These is high intertidal flat-topped reefs with distinctive lithified algal terraces and coralline algae (rhodolith banks) which form coral filled pools during low tides, as well as Porites micro-atolls (*e.g.* reef between Bathurst and Irvine Islands (Figure 9a); Turtle reef on north and south Molema Island (Figure 9f); and reef on east Tallon Island (Figure 9g).

Planar reefs

The planar reefs of the KIM are mainly characterised by their large area and are situated some distance offshore. These reefs are considered senile, where the lagoon is either completely infilled or semi infilled and a reef flat extends across the entire reef platform. The reef flats are usually emergent at low tides and can have a central low island and/or a sand cay. Planar reefs can be divided into two subclasses based on substrate type: (1) Sand Lagoon and (2) Coralgal (Figure 10).

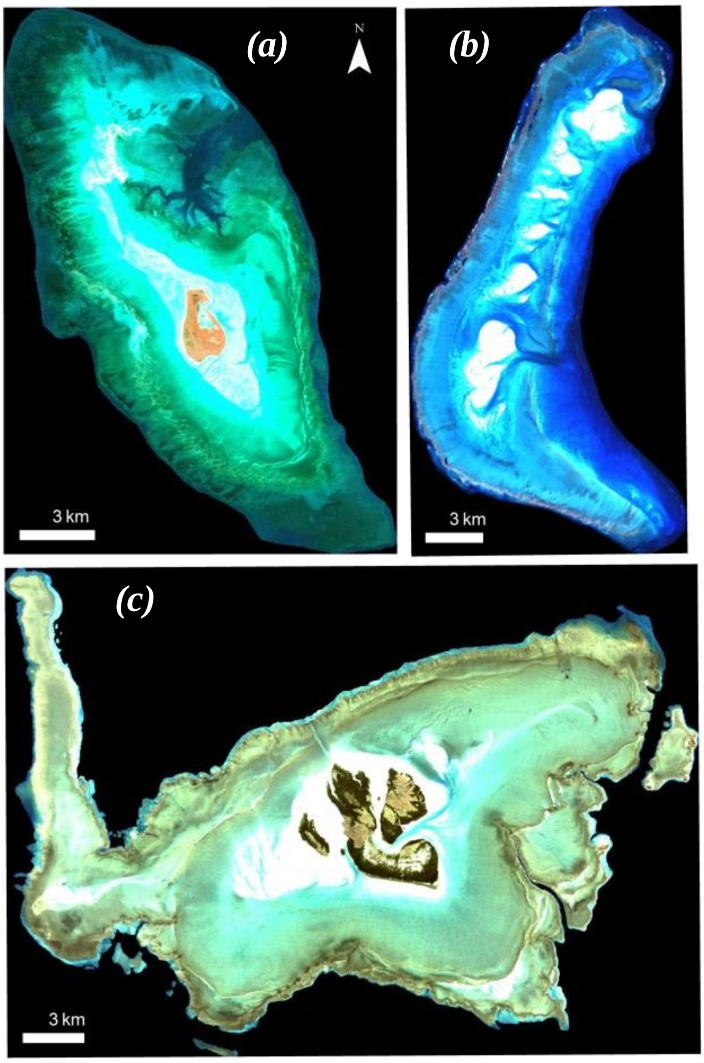

Figure 5. Low intertidal planar reef *(a)* Adele Reef and *(b)* Long Reef; and high intertidal planar reef *(c)* Montgomery Reef.

1. *Sand lagoon* planar reefs are the more common reef type with large areas of the central lagoon dominated by mobile sand sheets and sand filled lagoons, though it is not known whether these sand infilled relatively shallow or deep lagoons (*e.g.* Long Reef (Figure 10b)). Sand cays or vegetated sand islands can also be a characteristic feature.

2. *Coralgal planar* reefs are mainly found on larger reef platforms that have a central high island. They are characterised by distinctive lithified algal terraces and coralline algae (rhodolith banks) predominantly towards the edge of the reef flat (*e.g.* Montgomery Reef (Figure 10c). Some reef islands such as Adele Reef appear to show both coralgal and sand lagoon morphologies (Figure 10a)).

Patch Reefs

Patch reefs are mainly < 2 km in length. They can be divided into two subclasses based on perimeter geometry: (1) *Irregular margin* refers to patch reefs that have dentate or rugged edges; and (2) *Unbroken margin* refers to patch reefs that have circular, elliptic or regular edges (Fairbridge 1950, 1967; Hopley 1982).

Shoals

Shoals are submerged features and difficult to discern using airborne or satellite remote sensing techniques, therefore they were not catalogued as part of this study. However, they can be broadly divided into three subclasses based on dominant substrate types. The most common substrates that have been identified include (1) *Sand*, (2) *Reef,* and (3) *Proterozoic Basement*.

2.5 Coastline mapping approach

The Kimberley coastline has been mapped using a variety of different geomorphic and geological classification schemes (Teichert and Fairbridge, 1948; Brooke, 1997; IMaRS-USF and IR, 2005; ReefBase, 2015). However, most existing maps of the Kimberley coast were derived from low or moderate spatial resolution data sources. Furthermore, due to the macrotidal systems in this region, defining land-water boundaries marked by tides can be complicated and may not represent the shoreline in a geomorphic sense (*i.e.* Mangrove zones and sections of the reef flats are commonly classified as land on these maps). For this study, the marine-terrestrial boundary was remapped using the Mean High Water Neap (MHWN) level to ensure that mangroves and reef flats are not included on the land (Figure 2). A set of 24 orthophotographs that cover the entire KIM was used to accurately delineate the shorelines of mainland and nearshore islands. These orthophotographs were mainly in true colour composites (*i.e* RGB 321) and geometrically corrected, and had been acquired during MLWN tides. Although they usually do not have near infrared (NIR) bands as satellite images do, their spatial resolution is very high (< 1m) (see Table 1) and this resolution can bring out detailed features on the ground (Figure 2).

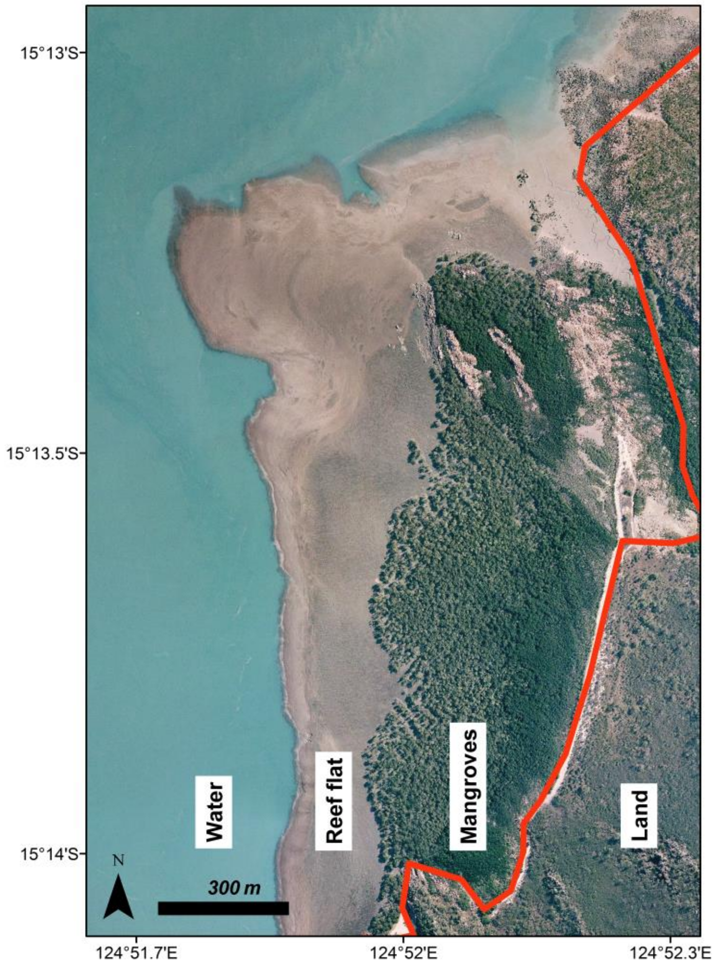

Figure 6. A high-resolution orthophotographs in true colour composite shows part of the geomorphic features of the coastline. The red line represents the coastline which has been accurately delineated in this study.

2.6 Reef mapping approach

The visibility of a reef depends on water clarity and exposure, however the extraordinary conditions of the Kimberley marine environment (*i.e.* extremely high tides and water turbidity) has the potential to prevent effective detection or mask reef features in this region. Hence mapping of reefs using remote sensing images alone was not going to be sufficient to detect the accurate number of reefs (Figure 3).

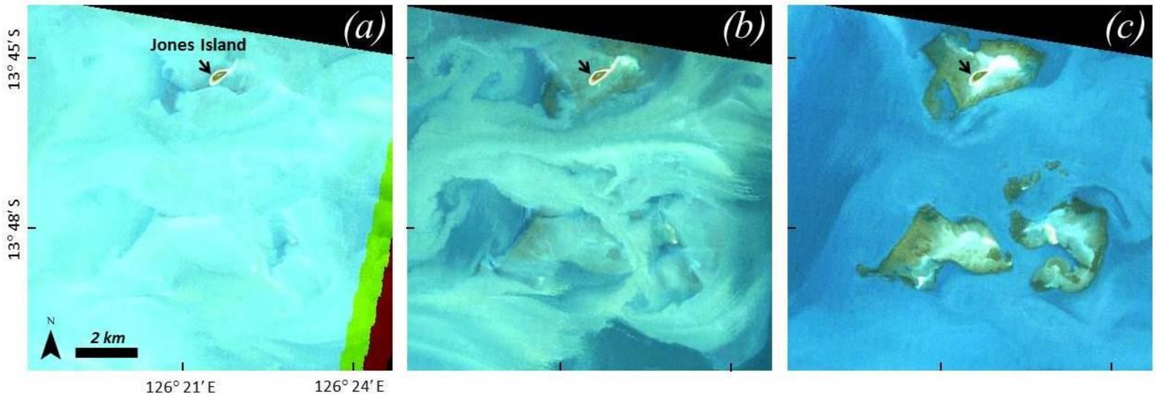

Figure 7. Landsat 5 TM images of reefs near Jones Island (north of the KIM) acquired on three different dates, *(a)* acquired in 30/04/2010 at extremely high tide (~ 6 m); *(b)* acquired in 17/01/2010 at high tide (~ 4 m); and *(c)* acquired in 21/10/2011 at low tide (< 2 m).

Accordingly, a mapping process was developed for this study in order to determine reef locations precisely (Figure 4). First, 18 bathymetric charts which cover the study area were used as a base map. Although the bathymetric maps do not present reefs and coastal features at a geomorphic standard, they are a good source of information on reef locations and water depth. Areas of interest, such as islands, reefs and shoals, were roughly delineated using ArcMap 10.1. The digitised map features were then stored in a vector format (Figure 4). Next, a dataset was developed using Landsat TM, ETM+ and OLI images at a consistent ~30 m resolution and using the visible (RGB) and near infrared (NIR) bands. More than 60 scenes covering the entire study area were acquired between 2000 and 2014. Regardless of the cloud cover, reefs could be detected on sections of the images that has no cloud cover because each scene covers a relatively large area (170 km north-south x 183 km east-west). However, mapping of reefs using satellite images is restricted to shallow areas (< 10 m for nearshore reefs and < 30 m offshore reefs) (Kordi and O'Leary, 2016). These data were then validated using ground truth and very high resolution orthophotos. Remote sensing images and digitised map features were imported to ArcMap 10.1 as data layers (Figure 4). Remote sensing images were then used as a base map and reef polylines were overlaid on these images to allow visual identification of coral reefs. Masking algorithms were applied using NIR bands to delineate islands and visible bands to delineate reefs. All detectable islands and reefs were accurately recorded and classified according to the reef classification that has been developed for this study. Moreover, a reef that has multiple features (*i.e.* comprising more than one polygon) is recorded in the GIS database as a single reef.

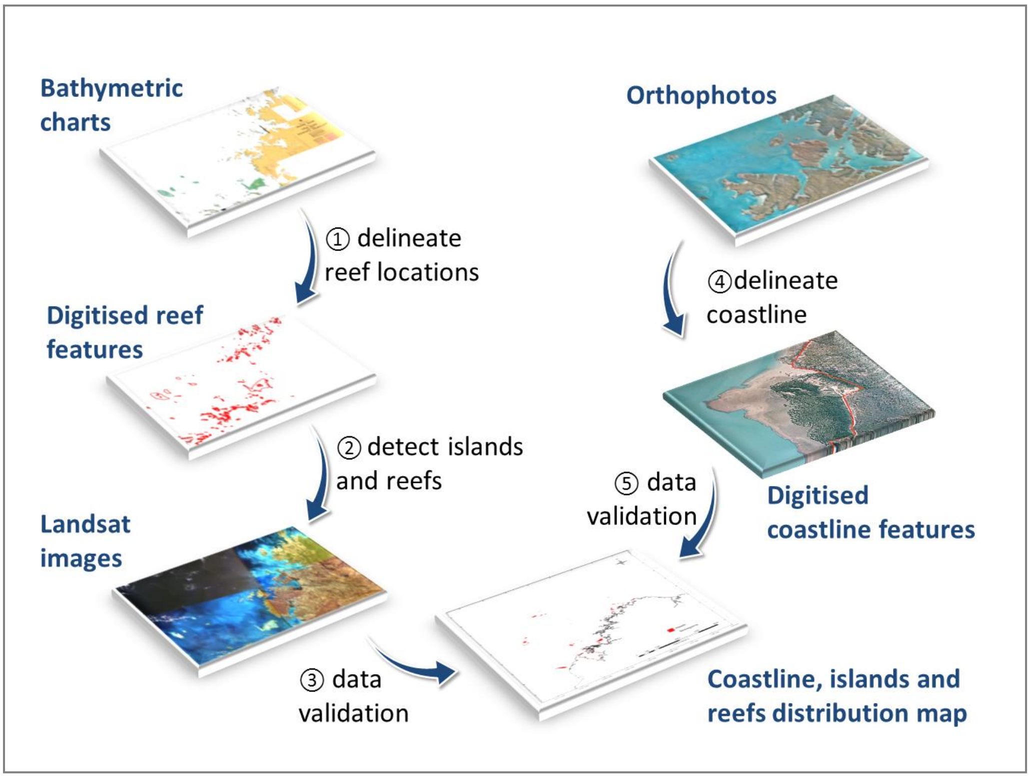

Figure 8. Methods employed to map locations and dimensions of the coastline, islands and reefs on the study area.

3 Results

3.1 Coastline, island and reef mapping

The geology of the Kimberley coast is characterised by a heavily jointed, faulted, and folded palaeo Proterozoic metasediment and volcanics which has resulted in a complex, highly discordant ria type coastline. The straight-line distance between Cape Londonderry and Cape Leveque is approximately 500 km, while the actual length of the coastline is 10 times longer, exceeding 5,000 km in length. However, if the lengths of island coastlines are taken into account, the total length of the Kimberley coastline is approximately 10,000 km (Figure 5).

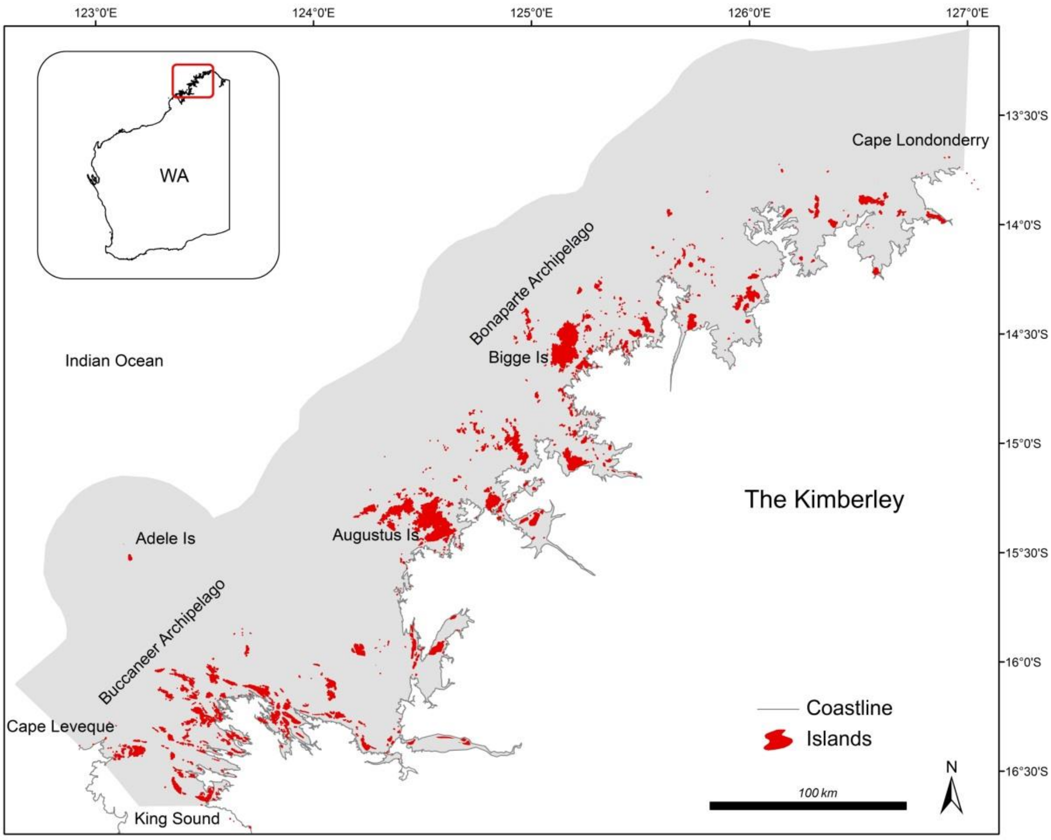

Figure 9. A digitised map shows the complexity of coastline features and island distribution along the Kimberley bioregion coast.

A total of 2,413 islands were mapped within the KIM, the vast majority being high rocky islands with only 31 low or reef islands recorded. Islands show significant geomorphologic complexity and spatial variability, with island numbers varying both latitudinally (Table 2) and across the shelf (Figure 6). Islands are primarily clustered into two main regions with about 40% of the islands situated between 14°S and 15°S near the mainland coastline and in the Bonaparte Archipelago, while the other group comprising about 36% of the islands is found between 16°S and 17°S in the Buccaneer Archipelago (Table 2).

Table 2. Number and percentage of islands by latitude across the Kimberley bioregion.

Latitude (S°)	Number	%
13° 30′ - 14° 00′	85	3.5
14° 00′ - 14° 30′	441	18.3
14° 30′ - 15° 00′	513	21.3
15° 00′ - 15° 30′	385	16.0
15° 30′ - 16° 00′	129	5.3
16° 00′ - 16° 30′	784	32.5
16° 30′ - 17° 00′	76	3.1
Total	**2,413**	**100**

The vast majority of Kimberley Islands are relatively small in size; over 35% of islands have an area of less than 25 hectares (< 0.25 km^2) and are little more than exposed rocks or islets, more than 75% of islands have an area of less than 1 km^2. The number of islands decreases exponentially with size; with less than 2% of islands having an island area larger than 5 km^2 (Table 3).

Table 3. Frequency and percentage of island by area category in the Kimberley bioregion.

Area (km^2)	Number	%
< 0.25	853	35.4
0.25 - 0.5	466	19.3
0.5 - 1.0	518	21.5
1.0 - 5.0	534	22.1
5.0 - 10	19	0.8
10 - 20	11	0.5
20 - 30	6	0.2
30 -40	2	0.1
40 -50	2	0.1
> 50	2	0.1
Total	**2,413**	**100**

In terms of spatial variability, the number of islands decreases dramatically moving away from the coastline (Figure 6). Over 63% of all islands are found within a short distance (< 5 km) of the mainland coast, a further 30% of islands are found between 5 km and 20 km offshore and, only 7% of islands are found at distances greater than 20 km from the Kimberley coastline. While there appears to be no relationship between island size and distribution, approximately 13% of total island area is located within < 5 km of the mainland coast, this increases significantly to more than half of the island area (over 55%) between 5 km and 20 km from the mainland coast. Between 20 and 30 km from the coast island area steeply declines to reach about 24% of the total island area. An additional drop in total island area continues until it reaches its lowest value of < 2% between 30 and 40 km from the coastline.

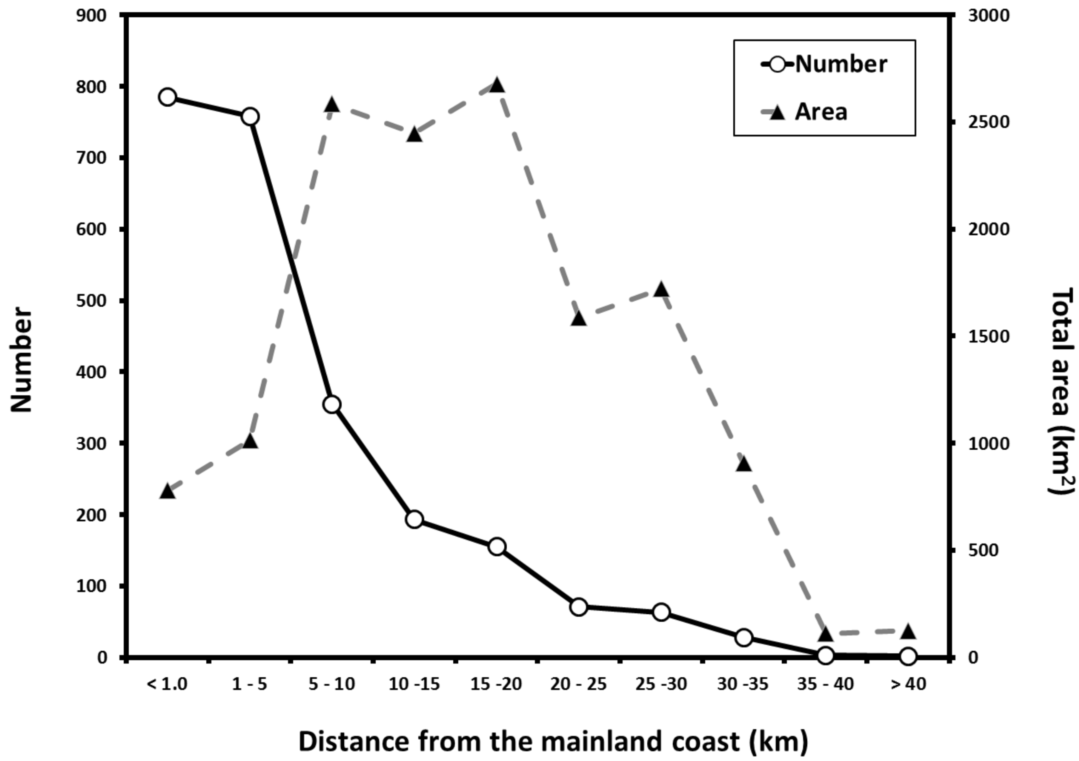

Figure 10. The number and size of islands across the north-west continental shelf. The horizontal axis represents distances from the Kimberley mainland coastline. The left vertical axis represents the number of islands and the correlation between the number of islands and distance from the coastline is shown in the black solid line. The right vertical axis represents total island area in (km2) and the correlation between the island areas and distance from the coastline is shown by the grey dashed line.

3.2 Reef distribution and size

Coral reefs occur extensively throughout the KIM and display a remarkable geomorphological diversity. A total of 853 reefs, with a combined reefal area of approximately 1950 km^2 were identified and mapped throughout the KIM. Each mapped reef was accurately recorded and classified according to the reef classification scheme described above (Figure 11).

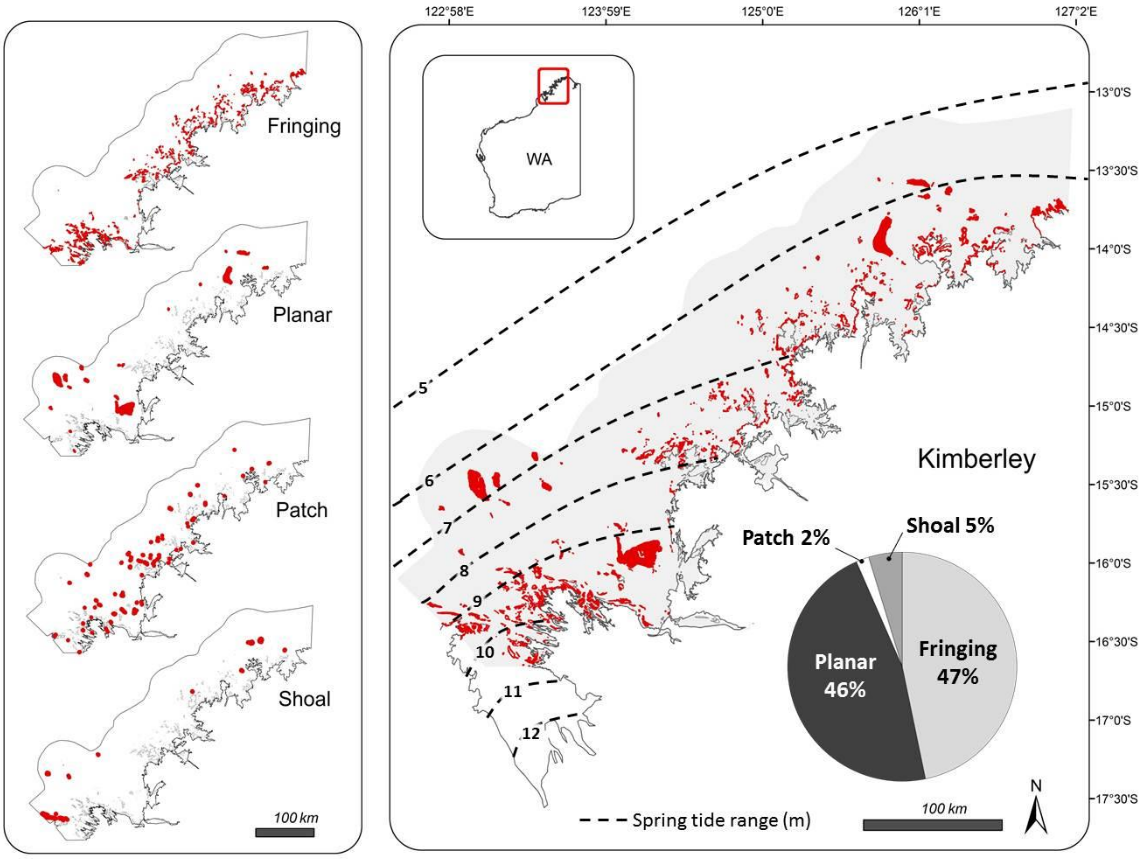

Figure 11. *(left plate)* Reef distribution in the Kimberley bioregion by type: fringing; planar; patch; and shoals. *(right plate)* Distribution map of reefs in the Kimberley bioregion with spring tidal range contours (calculated from the National Tidal Unit, Australian Bureau of Meteorology). The pie chart shows the percentage of area coverage of each reef type.

Fringing reefs are by far the most common type of reef, accounting for 687 reefs, covering more than 910 km^2 of reefal area fringing almost a quarter of the total Kimberley mainland and island coastline. The majority of fringing reefs (70%) have developed around islands (Figure 11).

There are approximately 20 planar reefs in the KIM, though their combined reefal area of > 909 km^2 is almost equivalent to the fringing reef area (Table 3.4). Fringing and planar reefs together comprise approximately 93% of the total reef area in the KIM. The remaining reefal area is covered by patch reefs (2%) and shoals (5%) (Figure 11).

Despite their large number and abundant distribution, individual fringing reefs are relatively small in size having a mean area of 1.3 km^2, whereas shoal reefs are somewhat larger having a mean area of 7.1 km^2 and planar reefs are significantly larger again having a mean area of 45.5 km^2. Among all the reef types of the study area, Patch reefs have the smallest size with a mean area of < 1 km^2 (Table 4).

Table 4. Lengths and areas of reefs by type.

Reef type	Number	Length (km)				Area (km^2)			
		Min	**Max**	**Mean ± SD**	**Total**	**Min**	**Max**	**Mean ± SD**	**Total**
Fringing	687	0.03	9.3	1.8 ± 14.0	2,638.7	$0.5x10^{-4}$	32.6	1.3 ± 3.3	910.7
Planar	20	3.2	22.1	10.9 ± 41.1	259	1.4	352.4	45.5 ± 90.1	909.4
Patch	133	0.04	2.9	0.85 ± 1.6	103	$3.7x10^{-4}$	3.4	0.27 ± 0.5	35.4
Shoal	13	1.3	12.4	4.9 ± 10.2	76.1	0.6	18.7	7.1 ± 6.9	92.3
Total	**853**				**3076.8**				**1,948**

Regarding spatial variability, the number of reefs declines markedly with distance from the mainland coast (Figure 3.12). As with the Kimberley islands nearly half of the reefs are located in close proximity (< 5 km) to the Kimberley coastline, a further 33% of reefs are found between 5 km and 20 km off shore. The number of reefs drops continuously up to 40 km off shore, with a slight increase (3%) beyond 40 km; this pattern can be attributed to fringing reefs being the dominant reef type. More than half of the total reef area in the Kimberley (> 54%) is found within 10 km of the coastline. At distances > 10 km from the coast, reef areas fall significantly to less than 4% at 25 km off shore, with a small increase in the reef area between 25 km and 35 km. An additional drop in reef area occurs at 40 km to reach its minimum value (< 0.5%). However, more than 40 km from the coastline of the Kimberley coastline the reef areas jump dramatically to approximately 15% which can be explained by a small number of large planar reefs located at this distance from the coast.

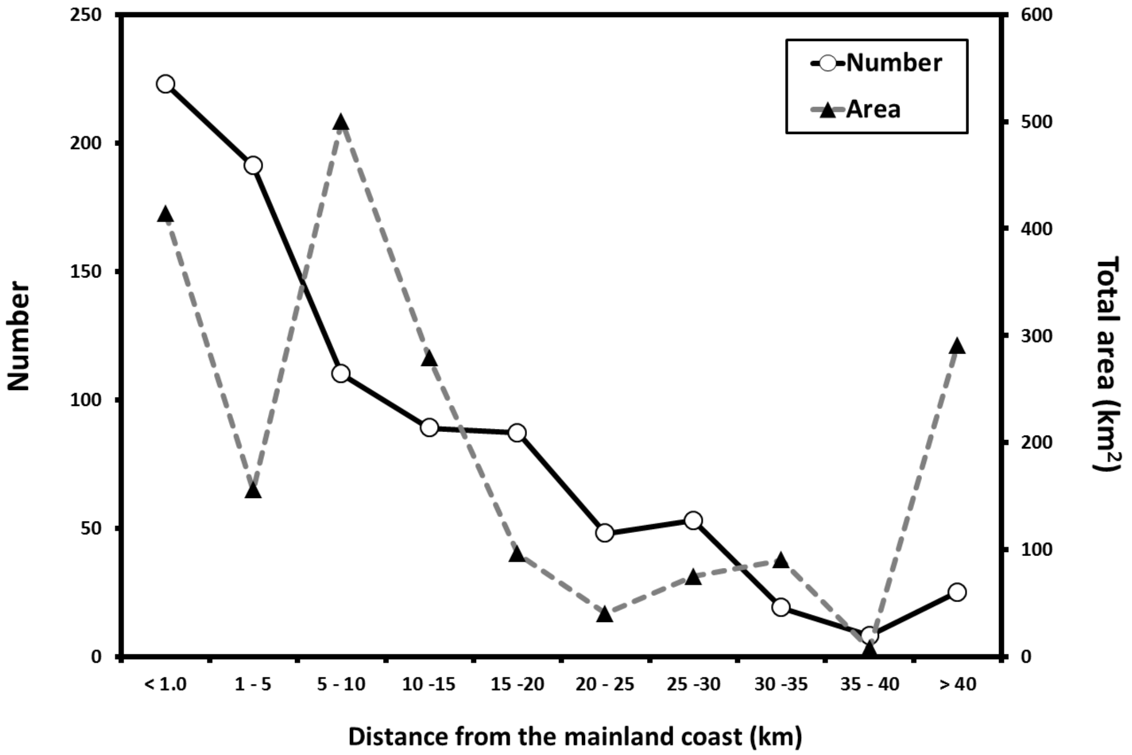

Figure 12. Number and size of reefs across the north-western shelf. The horizontal axis represents distance from the Kimberley mainland coastline. The left vertical axis represents the number of reefs and the correlation between the reefs number and distance from the coastline is shown by the black solid line. The right vertical axis represents total reef area in (km^2) and the correlation between reef areas and distance from the coastline is shown by the grey dashed line.

3.2.1 Reef distribution by latitude

Fringing reefs are found throughout the Kimberley but have particularly high concentrations within the archipelago regions. These include the Bonaparte Archipelago in the North (14° S to 15° S) and the Buccaneer Archipelago in the South (16° S to 17° S). These regions account for 33% and 39%, respectively of the total number of fringing reefs (Table 5).

Planar reefs are mainly developed offshore. Although they are relatively few in number, they are characterised by a large reefal area. They are clustered in two main areas, with 38% of their area found between 13° 30′ S and 14° 30′ S and over 52% of their area situated between 15° S and 16° S, including Montgomery Reef, and the Adele complex of 6 reefs. Planar reefs are rare or non-existent between 14° 30′ S and 15° 00′ S (Table 5).

Patch reefs are smaller in size and are widespread across the Kimberley coast. They are often hard to identify. Approximately 133 reefs have been counted in the bioregion within a short distance of the mainland coast. Their number gradually increases from the north toward the south of the Kimberley coast. They make up the highest proportion (42%) of reefs between 15° 00′ S and 16° 00′ S, south of which their number decreases (Table 5).

Submerged reefs or shoals are far less numerous. Approximately 13 reefs of this type have been mapped. Their number varies from the north to the south of the bioregion. However, they reach their greatest density in the south between 16° 00′ S and 16° 30′ S, and are rare or non-existent between 14° 30′ S and 15° 00′ S and on the outer edge of the KIM (Table).

Table 5. Frequency of reef types by latitude in the Kimberley bioregion.

Latitude (°S)	Fringing	Planar	Patch	Shoal	Total
13° 30’ - 14° 00’	48	6	6	3	**63**
14° 00’ - 14° 30’	140	2	9	2	**153**
14° 30’ - 15° 00’	119	0	13	0	**132**
15° 00’ - 15° 30’	74	4	56	1	**135**
15° 30’ - 16° 00’	11	7	19	2	**39**
16° 00’ - 16° 30’	259	1	29	5	**294**
16° 30’ - 17° 00’	36	0	1	0	**37**
Total	**687**	**20**	**133**	**13**	**853**

4 Discussion

Despite the early work of Teichert and Fairbridge (1948) and more recent investigations by Brooke (1997) and Wilson (2013), the KIM was never considered to be a major reef province. This view is mainly due to the low number of scientific studies which have investigated Kimberley reef systems, which can be attributed to its remoteness, lack of research infrastructure and settlements, challenging environmental conditions, and the focus of most Australian reef researchers towards the higher profile GBR. The results of this study show that the total area of the Kimberley reef is 1,948 km^2 and the number of reefs is 853 which is significantly greater (> 60% greater) than the reef number found in other available sources of information on reefs in this region (*i.e.* ReefBase and the Millennium Coral Reef Mapping Project). Compared with the GBR the Kimberley has a longer coastline, a greater number of islands, and although its total reefal area is 10 times smaller than the GBR (~2,000 km^2 compared to 20,000 km^2). Based on information of world's reef statistics (Spalding *et al.*, 2001), this study has confirmed that the Kimberley as one of the top 20 largest continental shelf reef provinces in the world.

Reef distribution in the KIM shows significant morphological complexity with clear regional patterns. Fringing reefs were found the dominant reef type and were widely distributed throughout the KIM. Coastal fringing reefs were more common in the northern Kimberley having developed intermittently along the extended mainland ria coast. These fringing reefs were observed more intermittent along the southern coast and areas proximal to major river mouths as a result of increased terrestrial runoff and higher water turbidity (Wilson, 2013).

The study showed that fringing island reefs have a far greater latitudinal spread and they were more common than other reef types in the KIM. As expected, fringing reef distribution associates strongly with the distribution of islands. The highest numbers of fringing reefs in the KIM were found around nearshore high islands of the Buccaneer Archipelago. At this location the folded and faulted King Leopold Fold Belt has been dissected into many islands as a result of drowning of the continental shelf during the Holocene (Solihuddin *et al.*, 2015). Fringing reefs were also abundant in the Bonaparte Archipelago at the north of the KIM; the history of these islands indicates that the area was previously part of the mainland (Johnson *et al.*, 2010). Both these areas have previously been suggested as being important for fringing reef development (Wilson, 2013).

It is also found that fringing reefs with a westerly aspect often have a wider, geomorphically mature reef flat with a steeply sloping reef front; these reefs were more often exposed to higher energy ground swells. Fringing reefs with an easterly aspect generally have a narrower gently sloping reef flat and tend to be sheltered from high swell energy. The asymmetric style of fringing reef development was particularly apparent around most islands in the Bonaparte Archipelago. This indicates that either exposed reefs grow faster than sheltered reefs, or they start growing earlier (Wilson, 2013).

A notable subclass of fringing reef 'inter-island' falls within this category. This type of reef was particularly common in the Buccaneer Archipelago (*e.g.* Molema Island, Bathurst-Irvine Islands, and Woninjaba Islands) (Kordi and O'Leary, 2016). The reef platform connects two or more islands and seems to have been formed by a coalescence of the fringing reefs that are attached to these islands (Hopley, 1982). Where coalescence is incomplete, many deep pools can be observed (*e.g.* reef between Bathurst-Irvine Islands) (Kordi and O'Leary, 2016; Solihuddin *et al*., 2016).

High intertidal fringing reef is a newly defined reef morphotype and is characterised by reef flat elevations above the level of MHWS tides, coralline algal terraces, and rhodolith banks (Richards and O'Leary, 2015). This reef type was best developed in the Buccaneer Archipelago and Sunday Island group, where tidal ranges can exceed 10 m (Kordi and O'Leary, 2016). However it is still unknown what process is ultimately driving the development of these high intertidal reefs.

The mapped planar reefs showed that these reefs were isolated features usually located some distance from the mainland coast, beyond the fringing reef zone in water depths of 30–50 m. These reefs appear to have developed on shallow, pre-existing topographic highs, between palaeoriver channels

(Collins *et al.*, 2015). The majority of these reefs have reached sea level with the reef flat mostly blanketed by a sand sheet and surrounded by an intertidal reef platform or rampart. Based on Hopley's evolutionary classification scheme these reefs can be classed as senile in that they have a central low, vegetated island (*e.g.* Adele Reef) or an unvegetated sand cay (*e.g.* Long Reef).

Patch reefs were scattered over the KIM. These reefs usually occur in low intertidal or subtidal zones. Due to their small size, their features are often difficult to detect using moderate spatial resolution remote sensing images, and/or because of high water turbidity rendering statistics unreliable. Thus, patch reefs have not been mapped in great detail in this study. Due to the lack of adequate information on patch and shoal types in addition to their small size and depth under water, where they do not represent an area of great significance, these reefs have not been studied in as much detail as high intertidal and low intertidal fringing and planar reefs. Therefore they have been noted in this study in terms of basic information such as their distribution, number and area, based on available data.

The study showed a steady relationship between island distribution and reef size because there were an abundance of reefs attached to islands near the coast. Thus, most Kimberley reefs can be found within 10 km of the mainland coast. However, some reefs cannot be identified within a distance less than 5 km from the shoreline where reef area drops significantly although the island's area remains high. The reason was most of the reefs are located on steeply sloped forereefs and in a water depth > 5 m where they cannot be detected using remote sensing images due to high turbidity. In such extreme conditions, high-resolution bathymetric and topographic data can be more efficient (Brooke *et al.*, 2010). This statistic was particularly significant from a management perspective as their close proximity to the coast means that there is a higher potential for reefs to be threatened or impacted by land use change.

5 Conclusions

In summary, this study presented the most comprehensive dataset of reef typology and distribution for the KIM. The study provided a firm scientific determination of the scale of reef habitats in the Kimberley.

The resulting data was the first most detailed spatial analysis of the KIM and will thus make available a reliable, spatially constrained data set for biodiversity assessment and reef structure comparisons. Furthermore, it will provide scientists and managers with quality information relevant to the monitoring, conservation and management of these vital natural resources. It also paves the way for future studies addressing the major threats to reef ecosystems in this region.

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