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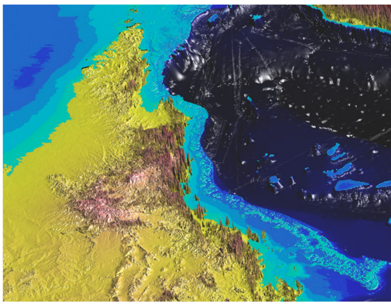

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Geological and geomorphological features of Outstanding Universal Value in the Great Barrier Reef World Heritage Area

Tanya Whiteway, Scott Smithers, Anna Potter and Brendan Brooke

Prepared for the Department of Sustainability, Environment, Water, Population and Communities

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GEOSCIENCE AUSTRALIA
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Executive Summary

This report provides the first comprehensive assessment of geomorphological and geological features of the Great Barrier Reef (GBR) whose intrinsic characteristics represent elements of the Outstanding Universal Value (OUV) of the Great Barrier Reef World Heritage Area (GBRWHA). Specific examples of these features are described and an initial assessment made of the environmental pressures that they currently experience or in the future may be exposed to. Importantly, the information compiled in this report improves our knowledge of an important set of physical and biophysical features in the GBRWHA with key natural heritage values and thereby has the potential to better inform the conservation and management of this unique region.

A wide range of geological and geomorphological feature types that occur within the GBRWHA have OUV as defined by the World Heritage Convention (Table 1.1). In particular, four criteria for World Heritage listing are satisfied by the features identified:

- ***Criteria vii:*** superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance;
- ***Criteria viii:*** outstanding example representing major stages of earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiographic features;
- ***Criteria ix:*** outstanding example representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals; and
- ***Criteria x:*** contains the most important and significant natural habitats for *in situ* conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

This report was undertaken for the Australian Government's Department of Sustainability, Environment, Population and Communities (DSEWPaC) as part of its strategic assessment of the OUV of the GBRWHA. The main objectives of this report are to:

1. Describe geological and geomorphological features of the GBRWHA that express OUV, including information on the known best examples; and
2. Undertake an initial assessment of the sensitivity of the identified geological and geomorphological features, including a brief assessment of their potential sensitivity to pressures on the environment of the GBRWHA as listed in the Great Barrier Reef Marine Park Authority's Outlook Report (2009).

Table 1.1 Best or representative examples (as identified in this report) of geological and geomorphological features with outstanding universal value.

Features	Best Examples	World Heritage Criteria
Fringing Reefs	Cape Tribulation, Yule Point, Hayman Is., Orpheus Is.	viii, ix
Inshore Turbid Reefs	Paluma Shoals, Middle Reef	vii, viii, ix
Shelf Reefs	Reef 17-065, Potter Reef, Taylor Reef, One Tree Is. / reef, Bushy Redbill Reef, Wreck Reef	vii, viii, ix
Ribbon Reefs	Tijou Reef, Yonge Reef, Ribbon 5 Reef	viii
Deltaic Reefs	Northern Deltaic Reefs, Pompey Complex	viii, ix
Northern Detached Reefs	Raine Reef*, Great Detached Reef*	viii, ix
Submerged Coral Reefs and Banks	Hydrographers Passage	viii, x
Carbonate Reef Islands	Raine Is.	viii, x
Gravel and Shingle Ridges	Curacoa Is., Lady Elliot Is.	viii, ix
Mangrove Shorelines, Mangrove Islands and Low Wooded Islands	Murdoch Is., Bewick Is., Hinchinbrook Is.	viii, ix
Halimeda (banks, bioherms and meadows)	Petricola Shoal*, Swain Reef*	viii, ix
Seagrass Beds	Barrow Point to Lookout Point*, Shoalwater Bay*	viii, x
Karstic Channels and Blue Holes	Blue Holes (Pompey Complex)	viii
Palaeochannels	Fitzroy River Palaeochannel, Burdekin River Palaeochannel	viii, ix, x
Continental Islands	Flinders Is. Group, Hinchinbrook Is., Magnetic Is., Whitsunday Is., South Percy Is., South Repulse Is., Wild Duck Is.	iii**, vii, viii, ix, x
River Deltas	Burdekin River delta	viii, ix
Dune Systems	Hinchinbrook Is.*, Curtis Is.*	vii, viii
Submarine Canyons and Turbidite Deposits	Outer shelf NE of Cairns*, Outer shelf at the southern end of GBRWHA*	viii, ix, x

**Representative example.*

***World Heritage Criteria iii: to bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared.*

The Outstanding Universal Value of the GBRWHA - Geology and Geomorphology

The GBR is a unique sedimentary basin, an extensive carbonate landform and a vast living reef system. As such, the GBR demonstrates OUV under all aspects of World Heritage criteria vii:

- provides a record of passive continental margin development associated with the formation of the Coral Sea. It records Australia's split from Gondwana, continental drift to the north, entry to the tropics and coral reef development;

- contains extensive coral reefs in shallow-water continental shelf environments that preserve a long history (at least 600,000 years) of cycles of coral reef growth and demise in response to changes in sea level driven by Quaternary glaciations;
- includes a geologically dynamic continental shelf and coast, with the ongoing formation of large coral reef structures and sedimentary deposits;
- forms the largest and most diverse coral reef system in the world.

Reefs and Banks

Many reefs in the GBRWHA are clearly unique or unusual (e.g. ribbon and deltaic reefs; inshore turbid-zone reefs) or are a distinctive feature of the GBR due to their abundance and diversity of form (e.g. fringing reefs) and thereby satisfy *criteria viii* of the World Heritage Convention. These reefs also provide unique detailed records of sea level and climate change that have occurred over geological (thousands of years) and historical (last 200 years) periods. The much less well studied submerged coral reefs and banks of the GBRWHA also preserve important records of past cycles of reef establishment, growth and subaerial erosion that have occurred over hundreds of thousands of years driven by major fluctuations in sea level.

Numerous reefs in the GBRWHA provide outstanding examples of ecological and biological evolution (*criteria ix*) because they show how reefs have adapted to environmental change (e.g. changes in sea level; wave/storm exposure; changes in salinity and water quality). Fringing reefs in particular have a wide range of morphologies that represent distinctive responses to temporal and spatial variations in environmental conditions. Shelf reef systems likewise display several clearly defined stages in their geomorphological evolution that record the timeframe over which key ecological processes operate.

Reefs also provide, or are components to, significant natural habitats important for biological conservation (*criteria x*). For example, submerged reefs and banks support high biological diversity, facilitate connectivity between reefs and provide refuge from environmental disturbance such as temperature variability (which protects seed stock for near-surface reef systems).

Carbonate Reef Islands and other Sedimentary Features

Carbonate reef islands and gravel and shingle ridges formed on a number of islands provide long-term records of reef, shelf and island development (*criteria viii*) in the GBRWHA. In particular, deposits forming these features preserve records of storm and cyclone activity that extend back thousands of years, well beyond the historical records. Carbonate reef islands are also essential for biological conservation as they provide important habitats for a range of key terrestrial species (e.g. turtles, birds, *Pisonia*; *criteria x*).

Accumulations of carbonate sediment produced by *Halimeda* in the GBRWHA are globally significant deposits, considered to be some of the largest and most actively accreting carbonate banks in the world (*criteria viii*) and preserve unique records of environmental change during the Holocene.

Mangrove coasts and islands in the GBRWHA are ecologically important as nurseries for fish, including endangered species; and river deltas likewise form extensive muddy coastal and inner shelf environments that support critical ecosystems (*criteria x*). Seagrass beds have an important function stabilising seabed sediments and provide habitat and foraging areas for key species such as dugongs.

Palaeochannels that cross the continental shelf of the GBRWHA and submarine canyons on the outer shelf indicate large-scale sediment transport pathways and provide unique habitat.

Pressures on geological and geomorphological features with OUV

This report focused on major threats identified in the 2009 Outlook Report (GBRMPA, 2009):

- **Climate Change**: rising sea surface temperature, ocean acidification, enhanced cyclonic activity and rising sea level;
- **Catchment Runoff:** sediments and contaminants (nutrients, pesticides, herbicides);
- **Coastal and Marine Development:** changes to sediment transport pathways, dredging and spoil disposal and coastal developments;
- **Direct Use:** shipping, trawling, mining, grazing and introduced pests.

Table 1.2 provides a summary of the assessment of the risk and sensitivity of geological and geomorphological features - risk refers to the likelihood that a type of pressure will impact on the feature; sensitivity refers to how easily and how much a feature might be impacted by a pressure.

The most significant risk identified in this preliminary assessment is the extensive range of climate change impacts, followed by catchment runoff and coastal and marine development. Reef formations on the outer shelf and carbonate reef islands may be particularly susceptible to climate change impacts such as rising sea level, increasing coral bleaching events and an increase in cyclone frequency and/or intensity. Seagrass beds and fringing reefs may be particularly susceptible to the impacts of catchment runoff and marine development which result in a decline in water quality.

Recommendations

1. To maintain the utility of this report it should be periodically updated as new data become available. Future work should include the development of an authoritative, online spatial database of the key geological and geomorphological features; and broader consultation with end-users of this environmental information.
2. Remote sensing techniques (e.g. Landsat satellite images) coupled with available ground-truth information could be employed as an effective approach to accurately identify change in the condition of features over time since the inclusion of the GBR on the World Heritage List. Existing and new satellite data could also be used to develop an effective method of providing fine-scale environmental data for monitoring the condition of features.
3. The assessment of pressures includes extensive professional opinion, as many of the features have not undergone an explicit assessment of pressures to which they may be exposed. In particular, cumulative impacts have not been addressed but are likely to be very important to the stability of both biotic and abiotic components of the GBRWHA. Further work is required to identify features that are particularly susceptible to cumulative impacts.

Table 1.2 An assessment of the risk of impact from, and sensitivity to, environmental pressures on geological and geomorphological features with OUV – Features listed in this summary are only those that have High or Unknown ratings (see for an assessment of all features described in the report).

	Climate Change		Catchment Runoff		Coastal and Marine Development		Direct Use	
	S	**R**	**S**	**R**	**S**	**R**	**S**	**R**
Fringing Reefs	M	M	M	M	H	V	M	M
Inshore Turbid Reefs	V	V	V	V	?	?	L	L
Ribbon Reefs	H	H	?	L	M	L	L	L
Deltaic Reefs	H	H	?	L	M	L	L	L
Northern Detached Reefs	H	H	?	L	M	L	L	L
Carbonate Reef Islands	H	M	L	L	V	V	L	L
Halimeda (banks, bioherms and meadows)	?	?	M	M	L	L	L	L
Seagrass Beds	?	?	H	H	H	H	M	L

Summary of the sensitivity (S) and risk (R) for each listed feature. L = Low, M = Moderate, H = High, V = Variable, and ? = Unknown.

1 Introduction

The Great Barrier Reef (GBR) is the largest coral reef system in the world. It covers more than 250,000 km^2, extending across 15^o of latitude between 9^o 30' S to 24^o 30' S, a distance of around 2,300 km, along the northeastern Australian coast (Hopley *et al.* 2007). In recognition of its spectacular beauty, environmental significance, intrinsic scientific value and iconic international status, the GBR was nominated for World Heritage listing in January 1981 and was inscribed on the United Nations Educational, Scientific and Cultural Organisation (UNESCO) World Heritage List in October that year (UNESCO, 2012). The document nominating the GBR to the World Heritage List (available at: http://www.gbrmpa.gov.au/__data/assets/pdf_file/0019/4906/mp_009_full.pdf) broadly describes why the GBR was considered of Outstanding Universal Value (OUV).

The submission successfully demonstrated that the GBR has OUV under four criteria of the World Heritage Convention (http://whc.unesco.org/en/criteria/) in that it:

- contains superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance (*Criteria vii* of the World Heritage Convention);
- is an outstanding example representing major stages of earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiographic features (*Criteria viii*);
- is an outstanding example representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals (*Criteria ix*);
- contains the most important and significant natural habitats for *in situ* conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation (*Criteria x*).

Cultural criteria were included in the justification and description sections, but outstanding natural heritage values underpinned the original nomination principally focusing on the coral reef ecosystem. A subsequent technical review of the original nomination acknowledged the OUV of the GBR with the statement:

'It seems clear that if only one coral reef site in the world were to be chosen for the World Heritage List, the Great Barrier Reef is the site to be chosen.' (IUCN, 1981:2)

In addition to a nomination document prepared for the World Heritage Committee assessment, a statement of OUV is also required to officially outline why a particular site is inscribed on the World Heritage List. This statement identifies the criteria of OUV met by the site, how the condition of the site was assessed, and how the requirements of protection and management are appropriate. Statements of OUV are also a reference point for monitoring and reporting on the status of World Heritage sites. Periodic assessments and reporting against these benchmarks are required, with failure to adequately protect and preserve the original values potentially leading to an 'in danger' listing or even deletion from the World Heritage List. The World Heritage Committee decided that all properties listed under the World Heritage Convention should have Statements of OUV in 2005. A retrospective statement of

OUV was subsequently developed for the GBR and was adopted by the World Heritage Committee in 2012.

Once the submission was accepted, Australia's obligation under the World Heritage Convention is to monitor and conserve the Great Barrier Reef World Heritage Area (GBRWHA) and to maintain its OUV. In addition to establishing ongoing legal and scientific monitoring and protection plans (Day *et al.* 2002; Fernandes, 2005; Dobbs, comp. 2011), Australia is also obliged to identify, monitor and conserve key features of OUV within the GBRWHA.

The first assessment of OUV for the GBR after its inscription on the World Heritage List was completed in 1997 (Lucas *et al.* 1997). That report concluded that the GBRWHA justifiably satisfied all four of the natural heritage criteria on which the original nomination was based, attributing the enduring outstanding universal value to a combination of the size of the system and effective management (Lucas *et al.* 1997). Lucas *et al.* (1997) also compiled a comprehensive list of GBRWHA attributes with OUV, with many features listed under multiple criteria.

1.1 Objectives

Since the Lucas *et al.* (1997) report, a new body of many scientific reports, journal papers and books have been published that are relevant to the assessment of the OUV of the GBR. The objective of this report is to more comprehensively describe geological and geomorphological features of OUV as defined under criteria *viii* of the World Heritage Committee's 1981 and 1996 operational guidelines. The report comprises a brief introduction to the GBR (Sections 1 to 5) followed by two major sections:

1. A description of geological and geomorphological features that express OUV (Section 6). This includes geological and geomorphological features with OUV that may not have been previously identified by Lucas *et al.* (1997). Also included is additional information on known features that have not previously been described in any detail.
2. An initial assessment of the sensitivity of the identified geological attributes, including a brief assessment of the potential sensitivity of these features to pressures on the environment of the GBRWHA that are listed in the Great Barrier Reef Marine Park Authority's Outlook Report (2009) (Sections 7 and 8).

2 Great Barrier Reef World Heritage Area

The Great Barrier Reef World Heritage Area (GBRWHA) (Figure 2.1) covers approximately 348,000 km^2, extending from the low tide elevation on the mainland to beyond the edge of the continental shelf. Areas of continental slope and deep oceanic waters are included within the GBRWHA. The GBRWHA starts at a latitude just north of Fraser Island (-24.50^o S) and extends to the northern tip of Cape York Peninsula (-10.69^o S) (including islands to the east of the mainland but not Torres Strait). Within this area, there are approximately 3,000 coral reefs, 617 continental islands and 300 reef islands (Hopley *et al.* 1989; GBRMPA, 2012a).

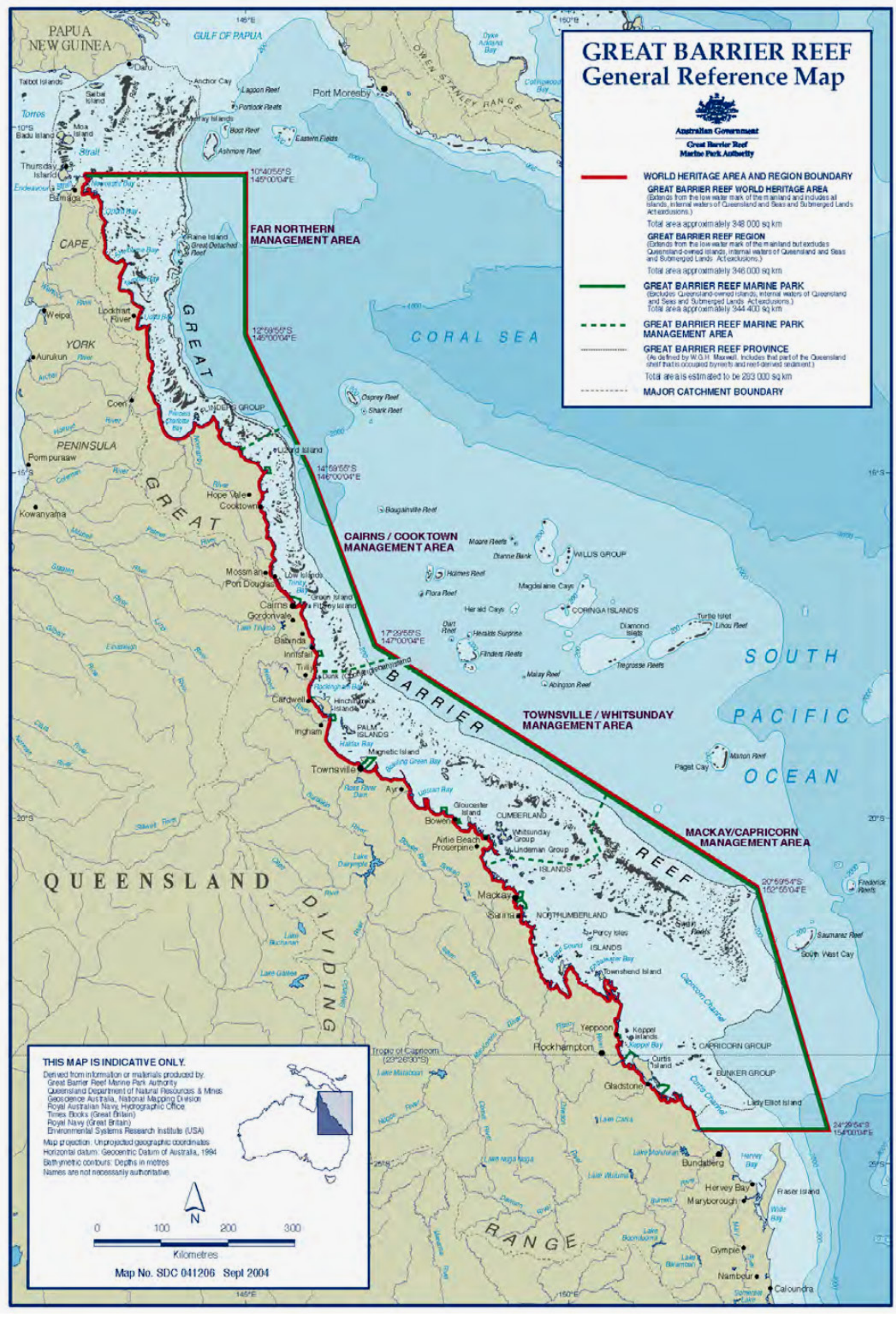


Figure 2.1 The Great Barrier Reef Region, showing boundaries of the World Heritage Area and Marine Park (Source: GBRMPA).

3 Identification of features of OUV

With reference to criteria *viii (*outstanding example representing major stages of earth's history) of the World Heritage Convention, Geoscience Australia undertook a review of the scientific literature to identify geological and geomorphological features that are outstanding exemplars or are features unique to the GBRWHA.

The review of literature was guided by the expert knowledge of the authors of this report and via brief consultations with marine and coastal geologists, geomorphologists and ecologists at Geoscience Australia, James Cook University and The University of Sydney, including:

- Dr Rob Beaman - Queensland Smart Futures Fellow, School of Earth and Environmental Sciences, James Cook University, QLD, Australia.
- Dr Tom Bridge - Postdoctoral Research Fellow, ARC Centre of Excellence for Coral Reefs Studies, James Cook University, QLD, Australia.
- Professor David Hopley – Emeritus Professor of Physical Geography, School of Earth and Environmental Sciences, James Cook University, QLD, Australia.
- Associate Professor Peter Valentine - Associate Professor of Environmental Science, School of Earth and Environmental Sciences, James Cook University, QLD, Australia.
- Dr Johnathan Kool, Coastal Marine and Climate Change Group, Geoscience Australia.
- Dr Rachel Przeslawski, Coastal Marine and Climate Change Group, Geoscience Australia.
- Dr Scott Nichol, Coastal Marine and Climate Change Group, Geoscience Australia
- Professor Andrew Short, School of Geosciences, University of Sydney.

Section 6 includes summary descriptions of eighteen key feature types with OUV. Specific examples of each feature type have been selected based on their unique attributes that reflect the relevant OUV of the GBRWHA. For each feature type, representative examples and the known best examples have been listed, selected primarily because they are the largest or better studied examples of a particular feature type. Those nominated as the best examples were selected based on the available literature or are features that have been visited by the authors or specialists that were consulted. It is likely that there are other excellent examples that were not found in the literature or have yet to be described.

In some instances, features identified as meeting the requirements of OUV criteria *vii* (outstanding example representing major stages of earth's history) also met criterion *vi* (superlative natural phenomena) and/or *ix* (ecological and biological processes) and this was noted. More detailed information has been collated for a sub-set of features (which represent exemplars of each feature type), which includes maps that show the location of the features (on a regional scale) and a description of:

- the feature and its location;
- the outstanding universal intrinsic values of the feature; and
- pressures on the condition of the feature.

As noted by Lucas *et al.* (1997) ‘*a consultancy team regardless of their individual expertise, could not have the breadth and depth of knowledge required for describing the 'outstanding universal value' of the Great Barrier Red World Heritage Area*.’ Geoscience Australia and James Cook University have undertaken this task within a short timeframe, and during our review of the available information it became clear that not all geological features of OUV could be described and discussed. The short timeframe of the report also precluded stakeholder consultation. As such, this report should be considered an initial review rather than a complete or exhaustive guide for all geological and geomorphological features of OUV on the GBR.

4 Geological evolution of the Great Barrier Reef

Continental drift moved the northern Australian coast into the tropics in the early Miocene (approximately 24 million years before present - 24 Ma), where seawater temperatures were sufficiently warm to support the potential development of coral reefs. The reef limestone underlying the modern reef system is thickest in the north, reaching a depth of approximately 2 km at Ashmore Reef (10°16'S, 144°28'E). However, the reefal sequence is typically much thinner, being generally less than 200 m thick below barrier reefs along the outer shelf and even shallower across the continental shelf. Drilling of continental shelf limestone deposits indicates that reef growth initiated in the northern GBR at around 500,000 years before present (500 ka). Older and thicker reef deposits are interpreted to occur on subsiding marginal plateaus of the Coral Sea offshore from the Great Barrier Reef, for example the Marion, Queensland and Kenn Plateaus (Brooke *et al.* 2012; Pigram *et al.* 1989).

At the peak of the last ice age, just 18 ka, the continental shelf was sub-aerially exposed and no living coral reefs existed in the present location of the GBR. However, as ice caps melted following the end of this ice age, sea levels rose and the continental shelf was flooded by the sea from around 12 ka, allowing coral reefs to grow and flourish, often (but not exclusively) at the same locations where they grew in earlier interglacial periods of high sea level (Hopley, 1982). Deep drilling and seismic investigations provide evidence of the influence of earlier fluctuations in sea level, with those of the past 400 ka reasonably well known. Cores drilled at Boulder Reef and Ribbon Reef 5 contain distinct reef units showing systematic changes in taxa associated with reef growth toward the surface during periods of high sea level, separated with solution unconformities formed during emergence at low sea levels (Webster and Davies, 2003). For at least the past 500 ka reef growth on the GBR has been punctuated by sea-level oscillations associated with the waxing and waning of the ice ages, with growth occurring only during periods of higher sea level which accounts for just 10-15% of the time. In short, the development of the GBR has been dominated by long periods of subaerial exposure and associated destructive processes, with just short periods of sea level submergence and rapid reef growth.

Today, coral reefs at varying stages of geomorphological development can be found on the GBR (Hopley, 1983, and described further in Section 6.3.1). These include 'juvenile' reefs, which are growing vertically, and many reefs at the 'mature' and 'senile' stages that have reached sea level and developed reef flats capable of supporting coral cays. There are around 300 coral cays on the GBR, composed almost entirely of skeletal material (calcium carbonate) produced by reefal organisms. In addition to coral cays there are 617 continental high islands, often with significant fringing reefs. These continental high islands are mostly composed of late Palaeozoic (330-270 Ma) and Cretaceous (140-100 Ma) igneous rocks (mainly granites and felsic volcanics) of the same types that dominate the hinterland of the adjacent mainland (Carson *et al*. 2006; Ewart *et al*. 1992; Bryan *et al*. 2000). Outcrops of these rock types vary in size from more than 570 km^2 (Curtis Island) to small rocky outcrops such as Bay Rock off Townsville, which is less than 150 m at its widest point. These islands are also varied in their topography (Mt Bowen, on Hinchinbrook Island, rises to 1,121 m above sea level, one of Queensland's highest peaks), geomorphology and terrestrial ecosystems, and in the ecosystem services that they provide to the GBR overall (for example, nesting habitat, or habitat sheltered from the prevailing winds).

5 Contemporary processes of the Great Barrier Reef

A detailed account of the oceanography and climatology of the GBR is provided in Chapter 4 of Hopley *et al.* (2007), and a review of contemporary chemical and physical processes in the GBR has also been undertaken as part of the GBRMPA's 2009 Outlook Report. The following is a brief summary of these and other works that identify key processes that influence the geomorphological and geological features of the GBR.

The geomorphology of the contemporary GBR reflects the interaction of the reef building organisms, the structures and sediments that they produce and range of physical and chemical processes. Due to the size and complexity of the GBR these processes and interactions vary both spatially and temporally. Contemporary seasonal processes affecting geomorphological development in the GBR are driven by a tropical climate with prevailing south-easterly trade winds during winter and northwest monsoons during summer (GBRMPA, 2009). The prevailing winds create high-energy environments on the outer shelf, impacting on the formation of reefs and resulting in unusual reef types such as ribbon reefs and deltaic reefs (Hopley, 2006). There is generally a significant decrease in wave height from south to north, and from the outer barrier reefs toward the mainland coast. Tides also have large variation, ranging from a maximum of around 8 m at Broad Sound (22°S 150°E) to just above 2 m at Cairns.

Tropical cyclones may affect parts of the reef during the wet season, as may the discharge of flood waters from adjacent onshore catchments. Both cyclone and rainfall activity are seasonally driven and appear to be particularly active during La Nina phases of the ENSO climate cycle.

In the GBR region, between 75% - 90% of rainfall occurs during the summer 'wet' season, resulting in large volumes of freshwater and sediment being discharged from rivers at the coast. Proximal coastal features such as nearshore reefs, mangroves and seagrass beds (Schaffelke et al. 2005) can be particularly impacted, however, plumes of suspended sediment extend some distance from the river mouth, influencing a much wider area (McKenzie, 2007).

Cyclone activity during the summer months occurs regularly, with 116 cyclones occurring in the GBR from the summer of 1970/71 to the summer of 2005/06 (GBRMPA, 2009). Intense rainfall, wind and waves associated with cyclone activity greatly impact the shape and surficial cover of many reefs, seabed sediment deposits and shallow-water and shoreline features. While cyclones have the capacity to destroy some features, there are others, such as carbonate reef islands and gravel and shingle ridges, that have the potential to accrete during storms and cyclones as newly eroded material is redeposited (Nott, 2006).

There is also a pronounced latitudinal temperature gradient which impacts on coral reef and habitat composition (GBRMPA, 2009). In the northern GBR the average maximum temperatures range from 30°C in summer to 26°C in winter. In the southern GBR average maximum temperatures are much lower, ranging from 26°C in summer to 15°C in winter.

Oceanic circulation in the GBR is highly variable (Choukroun, 2010). Major circulation is driven by the division of the Southern Equatorial Current into north and south flowing branches when it reaches the continental slope. These currents carry warm water and nutrients both on-shelf, and along the shelf. The northern current circulates around the northern Coral Sea, while the southern current carries warm water south along the east coast of Australia (Brinkman et al. 2002)

6 Geological and geomorphological features with OUV

Criteria *viii* states that a feature is of OUV if it is *'an outstanding example representing major stages of earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiographic features'*.

The GBRWHA in its entirety shows OUV in all parts of the Criteria *viii* statement in that it is:

- *an outstanding example representing a major stage in the Earth's History* – in particular, the GBR provides evidence of passive margin development associated with the formation of the Coral Sea, and can be viewed as documenting the final phase of Australia's split from Gondwana which began in the Eocene. Delivered into the tropics by continental drift, passive margin development associated with the formation of the Coral Sea has produced the subsiding continental shelf over which the GBR has grown during phases of high sea level;
- an *outstanding example representing the record of life* – through the development of extensive coral reef systems in shallow water shelf environments that preserve a long history of coral reef growth and demise in response to changes in sea level driven by Quaternary glaciations;
- a record of *significant ongoing geological processes in the development of landforms* - through the *ongoing* development of large coral reef structures and mixed carbonate and terrestrial sedimentary deposits, coupled with cycles of accretion and erosion, to form a geologically dynamic continental shelf and coast; and
- *a significant geomorphic and physiographic feature* - the largest and most diverse coral reef system in the world.

The various geological and geomorphological feature types forming the GBR are each important to the reef as a whole. The diversity of geomorphological and geological features is, in part, the reason that developmental stages in the evolution of the GBR are so well preserved, and why such great species and habitat diversity exists. As a result, a wide range of features have OUV as defined under criteria *viii*:

- unique records of the development of a wide range of different reef types/morphologies and habitats that make up the largest coral reef system in the world,
- record of the tectonic evolution of the northeast continental margin of Australia, driven by global plate tectonics, on which the GBR has developed (including neo-tectonic events),
- unique landforms and seabed structures seen only in the GBRWHA,
- unique or unusual environments that have allowed the development of habitats internationally recognised as critically important for key species,
- features that may be relatively common, but are unusually located within the GBRWHA,
- accurate records of modern sea level and past changes in sea level, and
- long records of climatic conditions and the effects of past changes in global climatic conditions.

This chapter provides summary descriptions of eighteen key feature types with OUV. For each feature type, a selection of representative examples have been included, with information on their OUV.

The listed features have been selected primarily because they are the largest or best studied examples of a particular feature type showing OUV. It is likely that other excellent examples may occur, but because they have not been investigated and described in detail their OUV cannot be defined. Indeed, it is critically important to recognise that although small sections of the GBR have been studied in detail for almost a century, the size, depth and remoteness of much of the system mean that even today the character and geomorphological diversity of large areas are still to be revealed (Bridge *et al.* 2012; Harris *et al.* 2012). Although recent efforts have provided excellent data for parts of the GBRWHA east of the shelf edge, only sparse data is available for many areas located on the continental shelf (Beaman, 2010).

Notes on Section 6:

- Descriptions of OUV are identified based on the UNESCO Wold Heritage criteria for selection, available from: http://whc.unesco.org/en/criteria/.
- The feature types described below are not listed in any order of perceived importance - all feature types are considered to be of equal importance.
- Only reefs and islands already mapped by GBRMPA have been included in spatial datasets. Additional features may be mentioned in the table and in scientific publications but agreed boundaries were not available, and hence were not included.

6.1 Fringing Reefs

6.1.1 Description

Fringing reefs are intertidal to subtidal reefs that grow along the mainland or around the margins of continental high islands (Smithers, 2011);Figure 6.1. Their development adjacent to terrestrial shorelines and catchments provides valuable baseline data on coastal water quality and information on how these reefs grew and developed prior to European settlement. The GBR includes many fringing reefs - 758 of the 2,904 named reefs identified by Hopley *et al*. (1989) are fringing reefs, which include 545 fringing reefs with recognisable reef flats and 123 incipient reef flats that are shore-attached but significant lack reef flat development. Generally fringing reefs are small (mean area <1 km^2) and all together comprise just 350 km^2 or 1.8% of the GBR's ~20,000 km^2 reef area (Hopley *et al*. 2007).

Because of their relative sea level history, fringing reefs on the GBR commonly extend up to mid-tide level. As the lowest astronomical tide datum defines the GBRWHA boundary on the mainland coast, the areas of mainland fringing reefs that emerge above low tide are not considered further in this report. However, the sub-tidal areas of fringing reefs on the mainland coast do lie within the GBRWHA, as do all fringing reefs located on continental high islands.

Fringing reefs are more common around continental high islands than along the mainland coast (Hopley *et al*. 2007), with 352 fringing reefs (~46% of the GBR total) concentrated between 20-22°S associated with the Whitsunday, Cumberland and Northumberland Island Groups. Coastal fringing reefs are only common along the mainland Whitsunday coast from Cape Conway to Cape Gloucester, while elsewhere on the mainland coast they are rare and mostly poorly developed. There are no mainland fringing reefs south of Cape Conway, or between Cape Gloucester and King Reef, some 300 km further north. North of King Reef small fringing reefs are sporadically developed on rocky headlands until Yule Point, where a larger fringing reef extends ~6 km alongshore. Further north, fringing reefs are only sporadically developed on the mainland coast except at Cape Tribulation where reef flats typically extend around 80 m offshore from beaches and headlands, and occasionally by as much as >1 km (Hopley *et al*. 2007). Fringing reefs on the GBR occur in three main coastal settings (Hopley *et al*. 2007):

1. attached to rocky headlands;
2. in embayments on continental high islands; and
3. adjacent to the beach base on usually linear stretches of sandy coast.

Stratigraphic and age investigations have been undertaken on only a very small sample of GBR fringing reefs (just 3% of the 758 fringing reefs). A variety of reef initiation substrates have been identified, including igneous bedrock, Pleistocene reef, gravel and boulders, and sand and Pleistocene clays (Smithers *et al.* 2006). The earliest known Holocene growth had commenced on the fringing reef at Hayman Island by 9.3 ka (Hopley *et al*. 1978; Kan *et al.* 1997), and radiometric dating of cores drilled through reef flats indicate that the most rapid rates of vertical reef growth generally occurred between 7 and 5 ka (Davies and Hopley, 1985), after which rates slowed as vertical accommodation space was exhausted as the reefs reached sea level (see Hopley *et al*. 2007). Recent investigations suggest that there was a hiatus in the initiation of reef growth on the inner GBR, including on many fringing reefs between around 4 and 2.3 ka (Perry and Smithers, 2010; Perry and Smithers, 2011), clearly pre-dating European influence and roughly coinciding with a similar decline recorded on other reefs in the eastern and Northern Pacific (Toth *et al*. 2012; Hamanaka *et al*. 2012). A structural classification of fringing reef development based on reef chronostratigraphic investigations was presented by Hopley and Partain (1987) and refined by Smithers *et al.* (2006) and Hopley *et al.* (2007). Five reef classes were identified:

1. simple fringing reefs that have initiated and prograded seaward over rocky foreshores;
2. complex fringing reefs where initial reef growth is stranded seaward by shoreline back-stepping during the postglacial transgression, but subsequently combines with the later developed fringing reef to form a contiguous feature;
3. fringing reefs developed over pre-existing positive sedimentary features such as leeward sand spits or gravel fans;
4. fringing reefs that prograde seaward by episodically developing a new reef structure parallel to the reef front; and
5. fringing reefs that initially developed as nearshore shoals offshore of sedimentary coasts, which subsequently prograde seaward to abut the reef structure.

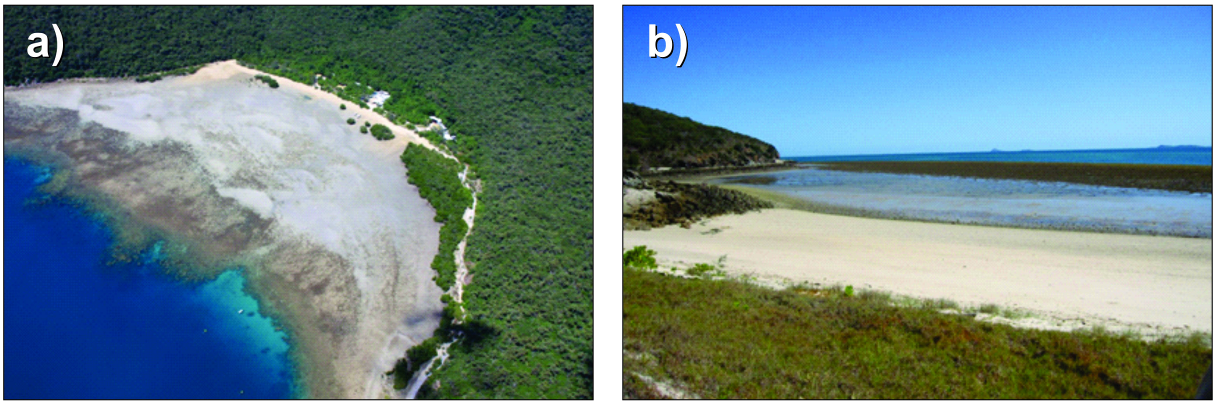


Figure 6.1 Examples of Fringing Reefs a) Pioneer Bay (Orpheus Island), and b) below the beach at Middle Island (Keppel Island Group) (Photographs: S Smithers).

Most fringing reefs on the GBR are located on islands near to the mainland coast or adjoin the mainland itself, where they have experienced a relative sea level fall of 1-1.5 m since the mid-Holocene (7-4 ka). This fall in relative sea level is associated with hydro-isostatic adjustment of the continental shelf to the load imposed by the sea transgressing across the shelf following the end of the last glacial maximum. Hydro-isostatic adjustment typically involves subsidence of the outer shelf due to deeper inundation and higher load, with compensatory upward flexure of the inner shelf to the west of a hinge point referred to as the zero isobase line (Chappell *et al.* 1982; Lambeck and Nakada, 1990; Lewis *et al.* 2012). A consequence of this history is that most fringing reefs on the GBR include emergent back reef zones which were constrained by higher mid-Holocene sea levels, and reef flats that slope toward the contemporary reef edge that developed as the reef prograded seaward as relative sea level fell (Chappell *et al*. 1982; 1983). Fossil corals, including microatolls whose upper surfaces reliably record the position of low tide datum (Smithers and Woodroffe, 2000), are well preserved over many of these reef flats. Some live coral survives over the emergent back reef zones in pools held over the reef flats at low tides, but at most fringing reefs on the GBR live coral is now restricted to the outer fringe and slopes, where the modern equivalents of fossil corals observed on the emergent backreef zones - including those exhibiting microatoll morphology - can usually be identified. Although the emergent backreef zones are considered by some to be aesthetically less interesting than the lower zones dominated by living coral, they preserve important information about how coral reefs responded to relative sea level change through the late Holocene and also key records of geological processes such as isostatic adjustment and tectonics (see Lambeck and Nakada, 1990).

In addition to being vertically constrained by sea level, radiometrically dated microatolls that occur across the surfaces of fringing reefs on the GBR indicate that lateral growth or progradation has also been limited on many reefs over the past few millennia, even though they appear to have supported productive coral communities on their reef crests and fore slopes in the recent past (Smithers *et al.* 2006). The factors responsible for producing and maintaining this senescent growth phase remain poorly understood, but are critical for understanding and projecting the growth potential of other modern reefs.

6.1.2 Description of OUV

- The high number and diversity of fringing reefs on the GBR is exceptional. Although we identify specific examples in Table 6.1, we again emphasise that it is the size and diversity of the GBR system in its entirety that underpins its integrity and OUV, in this case by providing a diversity of fringing reef geomorphologies that have developed and survive over a range of environmental conditions such as radical changes in sea level, tide range, storm exposure, sea temperature and salinity regimes, and water quality (*criteria viii and ix)*.
- Through the cementation and preservation of the aragonitic skeletons of their corals, fringing reefs preserve in their geological structure and taxonomic composition histories of environmental conditions on the GBR over the past 9 ka , and where they grow over Pleistocene reefal substrates, beyond that (*criteria viii)*.
- Fringing reef structures are archives of palaeoecological and palaeoenvironmental conditions and processes extending back to the early to mid-Holocene. These archives of baseline environmental information also extend to geochemical proxies of conditions such as sea surface temperature, salinity, and water quality – and of coral calcification and growth responses to these fluctuations - preserved in the skeletons of corals (*criteria viii).*
- The morphology and preservation of sea level indicators such as coral microatolls on fringing reef flats has enabled the reconstruction of detailed and precise sea level histories on many fringing reefs (*criteria viii)*.
- Spatial variations in relative sea level histories reveal the influence on reef growth of geological processes such as isostatic adjustment and flexure of the continental shelf, driven by the global rise in sea level at end of the last glaciation (*criteria viii)*.
- Fringing reef flats on the GBR have formed over a wide range of substrates, unlike shelf reefs that grow almost exclusively over antecedent Pleistocene reef substrates. They offer important insights into coral colonisation processes and potential locations for reef initiation and growth into the future (*criteria viii)*.

*Table 6.1 Selected examples of fringing reefs with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.1).*

Feature	Outstanding Universal Values	References
Cape Tribulation**	• Mainland fringing reefs (rare). • Adjacent to Wet Tropics WHA. • Beach base and gravel fan substrates and settings. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Lucas *et al*. 1997 • Veron, 1987a • Johnson and Carter, 1987 • Partain and Hopley, 1989 • Hopley *et al*. 2007
Yule Point**	• Mainland fringing reef (rare). • Initiated as a nearshore shoal before transforming to fringing reef through seaward progradation of mainland shore. • Large well-developed feature. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Hopley *et al*. 2007 • Bird, 1971
King Reef	• First mainland fringing reef north of Whitsundays. • Initiated as a nearshore shoal before transforming to fringing reef through seaward progradation of mainland shore. • Has developed over varied substrates including coffee rock, Pleistocene clays, sand, and mangrove muds. • Large well-developed feature. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting. • Contains excellent examples of large *Porites* bommies and microatolls critical to establishing environmental and sea level histories.	• Hopley *et al*. 2007 • Hendy *et al*. 2003 • Roche *et al*. 2011 • Daley, 2005
Dingo Beach	• Mainland fringing reef on Whitsunday coast. • Embayment setting. • Large, well developed feature • Developed over a variety of substrates (Pleistocene clay, mangrove muds, igneous bedrock). • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Lucas *et al*. 1997 • De Vantier *et al*. 1996 • Hopley *et al*. 2007
Lizard Island	• Continental High Island in Northern GBR. • Fringing reefs occur as part of a complex reef and barrier system • Fringing reef relatively close to outer reef margin. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting. •	• Hughes, 1999 • Rees *et al*. 2006

Feature	Outstanding Universal Values	References
Dunk Island	• Continental High Island – inshore Wet Tropics. • Diversity of fringing reef development observed around the island with development over sandspit at resort reef and development over rocky headlands and boulders observed at Stingaree Reef. • Complex growth histories determined. • Contains excellent examples of large *Porites* bommies and microatolls critical to establishing environmental and sea level histories. • Stingaree Reef is large with a width of 1.2 km. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Hopley *et al.* 2007 • Daley, 2005 • Perry and Smithers, 2011
Orpheus Island - Iris Point**	• Continental High Island – Large windward fringing reef • Large and broad windward reef flat, which is unusual on the GBR. • Developed over boulder beach which provides record of 'Holocene high-energy window', a period in the early to mid-Holocene when the outer GBR was not yet at sea level and inshore reefs were more exposed to storm waves. • Contains excellent examples of large *Porites* bommies and microatolls critical to establishing environmental and sea level histories. • Highly complex reef flat morphology (8 separate zones) that preserves evidence of past and contemporary environmental conditions and processes. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Lucas *et al.* 1997 • De Vantier, 1996, pers Comm. • Hopley, 1984 • Hopley and Barnes, 1985 • Hopley *et al.* 1983 • Hopley *et al.* 2007 • Chappell *et al.* 1983 • Gagan *et al.* 1996
Orpheus Island - Pioneer Bay**	• Continental High Island - Broad leeward embayment fringing reef. • Developed over transgressive muds. • Contains excellent sequence of mid-late Holocene microatolls across emergent reef flat critical to establishing reef growth, environmental and sea level histories. • Continues to prograde, but at apparently slowing rate. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Hopley *et al.* 1983 • Hopley *et al.* 2007 • Chappell *et al.* 1983 • Slocombe, 1981
Fantome Island	• Continental High Island - Broad leeward embayment fringing reef. • Relatively muddy reef fabric. • Continues to prograde, but at apparently slowing rate. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Hopley *et al.* 2007 • Johnson and Risk, 1987
Palm Island	• Continental High Island – examples of simple fringing reefs formed on rocky shores on eastern shoreline. • Intrinsic scientific value as example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Hopley *et al.* 1983 • Hopley *et al.* 2007

Feature	Outstanding Universal Values	References
Hayman Island**	• Continental High Island with broad fringing reef developed over Pleistocene reef foundations – rare on GBR. • Earliest known initiation age for fringing reef growth on GBR. • Detailed palaeoecology and stratigraphy established from surveys through dredged channel to resort. • Type example of complex fringing reef development through detrital infill behind initial fringing reef stranded offshore by back stepping of the shoreline during the transgression combined with seaward progradation of fringing reef established once sea level stabilised. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Hopley *et al.* 1978 • Harvey *et al.* 1979 • Kan *et al.* 1997 • Hopley *et al.* 2007
Scawfell Island	• Continental High Island with thickest known Holocene sequence. • Chronostratigraphic evidence suggests that may have established as headland attached – rare example. • The thickest vertical accumulations of Holocene fringing reef growth established to date, rising from a bedrock foundation 18 m below mean low water to the sea surface. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Hopley *et al.* 2007 • Kleypas 1991 • Kleypas and Hopley, 1992
Redbill Reef	• Small Continental High Island with large fringing reef, including lagoon. • Unique small granitic Island (0.016 km^2) with 8.8 km^2 of fringing reef around it • Classic lagoonal reef that has completely infilled. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Hopley *et al.* 1984 • Hopley *et al.* 2007
Digby Island	• Continental High Island fringing reef that is the only confirmed occurrence of Pleistocene reef exposed at the surface on the GBR. • Limited accommodation space and patchy thin development of Holocene reef over shallow Pleistocene reef substrate. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Kleypas 1991 • Hopley et al. 2007
Wild Duck Island	• Small Continental High Island with fringing reef in area with large tidal range (~7 m) and high turbidity normally assumed limiting to coral and coral reef growth. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Lucas *et al.* 1997 • De Vantier 1996 pers Comm • Kleypas 1996

Feature	Outstanding Universal Values	References
Keppel Island Group	• Continental High Islands on inshore southern GBR with substantive fringing reef development. • Fringing reefs are typically less well developed than their northern counterparts. • Most southerly fringing reefs in GBR due to absence of appropriate substrates further south. • Exposed to episodic flood plumes from Fitzroy River, which drains the largest coastal catchment in Queensland. • Intrinsic scientific value as rare example to improve understanding fringing reef evolution and dynamics in unusual setting.	• Hopley *et al.* 2007 • Lucas *et al.* 1997 • Van Woesik *et al.* 1995 • Byron, 1994 • Daley, 2005

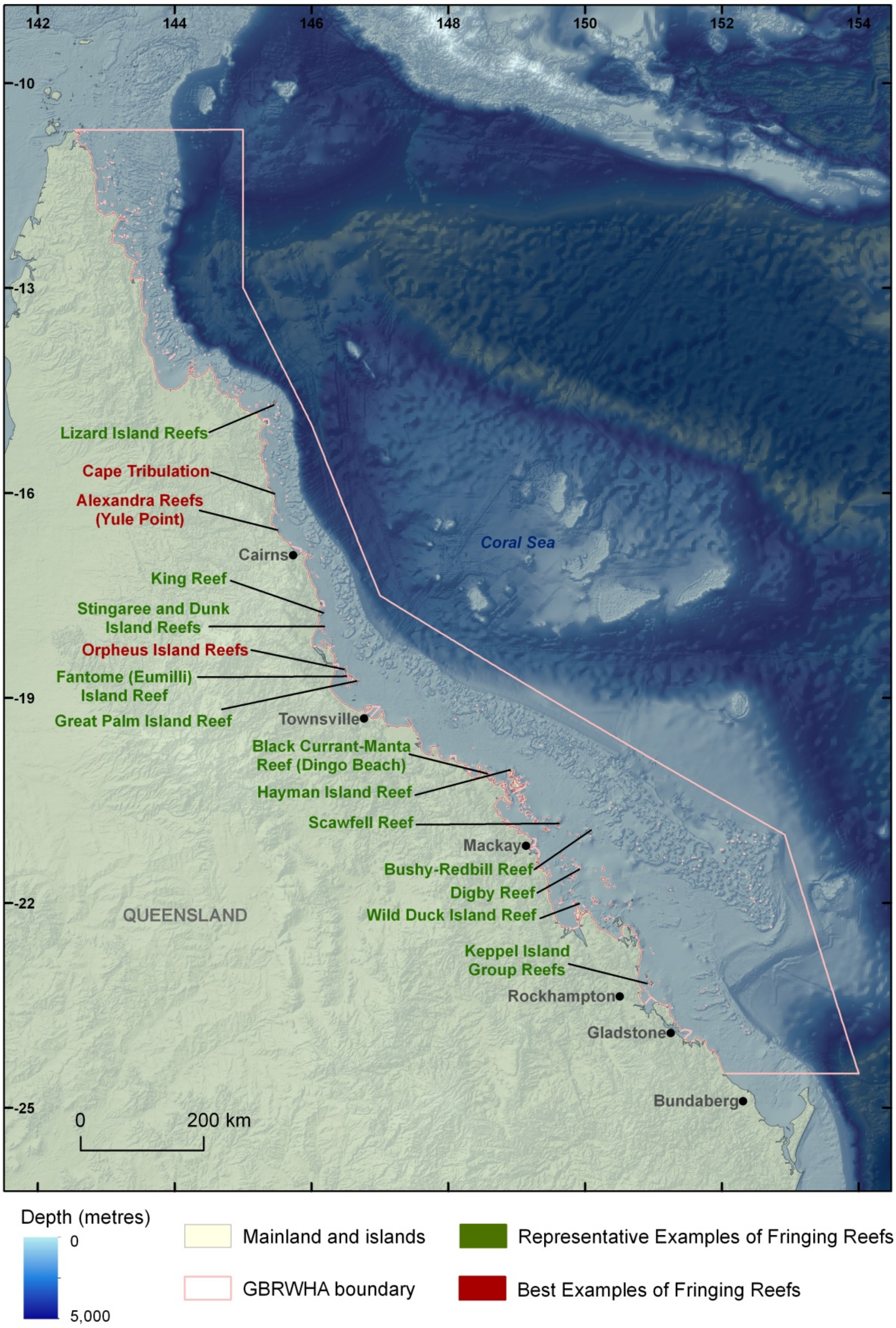


Figure 6.2 Selected examples of fringing reefs in the GBRWHA.

6.2 Inshore Turbid Zone Reefs

6.2.1 Description

Inshore turbid zone reefs are coral reefs that develop under the influence of sediments derived from the mainland or islands (terrigenous), either directly where high levels of terrigenoclastic sediment accumulation or sediment flux occur, or indirectly where turbidity is high because fine-grained sediments are continuously or episodically in suspension. They are important localised sites of carbonate production within otherwise terrigenous sediment-dominated marine environments. Inshore turbid reefs are typically located in turbid water shallower than 10 m, and usually within 10 km of the coast. They include both shore attached (fringing reefs in locations close to the mainland) and non-shore attached shoals. They occur in locations where reef development is affected by terrigenous sediment inputs, elevated turbidity and fluctuating salinities (24-36 parts per thousand (ppt)). Since European settlement, some of these inshore areas have experienced diminished water quality due to nutrient and pollutant influx and enhanced sediment loads from urban and agricultural runoff. They may be directly or indirectly exposed to terrigenous-clastic sediments through sediment delivery by flood plumes from coastal catchments, or by sediment and turbidity generated by the resuspension of previously delivered sediments by waves and currents (Browne *et al.* 2012). They are commonly obscured from view by muddy waters, and as a result their distribution, geomorphological traits and ecological roles are not well understood. Inshore turbid zone reefs grow in conditions usually considered marginal for reef growth (Fabricius, 2005) and are more restricted both spatially and bathymetrically than clear-water reefs (depth is limited by the shallowness of the photic floor in turbid settings, although many key taxa have demonstrated heterotrophic capacity (Anthony, 2000). However, as research on these systems has increased over the past decade it has shown that inshore turbid zone reefs are relatively common, support high diversity and high coral cover, are typically relatively young, and can grow very rapidly (Smithers and Larcombe, 2003; Perry and Smithers, 2006; Perry and Smithers, 2010; Palmer *et al.* 2010; Browne *et al.* 2010). Species assemblages and reef fabrics and structures from inshore turbid zone reefs also appear analogous to basal reef units in deep cores retrieved from the outer reefs (see Webster and Davies, 2003), suggesting that an improved understanding of contemporary inshore turbid zone reef systems can provide insights into the earliest phases of reef establishment on the shelf at the onset of the development of the GBR.

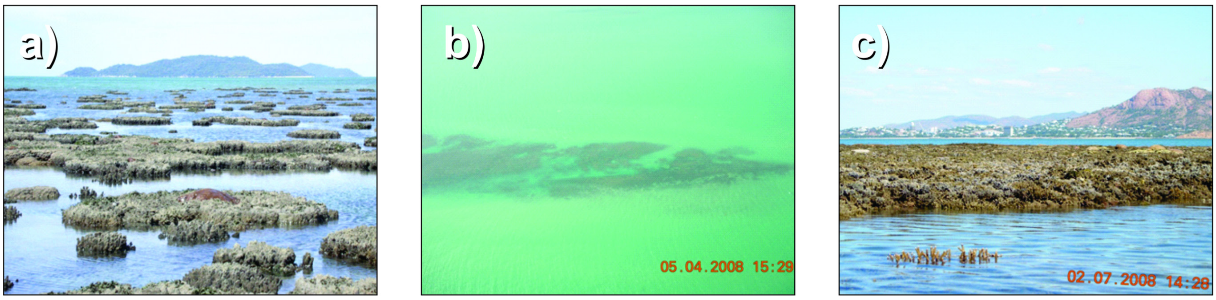


Figure 6.3 Examples of Inshore turbid zone reefs a) Lugger Shoals (Looking towards Dunk Island), b) Middle Reef (offshore Townsville) (aerial photograph) and c) Middle Reef on a low spring tide (Photographs: S Smithers).

6.2.2 Description of OUV

- Inshore turbid zone reefs have diverse and unique coral communities that form distinctive reef structures (*criteria viii and ix)*.
- Provide in-reef structures and contributing species assemblages, and archives of reef growth and baseline environmental conditions in marginal settings (*criteria viii)*.
- Because of their proximity to the coast, they are exposed to more terrestrial and nearshore disturbances compared to most other reefs on the GBR, and thus can provide greater insights into coral impacts and recovery in this environment (*criteria viii)*.
- Are often relatively young reefs, in many cases still actively accreting (*criteria viii)*.
- Can accrete at remarkably rapid rates, often more rapidly than clear water reefs (*criteria viii and vii)*.
- Build reefs that incorporate both reef carbonates and terrigenous sediments that differ in fabric and constructional dynamics from better-known clear-water coral reefs (*criteria viii)*.
- The inshore turbid zone reefs of the GBR are amongst the best described and studied of this unique type in the world (*criteria viii)*.
- Provide important insights into reef and coral growth potential under elevated sediment and nutrient loads. As they are located close to sites of human activity they also form important environmental indicators of direct human impact (*criteria viii)*.
- Provide great insights into the initiation of coral reefs in sedimentary settings, analogous to original start up conditions for the earliest reefs in the GBR and other regions (*criteria viii)*.
- Inshore turbid zone reef structures are archives of palaeoecological and palaeoenvironmental conditions and processes extending back to the mid-Holocene. These archives also extend to geochemical proxies of conditions such as sea surface temperature (SST), salinity, and water quality – and of coral calcification and growth responses to these fluctuations - preserved in the skeletons of corals (*criteria viii)*.

*Table 6.2 Selected examples of inshore turbid zone reefs with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.3).*

Feature	Outstanding Universal Values	References
Lugger Shoals	Inshore turbid zone reef located in the Wet Tropics (along the Great Dividing Range of NE QLD, between Townsville and Cooktown) • Developed over subtidal sands • Contains pre-4000 unit and a more recent phase of reef growth extending to the present. • Includes many *Porites* microatolls. • Has only nascent reef flat development. • Scientific value as example of turbid zone reef in wet tropics to improve understanding of inshore turbid zone reef evolution and dynamics.	• Perry and Smithers, 2006
Paluma Shoals**	Inshore turbid zone reef located in an exposed bay setting in the Dry Tropics (Burdekin River catchment and associated coastal and marine areas). • Relatively large complex of inshore shoals. • Includes both shore attached and nearshore components. • Includes many *Goniastrea* microatolls. • Example of an inshore turbid zone reef located in a relatively high-energy setting. • Extensive reef flat development. • Mostly accumulated in the past 1500 years. • Intrinsic scientific value as example of turbid zone reef in relatively high-energy dry tropics setting to improve understanding of inshore turbid zone reef evolution and dynamics.	• Larcombe *et al.* 2001 • Smithers and Larcombe, 2003 • Palmer *et al.* 2010
Middle Reef**	Inshore turbid zone reef located in an sheltered setting in the Dry Tropics • Middle Reef is a relatively large, linear structure, extending 1.2 km from the north-west to the south-east and 300 m across at its widest point. It is aligned with the dominant north-westerly (NW) currents that flow between Magnetic Island and the mainland. • Provides an excellent example of reef growth and composition at a site regularly exposed to turbidity of up to 50 mg/l. • Includes many *Goniastrea* microatolls across the reef flat. • Example of an inshore turbid zone reef located in a relatively high-energy setting. • Extensive reef flat development. • Mostly accumulated in the past 600 years. • Exposed to an active disturbance regime but exhibits high coral cover (39.5% compared to an average over the GBR of <27%), high diversity, and rapid rates of coral growth and reef accretion. • Despite location in highly turbid setting and potential exposure to run-off of storm water from Australia's largest tropical city Middle reef has exhibited resilience to these pressures and very good capacity to recover from disturbance events such as mortality and bleaching events associated with wet season flooding. • Intrinsic scientific value as example of turbid zone reef in relatively low-energy dry tropics setting to improve understanding of turbid zone reef evolution and dynamics.	• Perry *et al.* 2012 • De'ath and Fabricius, 2010 • Browne *et al.* 2010 • Sweatman *et al.* 2007

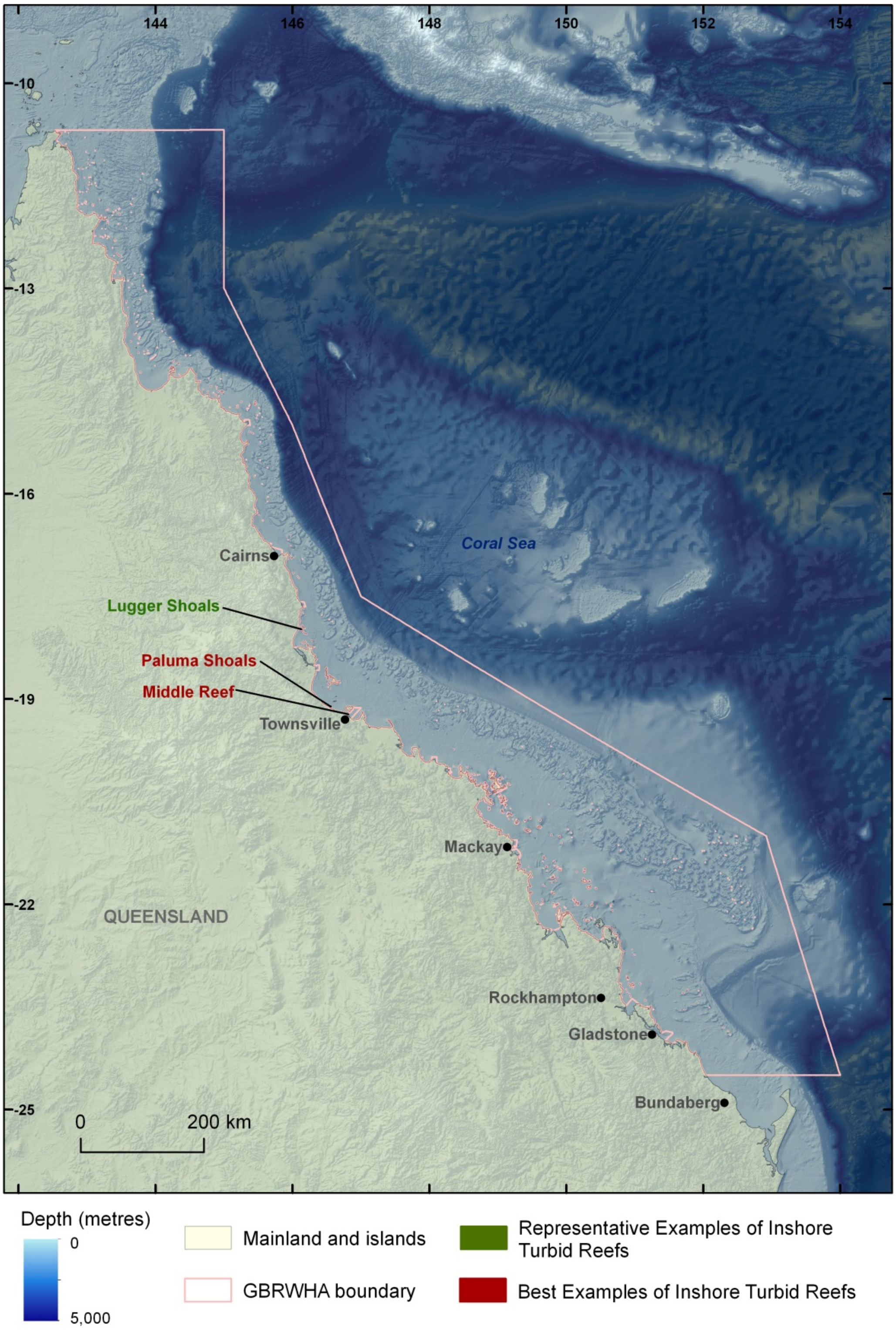


Figure 6.4 Selected examples of inshore turbid zone reefs in the GBRWHA.

6.3 Shelf Reefs (Excluding Fringing, Ribbon and Inshore Turbid Zone Reefs)

6.3.1 Description

Shelf reefs are located on the continental shelf, which extends from the more sheltered but runoff affected shore zone out to the exposed, higher energy environment of the shelf edge. Reefs in the mid-shelf zone experience higher energy than the shore zone and are less affected by terrestrial runoff.

Coral reefs on the GBR display a remarkable geomorphological diversity, including reefs of varying size, shape and depth, encompassing a range of reef types including unmodified antecedent platforms, irregular reef patches, crescentic reefs, lagoonal reefs, and planar reefs (described below). Although this diversity may appear random, variations in reef geomorphology may be interpreted as a function of key variables such as suitable substrate size, depth, and morphology, and to a lesser extent relative sea level history and carbonate-organism productivity (Hopley, 1982; 1983). Moreover, it is possible to consider a reef's morphology as part of a spectrum of possible reef types, with reefs transitioning through the spectrum with time. Hopley (1982) developed a morphogenetic classification scheme for mid-shelf reefs on the GBR that explains their morphological diversity and provides a broader understanding of the development of reef geomorphology elsewhere, including outside of the GBR. The essential framework for understanding the morphological and evolutionary development of shelf reefs can be summarised as:

1. large reefs usually grow over large antecedent substrates, but it is possible for small reefs to grow on large substrates, at least initially;
2. reef growth is usually most productive on the windward margin of platforms;
3. reefs growing from deeper substrates will reach the sea surface later than reefs growing from shallower substrate; and
4. the larger a reef, the longer it will take to infill its lagoon to form a planar reef.

Reefs without substantive reef flat development (unmodified antecedent platforms, submerged reefs, irregular reef patches) were defined as juvenile reefs, while those with reef flats and an unfilled lagoon (crescentic reefs, lagoonal reefs) are considered mature, and planar reefs where the lagoon is completely infilled and a reef flat extends across the entire reef platform are classified as senile. It is important to note that within each of these classes there are also transitional forms; for example, an incipient crescentic reef may have only a weakly developed hard coral line and a mature crescentic reef may be hard to distinguish from an incipient lagoonal reef. Within this framework it becomes apparent that most planar reefs have progressed to that stage because they are relatively small and have developed over relatively shallow foundations (allowing rapid growth to sea level and a small volume lagoon to infill). Many reef patches and crescentic reefs grew on relatively deep foundations and consequently took longer to reach sea level. As a result they progress more slowly though the evolutionary sequence. Most lagoonal reefs rise above relatively large foundations and require a longer time to infill their lagoons.

The stages and reef types described below are after Hopley *et al.* (2007):

JUVENILE

- **Unmodified antecedent platform reefs**
  - Pleistocene foundation, no modern growth.
  - Mesophotic coral ecosystems (MCEs - discussed in Section 6.7).
  - Reefs not at modern sea level but with some modern growth – typically these submerged reefs grow over topographic high points on the underlying substrate.
- **Irregular reef patches**
  - Reefs growing on Pleistocene foundations that have reached current sea level to form small and irregular 'patches at sea level' that have not yet coalesced to form substantive contiguous reef flats.

MATURE

- **Crescentic reefs**
  - Coalescence of patch reefs at the windward (most productive) margin of platforms to form crescent–shaped reef flats with open back-reef areas.
- **Lagoonal reefs**
  - Extension of reef patches around the lagoon margin to enclose or partly enclose the lagoon.

SENILE

- **Planar reefs**
  - Infilling of lagoons with patch reef growth and sediment derived from reef flat margins – eventually forms an extensive sediment covered reef flat.

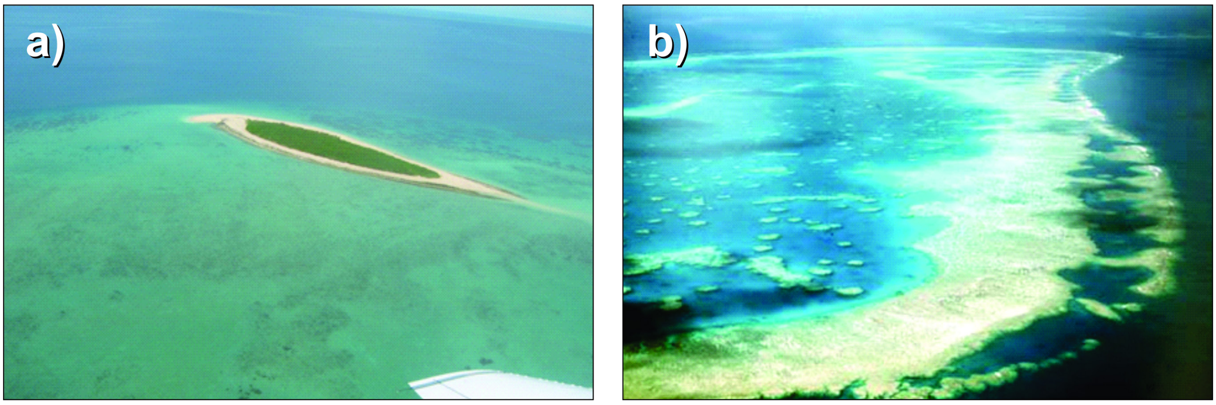


Figure 6.5 Examples of Shelf Reefs a) Stapleton Reef and Cay (aerial view) (Photograph: S Smithers), and b) Middle Reef (on the GBR shelf - aerial photograph) (Photograph: D Hopley).

Hopley *et al*. (2007) identified two additional reef types – ribbon reefs and fringing reefs - both of which are important elements of the GBR. A large number of fringing reefs occur on the GBR and ribbon reefs characterise much of the outer reef margin north of Cairns. Fringing reefs are described in Section 6.1 and ribbon reefs in Section 6.4.

6.3.2 Description of OUV

- The geomorphological diversity of shelf reefs on the GBR effectively preserves a unique record of reef development over time, with different geomorphological forms representing different stages of reef evolution, as well as the evolution and development of different parts of the GBR system (*criteria viii)*.
- The distribution of different reef types across and along the GBR allows the relative influence of driving factors to be evaluated in different environmental settings (*criteria viii and vii)*.
- Understanding the processes that drive reef progression through the geomorphological sequence, and the rates at which this occurs, is critical to understanding the dynamics and trajectories for reef growth and stability. Importantly, this knowledge is essential for understanding the form and dynamics of natural changes in physical and ecological processes (for example as reefs patches coalesce backreef areas develop) and habitat provision for key biological species (lagoonal habitats are lost as productive reefs infill lagoons), and can underpin effective conservation and management (knowledge of the successive development of reefs indicates the time frames over which key habitat/processes will be sustained or lost as reefs mature and become senile) (*criteria viii and ix)*

*Table 6.3 Selected examples of shelf reefs with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.6).*

Feature	Outstanding Universal Values	References
Reef 17-065 **	Patch Reef – collection of irregular patches on mid-shelf of central GBR. • To date this is the only patch reef with (limited) data available for its Holocene evolution. • Just one hole drilled to 9.3 m depth, did not reach pre-Holocene substrate, indicating that the Holocene reef record is thick here and well-represented. • Least mature (most juvenile) so-far reef drilled on GBR. • Intrinsic scientific value as rare example of dated patch reef to help inform reef evolution and dynamics.	• Hopley *et al.* 2007 • Graham, 1993
Williamson Reef	Crescentic Reef developed over medium sized reef substrate on northern GBR. • Holocene growth history captured in one drill core to Pleistocene (17 metres below sea level) at windward rim. • Intrinsic scientific value as unusual example of crescentic reef morphology with significant reef flat development from which four dated drill cores are available.	• Hopley *et al.* 2007 • Davies and Hopley, 1983 • Davies *et al.* 1985
East Hope Reef	Crescentic Reef developed over relatively small sized reef substrate on northern GBR. • Crescentic reef with relatively large reef flat interpreted as forming through the coalescence of reef rim and large patch reef. • Intrinsic scientific value as unusual example of crescentic reef morphology with significant patch reef and broad reef flat development, and which is able to support a well vegetated sand cay.	• Hopley *et al.* 2007 • Davies and Hopley, 1983 • Hopley, 1982
Potter Reef **	Crescentic Reef developed over medium sized reef substrate on central GBR. • Crescentic reef without full hardline reef development along windward rim, but where it has developed it is clear that it has formed through the merging of two parallel reef lines. • Intrinsic scientific value as unusual example of crescentic reef morphology that can be examined further to inform knowledge of shelf reef development.	• Hopley *et al.* 2007 • Graham, 1993

Feature	Outstanding Universal Values	References
Taylor Reef **	Crescentic Reef developed over medium sized reef substrate on central GBR. • Excellent example of a relatively mature crescentic reef, with reef flat enclosing more than 50% of the reef platform. • Well-developed patch reefs in lagoon • Large patch reefs of sufficient size to enable unvegetated cay formation. • Intrinsic scientific value as unusual example of crescentic reef morphology that can be examined further to inform knowledge of shelf reef development.	• Hopley *et al.* 2007 • Graham, 1993
Britomart Reef	Large Crescentic or Open Lagoonal Reef located on the central GBR. • Very large mid-shelf reef, with a platform 23 km from east to west and covering 134.4 km^2 in area. • Two dated drill cores are available, both of which encountered the Pleistocene substrate. • Intrinsic scientific value as excellent example of crescentic reef morphology and development over large substrates.	• Hopley *et al.* 2007 • Johnson *et al.* 1984
Grub Reef	Crescentic Reef developed over medium-sized reef substrate on central GBR. • Unusual morphology in that the reef rim is not fully developed around the windward platform margin, but where it has reached sea level has formed an almost fully enclosed lagoon that occupies around 24% of the reef platform area. • Where the reef has not yet reached sea level on the windward margin an immature crescentic rim can be mapped and will reach sea level in the future. • Large patch reef development across the platform, some of which are relatively large. • Intrinsic scientific value as unusual example of crescentic reef morphology with various parts of the reef apparently at different stages of the evolutionary sequence.	• Hopley *et al.* 2007
Stanley Reef	Crescentic Reef developed over medium to large-sized reef substrate on central GBR that is transitioning toward an open lagoonal reef. • Windward reef rim to 400 m wide occurs along 45% of the platform margin, and continues as a submerged feature for another 30%. • Patch reefs well developed in lagoon. • Reef platform bisected by a deep channel to 60 m depth. • Intrinsic scientific value as example of crescentic reef transitioning to lagoonal phase, and because of the unusual channel feature.	• Hopley *et al.* 2007 • Hopley 1982 • Davies and Hopley, 1983 • Davies *et al.* 1985 • Marshall, 1985
Davies Reef	Crescentic Reef developed over medium-sized reef substrate on central GBR that is transitioning toward an open lagoonal reef. • One drill core from this reef is noteworthy as it captures a palaeosol below the Holocene reef unit (which begins 26 m below the reef surface) that demonstrates that the Pleistocene reef was sub-aerially exposed during glacial lowstands (periods of sea level regression) and then recolonised by the Holocene reef following the post-glacial marine transgression. • Reef flat has developed around 70% of the platform margin, and includes a double front morphology over large sections. • Intrinsic scientific value as example of crescentic reef transitioning to lagoonal phase, and because of palaeosol evidence in the drill core and the prevalence of the double front reef rim morphology.	• Hopley *et al.* 2007 • Grimes 1982

Feature	Outstanding Universal Values	References
Darley Reef	Large reef platform in the central GBR with different parts classified as Crescentic or Lagoonal Reef • Large (81.3 km2) platform with very complex morphology • Numerous small lagoons and 'crescentic' reef flats developed over various parts. • Major channel (500 m wide, 4 km long) dissects platform. • Intrinsic scientific value as example of potentially complex development over large reef platform foundations.	• Hopley *et al.* 2007 • Hopley and Harvey, 1982 • Hopley, 1982 • Harvey, 1980
Gable Reef	Lagoonal (open) Reef developed over medium-sized reef substrate on central GBR. • Continuous reef rim around 70% of margin, with submerged rim and patches over remaining 30%. • Distinctive double rim. • Intrinsic scientific value as example of mature lagoonal reef with best example double rim.	• Hopley *et al.* 2007
One Tree Island / Reef **	Lagoonal Reef developed over medium-sized reef substrate on southern GBR. • Considered to be a classic example of a lagoonal reef. • One of the best studied reefs of the GBR. • Supports a vegetated shingle cay on the windward rim (islands of this type are rare on the GBR).	• Hopley et al. 2007 • Daley, 2005 • Davies and Marshall, 1979 • Davies and Hopley, 1983 • Marshall and Davies, 1982
Corbett Reef	Large Planar Reef on northern GBR. • Very large – 207.5 km^2	• Hopley *et al.* 2007
Stapleton Reef	Planar Reef on northern GBR developed over medium to small reef substrate. • Sandy cay developed on planar reef flat. • Pleistocene substrate at 14.6 m. • Scientific value as example of mature planar reef of medium size developed over a deeper Pleistocene reefal substrate, but not having formed a low wooded island.	• Hopley *et al.* 2007 • Thom *et al.* 1978
Bewick Reef	Planar Reef on northern GBR developed over small and shallow reef substrate. • Low wooded island developed on planar reef flat. • Pleistocene very shallow (4 m) below modern reef flat. • Scientific value as example of mature planar reef of small size developed over a shallow Pleistocene reefal substrate.	• Hopley *et al.* 2007 • Thom *et al.* 1978 • Kench *et al.* 2012
Boulder Reef	Planar Reef on northern GBR developed over medium reef substrate. • Location of deep cores through to pre-reefal basement • Reef flat occupies 85% of platform area. • Scientific value as location of deep drilling cores capturing the entire reef sequence.	• Hopley *et al.* 2007 • Davies and Hopley, 1983 • Davies *et al.* 1985 • Webster and Davies, 2003

Feature	Outstanding Universal Values	References
Wheeler Reef	Planar Reef on central GBR developed over small reef substrate. • Small Planar Reef that appears more like a larger patch reef than typical planar reef. • Supports a mobile unvegetated cay • Reef flat interpreted to be recently at sea level due to live coral cover across most of it. • Scientific value as appears to have evolved differently from other planar reefs.	• Hopley *et al.* 2007 • Davies and Hopley, 1983 • Davies *et al.* 1985 • Harvey, 1980
Bushy Redbill Reef **	Planar Reef on central GBR developed over medium reef substrate. • Lagoon almost completely infilled • Developed rapidly, possibly transforming from lagoonal to planar in about 4000 years • Unique in that it has a small granitic outcrop (1.6 ha) exposed on the western side of the platform	• Hopley *et al.* 2007 • Hopley *et al.* 1982 • Hopley *et al.* 1984
Wreck Reef **	Planar Reef on southern GBR developed over medium reef substrate. • Leeward vegetated cay • Pleistocene substrate inferred from seismic data to be relatively shallow (8-17 m) • Planar reef form evolved about 1 ka	• Hopley *et al.* 2007 • Davies and Marshall, 1979 • Davies and Hopley, 1983
Fairfax Reef	Incipient Planar Reef on southern GBR developed over medium reef substrate. • Small vestigial lagoon remains. • Unusual as it supports both a windward shingle cay and a leeward sand cay. • Pleistocene substrate at only 8 m depth below windward reef.	• Hopley *et al.* 2007 • Daley, 2005 • Davies and Marshall, 1979 • Davies and Hopley, 1983

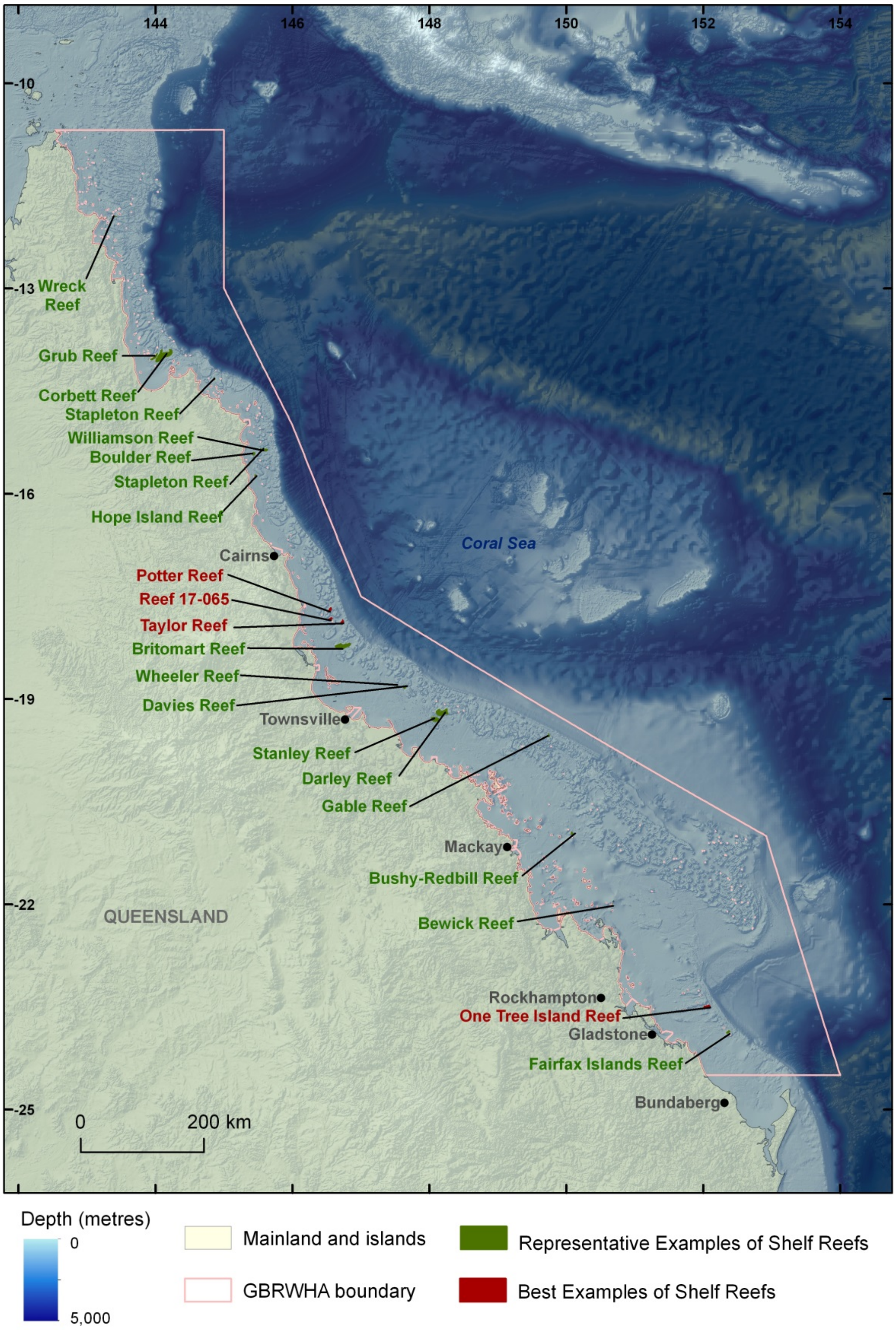


Figure 6.6 Selected examples of shelf reefs in the GBRWHA.

6.4 Ribbon Reefs

6.4.1 Description

Ribbon reefs are recti-linear shelf-edge barrier reefs located along the continental shelf edge of the northern GBR between 10^{o} and 15^{o} S (Andrefouet and Cabioch, 2011). The ribbon reefs are distributed over approximately 700 km of the shelf edge between Cooktown and Torres Strait, with individual ribbon reefs extending to as much as 28 km in length. Seaward of the ribbons the shelf quickly drops to considerable depth, reaching 1,000 m within a kilometre of the reef edge. Narrow passages typically less than 800 m wide separate adjacent reefs. Tidal and other current exchange between the GBR lagoon and the open ocean is concentrated through these passages. Resultant flows are relatively strong and spatially focused, with passage location controlling the spatial distribution of these exchanges including, for example, nutrient-rich waters upwelled from deeper waters off the shelf edge. The linear morphology of the ribbon reef is strongly controlled by the shape of the antecedent structures over which they grow, with the passages in some cases clearly being inherited river valleys or estuaries active during lower sea levels.

Drill core data indicates that Holocene reef growth on most ribbon reefs began soon after the Pleistocene substrate was flooded around 8 ka. Once the ribbons reached the sea surface they developed a morphology that reflects the high energy setting in which they are located, with zonation usually very well developed, and algal pavements with large reef blocks common. Back reef areas are typically sandy and as such support more fragile coral forms.

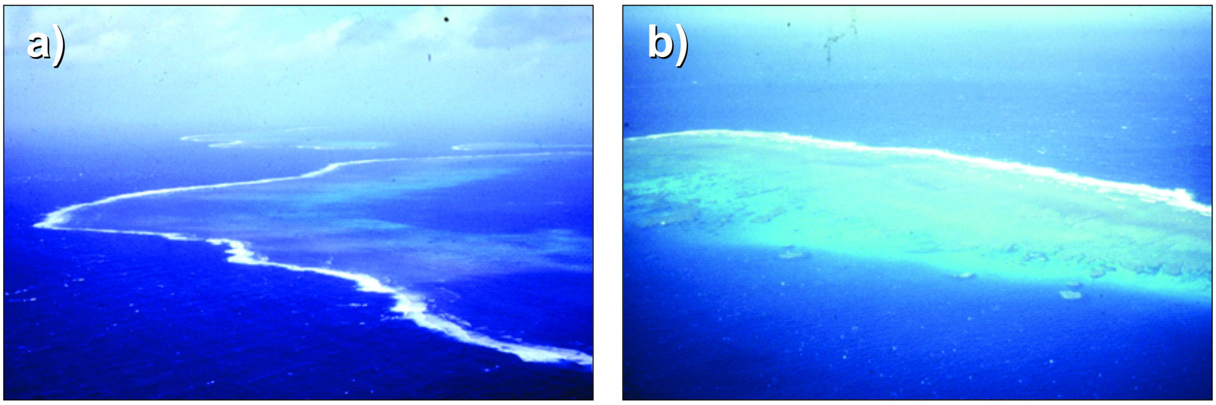


Figure 6.7 Examples of Ribbon Reefs (a & b) Northern Ribbon Reefs (aerial views) (Photographs: D Hopley).

6.4.2 Description of OUV

Ribbon Reefs exhibit key aspects of the OUV of the GBR:

- They are limited to the northern GBR shelf edge, and as such are relatively uncommon and spatially restricted in the GBRWHA (*criteria viii)*.
- Their morphology reflects the combined influences of the antecedent substrate over which the modern reef has grown, and the high incident wave energy approaching from the Coral Sea(*criteria viii).*

- They concentrate tidal currents through the passages that separate neighbouring ribbon reefs, forming distinctive high-energy clear-water habitats (*criteria viii)*.
- They control the distribution of hydrodynamic energy and thereby play a critical role in structuring reef and *Halimeda* habitats across the reef margin (*criteria viii)*.

Their shelf margin location has enabled them to preserve a record of shelf margin subsidence, past sea level oscillations and past phases of shelf-margin reef growth (Veron and Hudson, 1978) (*criteria viii)*.

*Table 6.4 Selected examples of ribbon reefs with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.8).*

Feature	Outstanding Universal Values	References
Three Reefs	Ribbon Reef exposed to strong tidal currents and very strong wave action. • Unique morphology with a reef surface comprised almost entirely of bare limestone, and with spur and groove morphology extending to western reef margin.	• Veron and Hudson, 1978
Tijou Reef**	Very long Ribbon Reef (27.8 km), with width varying from 1,550 m to 640 m. Displays varying morphology along its length. • Steep outer slope, well-developed spurs and grooves, and a reef flat that is mostly devoid of living coral, except along the back reef margin. • The reef is wider at the southern end, and the reef flat is punctuated by two lagoons that reach 40 m in depth and can be several 100 m wide. • Suggest a complex evolution that is yet to be investigated and understood.	• Veron and Hudson, 1978
Yonge Reef**	Well-studied ribbon reef. • Three cores recovered from this reef, including one that reached the Pleistocene basement at 18 m depth. • Described by Stephenson *et al.* in 1931 – long record of historical record not matched by other ribbons on the GBR. • Drill core data contribute to global understanding of sea level change and neotectonics.	• Stephenson *et al.* 1931 • Harvey 1977 • Hopley, 1977 • Veron and Hudson, 1978 • Hopley, 1994 • Hopley *et al.* 2007 • Davies *et al.* 1985
Carter Reef	Well-studied ribbon reef. • Effects of stripping by TC Ivor observed by Hopley and colleagues. Unmatched opportunity to examine recovery of these systems to such impacts. • Drill core data available. • Drill core data contribute to global understanding of sea level change and neotectonics.	• Harvey 1977 • Hopley, 1977 • Hopley, 1994 • Hopley *et al.* 2007 • Davies *et al.* 1985
Ribbon 5 Reef **	Well-studied ribbon reef and site of shelf edge drilling through entire reef sequence. • Dating from a core taken from Ribbon 5 confirms the GBR foundation age of between 452 and 365 ka (Pleistocene) – main reef section • Prior to this a record of 'ephemeral' reef development may have occurred – as indicated by the thin sections found at the base of this reef • Excellent, long record of reef development and sea level change. • Drill core data contribute to global understanding of sea level change and neotectonics.	• Webster and Davies, 2003 • Hopley, 2006 • Hopley *et al.* 2007

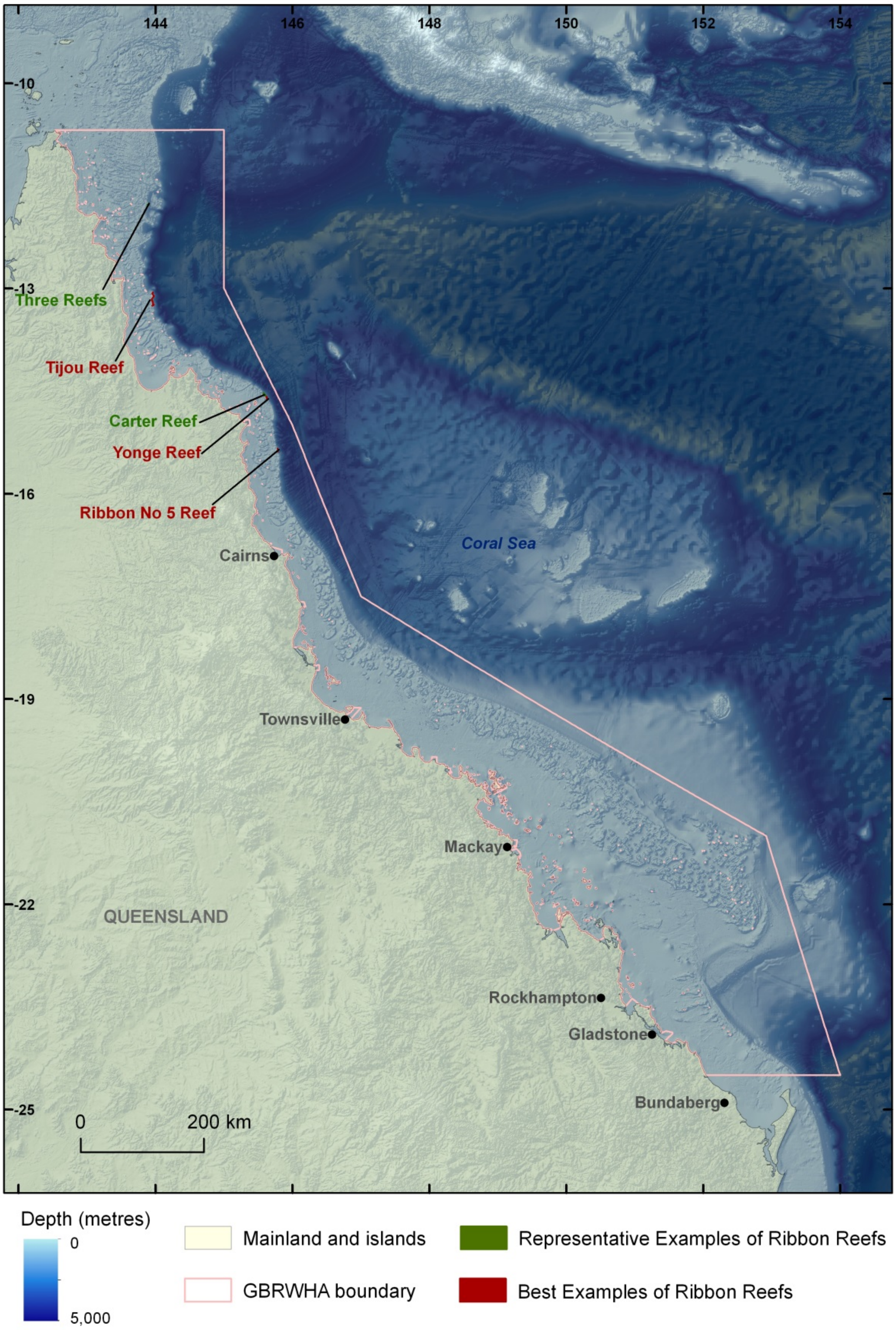


Figure 6.8 Selected examples of ribbon reefs in the GBRWHA.

6.5 Deltaic Reefs

6.5.1 Description

Deltaic reefs are shelf-edge reefs with delta-like platform morphology. They occur predominantly in the northern GBR (Veron, 1978; Hopley 2006; Hopley *et al.* 2007), but several examples also occur within the Pompey Complex further south (Hopley, 2006). The northern deltaic reefs occupy the northernmost 96 km of the GBR shelf-edge, and consist of short ribbon-like reefs (<4 km) parallel to the shelf edge, separated by passages up to 200 m wide and 35 m deep. Delta-like lobes extend west into the GBR lagoon from these passages, but do not develop to the east, beyond the shelf edge, where the steep shelf slope rapidly drops into deep water. Maxwell (1970) showed these features form as strong flood tide currents funnel through the narrow passages and transport sediment into quieter back reef zones where deposition occurs, and these deposits are then colonised by reef communities. Hopley (2006) identified similar deltaic lobes on both the western and eastern sides of the passages through the confining reefs in the Pompey Complex. He surmised that ebb tide deltas were able to form on the seaward side because the shelf slope is less steep than occurs adjacent to ribbon reefs, and that sediments transported east by ebbing tides accumulate and provide the foundation for reef growth. This process appears largely responsible for the complex reef morphology found in many parts of the Pompey Complex.

Veron (1978b) considered that the northern deltaic reefs were 'in the process of active development' due to physical process eroding and redistributing sediment together with the input of new reefal material produced by actively growing reefs. It should be noted, however, that these features likely developed over long periods of time (hundreds of thousands of years), over multiple sea level cycles during the Middle to Late Quaternary. Indeed, Hopley (2006) has suggested that cementation that occurs when these features are sub-aerially exposed during lower sea levels may play an important role in stabilising the deposits so that coral colonisation can occur during highstands (periods of sea level inundation). The stratigraphy preserved in these features may thus preserve important information on Quaternary sea level changes and tidal conditions through the past marine transgressions.

6.5.2 Description of OUV

On the GBR the distinctive morphology of deltaic reefs is restricted to the most northern outer shelf, and to the Pompey Complex. Importantly, the deltaic reefs in these two areas are different, with the northern cohort comprising well-developed flood tide deltas but lacking ebb-tide delta formation. Those in the Pompey Complex typically exhibit both flood and ebb-tide deltas. Deltaic Reefs are important elements of the GBR as:

- They are rare (*criteria viii*).
- They are distinctive reef systems clearly illustrating the relationship between hydrodynamic (tidal) processes and reef evolution and vice versa (*criteria viii*).
- The relationships between the sedimentary deposits on which they form and the overlying reef units can be investigated to better understand reef initiation, growth, sediment dynamics, reef productivity and the response of reefs to Quaternary climate and sea level changes (*criteria viii*).
- Are highly geomorphologically active reefs (*criteria viii and ix*).

*Table 6.5 Selected examples of deltaic reefs with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.9).*

Feature	Outstanding Universal Values	References
Northern deltaic reefs **	Geomorphologically active deltaic reefs on the northern GBR. • Most northern shelf edge reefs of the GBR. • Dominated by flood tides. • Noted to be actively developing – intrinsic scientific value as site of potentially high productivity and geomorphological development.	• Veron 1978a and b
Pompey Complex **	Deltaic reefs further south on the GBR with both flood and ebb-tide deltaic development (fastest tidal currents in the GBR, >4 m/s). • Distinctive morphology key to the formation of the complex reefs of the Pompey Complex. • Dominated by flood and ebb tides. • These reefs are the largest in the GBR, with many >100 km2. • Pompey Complex deltaic reefs have formed over multiple sea level cycles during the Late Quaternary (transgressions and regressions). • The Pompey Reef system records high and low sea levels through several phases of sea level change. These are recorded in the karst morphology, as well as in the cemented deltaic lobes. • Reef lobes stabilised as a result of coral colonization and cementation after sub-aerial exposure and tidal scour between the lobes. • There are four blue holes (karst features) in the complex – which suggests that these reefs have been subaerially exposed, allowing for erosion of deep holes in the reef.	• Hopley *et al.* 2007 (p301-305) • Maxwell, 1970 • Hopley, 2006

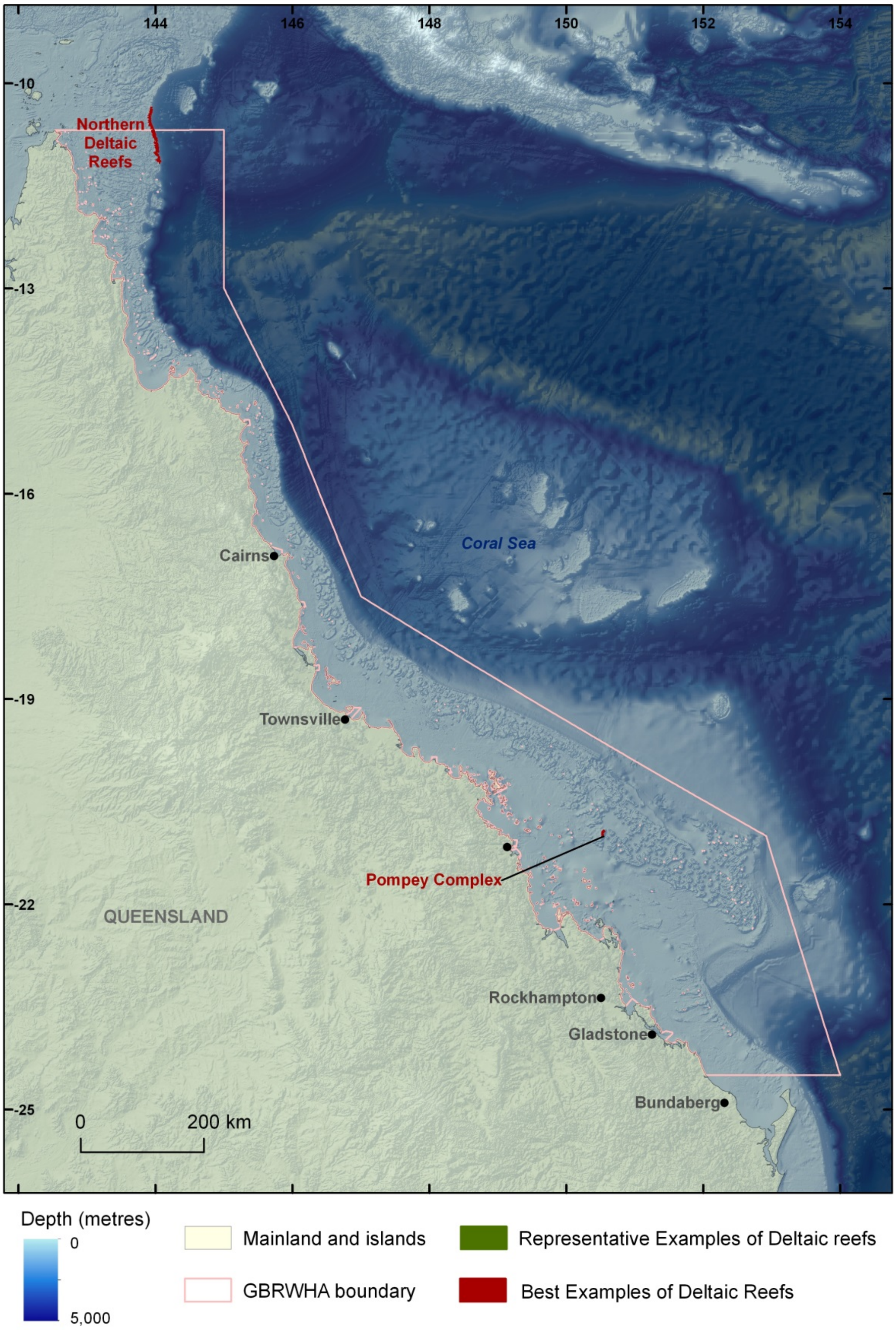


Figure 6.9 Selected examples of deltaic reefs in the GBRWHA.

6.6 Northern Detached Reefs

6.6.1 Description

Detached reefs are shelf-edge reefs that appear to form on isolated pinnacles of continental crust separated from the main shelf edge by deep channels that may exceed 280 m depth and be as much as 6-7 km wide (Veron and Hudson, 1978; Hopley *et al.* 2007). Smaller detached reefs tend to be planar, with reef flats occupying the reef platform whereas the larger detached reefs have a more varied morphology (Hopley *et al.* 2007). The Northern Detached Reefs are a specifically identified cluster of detached reefs located in the most northern section of the GBR, west of Cape York Peninsula (Figure 6.10). The Great Detached Reef (Figure 6.10) is one of the largest, forming a plateau ~175 km^2 in area, with narrow ribbon-like reefs on its windward perimeter and *Halimeda* meadows across most of the relatively shallow (~35 m) platform.

6.6.2 Description of OUV

The Northern Detached Reefs have a range of unique characteristics:

- They form 'outer barriers' that significantly influence physical processes and ecological conditions on reefs in their lee (*criteria viii and ix*).
- They provide examples of 'oceanic' type reefs within the GBRWHA (*criteria viii*).
- Cays formed on detached reefs – such as Raine Island – are critically important ecologically, in part due to their isolation location outside the main line of barrier reefs (*criteria viii*).

*Table 6.6 Selected examples of northern detached reefs with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.10).*

Feature	Outstanding Universal Values	References
Raine Reef	• Detached reef about which the most information regarding its formation is available. • Approximately 3 km long and supports on its western end Raine Island, a coral cay of great importance to nesting turtles and seabirds.	• Hopley *et al.* 2007
Great Detached Reef	Largest detached reef on the GBR with plateau 175 km^2 in area • Reef front 30 km long • Ribbon reefs on eastern rim • Reefs and banks on western rim appear to align with those on the GBR shelf margin • *Halimeda* gravels abundant over most of the plateau.	• Hopley *et al.* 2007 • Veron and Hudson, 1978

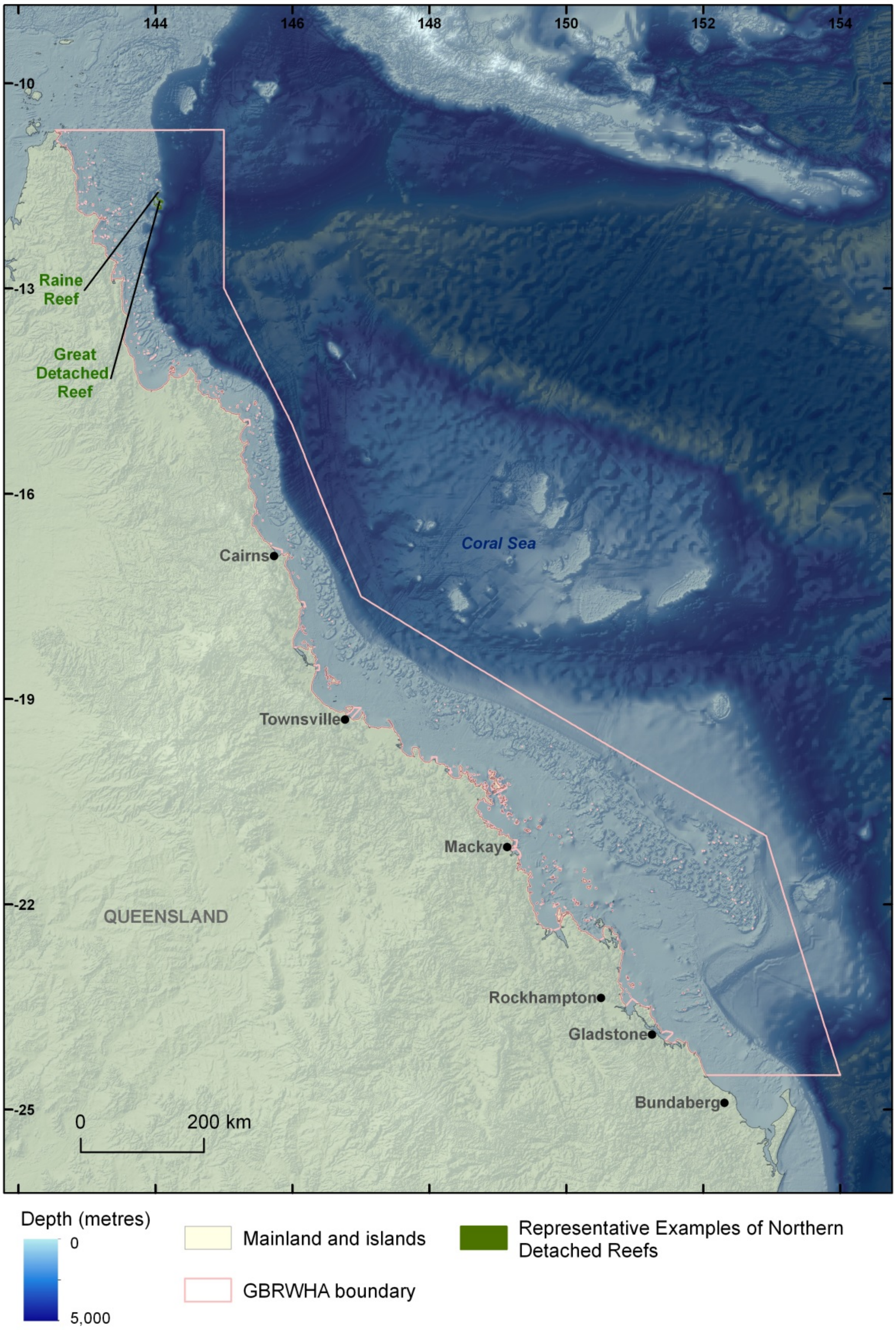


Figure 6.10: Selected examples of northern detached reefs in the GBRWHA.

6.7 Submerged Coral Reefs and Banks (Mesophotic Coral Ecosystems)

6.7.1 Description

Submerged reefs are reef structures formed during periods of lower sea level, which are currently submerged and have little or no modern vertical coral framework accretion (Abbey and Webster, 2011; Bridge and Guinotte, 2012). Underlying most submerged reef systems in the GBR are elongate, relict limestone formations, or banks, that form a "pedestal" on which modern reefs have formed (Harris *et al.* 2012). The submerged state of these reefs is most often attributed to 'drowning' when rapid post-glacial sea level rise out-paced vertical reef accretion which was limited by difficult conditions for coral reef growth associated with environmental changes during the last deglaciation (e.g. Fairbanks, 1989; Abbey and Webster, 2011). Adopting Hopley et al.'s (2007:152) definition they are 'reefs not at modern sea level, but with some growth over the older foundations, usually most prolific on the highest parts of these Pleistocene foundations'. Importantly, MCE's have been identified as potential refugia, and a source of seed stock for the regeneration of near-sea-surface coral reefs which are impacted by natural and anthropogenic effects including coral bleaching (Harris et al. 2008; van Oppen et al. 2011; Harris et al. 2012).

On the GBR submerged reefs are most often found in water depths ranging from 20 to 120 m (but can be deeper), with examples occurring both on the shelf and along the shelf edge. Mesophotic coral reef ecosystems (MCEs) are light-dependent coral communities (and associated communities of algal, sponge and fish species) that occur in the mid to lower photic zone (starting at 30 to 40 m and extending below 150 m depth, Bridge et al. 2012; Figure 6.11), and are often associated with submerged reefs. Extensive submerged reef systems occur along the GBR shelf edge, typically developing distinctive morphologies as slope and seabed morphology along the margin vary (Hopley, 2006). Particularly well-developed submerged reefs are common over almost 800 km of the central GBR shelf edge, where the shelf shoulder is broad and less steep (Figure 6.12). Submerged reef morphologies identified by Abbey et al. (2011) include submerged barrier reefs, reef terraces, and isolated coral reef pinnacles (high pointed piece of rock) and knolls (small rounded hill or mound). Submerged reefs also occur on the shelf – of the 2,904 reefs named on the GBR almost one fifth (566 reefs) are classified as submerged (Hopley *et al.* 1989). These reefs have a mean size of 6.2 km^2 and are distributed along the length of the shelf, but are more numerous in the north between 11-14°S and in the south between 20-23°S (Hopley *et al.* 1989; 2007).

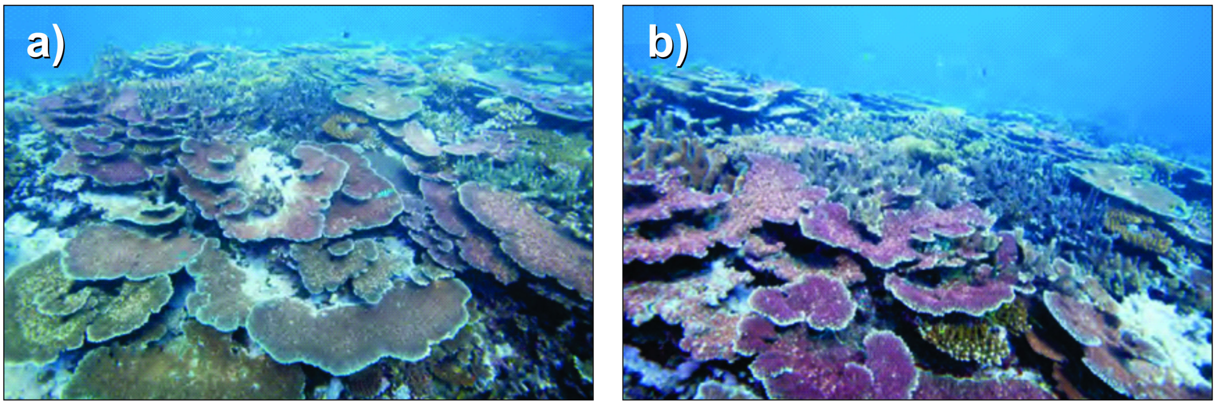
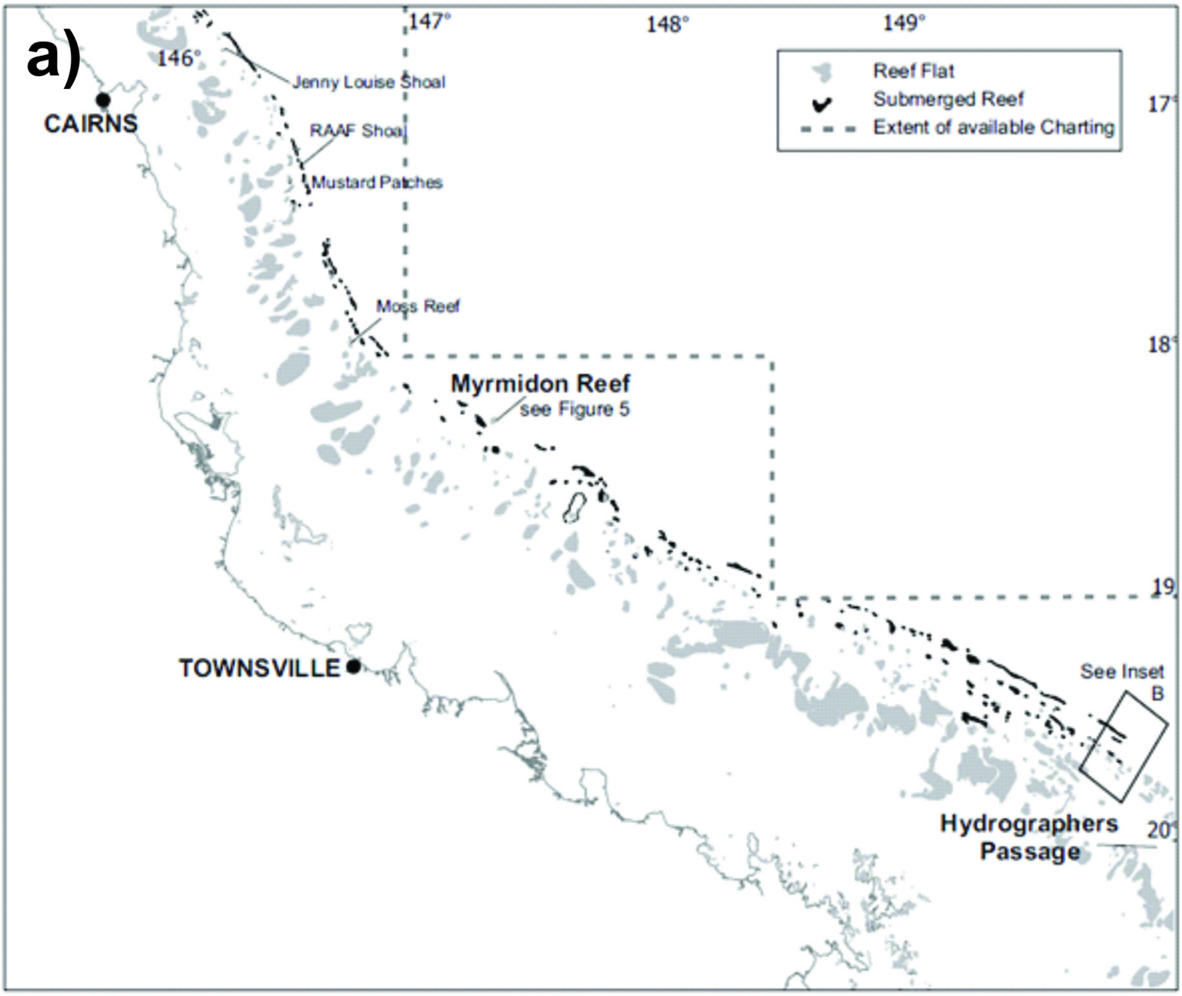


Figure 6.11 High coral cover on mesophotic submerged shelf edge reefs near Noggin Reef, Northern GBR (photographs: T Bridge).

Harris *et al.* (2012) recently quantified the potential extent of submerged banks suitable as coral reef habitat on the GBR using a 100 m bathymetric grid of the seafloor to identify morphological features. They identified a total of 1,581 submerged bank features with a total surface area of 41,709 km^2, with three major submerged bank morphotypes defined on the basis of cover by near-sea-surface reef growth, mean depth and size (Harris *et al.* 2012). Type 1 submerged banks are the largest and are at least partly covered by near-surface reefs. Banks without near-sea-surface reefs (but often with active MCEs) comprise types 2 and 3; type 2 banks have a mean depth of 27 m (comparable to type 1 banks) but are smaller and irregular in shape. Type 3 banks have a mean depth of 56 m but are otherwise very similar to type 1 banks. Type 2 banks are most common on the northern GBR but rare in the south, whereas type 3 banks have the opposite distribution (Harris *et al.* 2012).

Of the 41,709 km^2 total submerged bank surface area, Harris *et al.* (2012) identified an area of 16,110 km^2 currently covered by near-sea-surface reefs. Importantly, this leaves 25,599 km^2 of submerged banks that do not support near-sea-surface reefs. Further investigation by Harris *et al.* of characteristic submerged banks showed that MCE's on these banks could potentially cover approximately 55% ±23% of Types 1 and 3 banks. Hence, the calculated total area of coral reef in the GBR may be greatly underestimated, with MCE's potentially representing an additional 14,000 ±6,000 km^2 of reef.



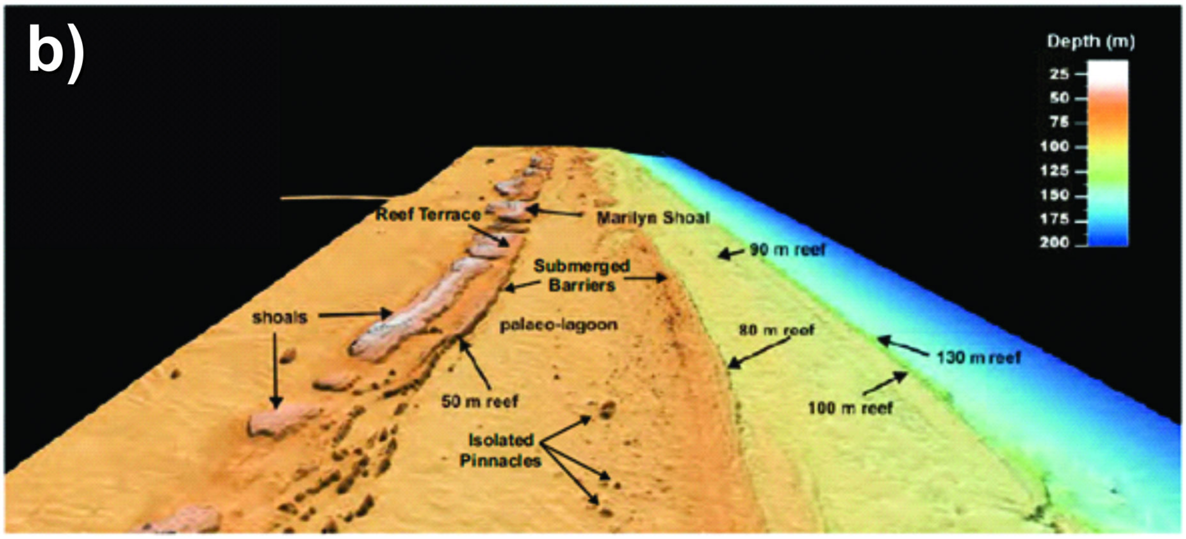


Figure 6.12 a) Location of submerged shelf-edge reefs on the Central GBR, showing locations of Myrmidon Reef and Hydrographers Passage (after Hopley et al. 2007). b) Multibeam sonar image of shelf edge reefs just to the north of Hydrographers Passage (with kind permission of T. Bridge). The deeper reefs are interpreted to have been largely constructed during lower sea levels.

6.7.2 Description of OUV

The submerged coral reefs and banks and associated mesophotic coral ecosystems are a significant component of the OUV of the GBR:

- The reefs record fluctuations in sea level and reef growth that occur through depth ranges not captured by the shallower reefs. Most of the modern reefs of the GBR have formed only during phases when sea levels were above the continental shelf, which accounts for just 15% of the past 600,000 years generally accepted as encompassing the timeframe of most carbonate reef accumulation on the GBR (International Consortium For Great Barrier Reef Drilling, 2001) (*criteria viii*).
- They reveal that for most of the Great Barrier Reef's history, growth was concentrated on the shelf edge (Davies, 1988), and submerged reefs thus have great importance as archives of past geological, environmental and climatic events critical to the evolution of the GBR (*criteria viii*).
- They preserve evidence of the importance of sub-aerial erosion during lower sea levels on modern reef morphology, and the interaction of morphology with reef accretion when sea levels are higher (Harris and Davis, 1989) (*criteria viii*).
- The reefs preserve a comprehensive record of post-glacial marine transgression (Hopley *et al.* 2007; Maxwell, 1968; Carter and Johnson, 1986) (*criteria viii*).
- The reef structures form important habitats, supporting high biodiversity, facilitating connectivity through the GBR system, and offering refuge from environmental disturbance (and potential seed stock for shallower reefs) (*criteria x*).

*Table 6.7 Selected examples of submerged coral reefs and banks with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in* *Figure 6.13**).*

Feature	Outstanding Universal Values	References
Ribbon Reef 5	• Submerged Reefs on steeply sloping shelf margin. • Holocene reef at sea level, but distinctive reef features at 50 m and 70 m depth before slope steepens to almost vertical.	• Hopley *et al.* 2007 • Webster and Davies, 2003 • Beaman *et al.* 2008
Noggin Passage	• Outer shelf includes a series of submerged features, including submerged barrier reefs, lagoons, pinnacles and terraces across the shelf shoulder.	• Abbey *et al.* 2011 • Abbey and Webster, 2011 • Webster *et al.* 2011
Reefs north and seaward of Moss Reef	• Series of five broadly spaced parallel submerged reefs aligned with the shelf edge rising substantially above shelf substrate in northern GBR. • Seismic transect suggests modern reefs have developed over antecedent precursors.	• Graham, 1993 • Hopley *et al.* 2007
Myrmidon Reef	• Located on shelf edge with seaward slope of this reef dropping to more than 200 m depth, with a slope averaging around 45 degrees. • 100% coral cover at approximately 90 m water depth. • Possibly separated from the main shelf edge by a channel exceeding 100 m depth – analogous to detached reef.	• Hopley *et al.* 2007
Hydrographers Passage ** (Southern Region)	• Series of broadly spaced parallel submerged reefs aligned with the shelf edge rising substantially above shelf substrate in northern GBR. • Covers large depth range from near surface to 130 m depth. • Well documented submerged reefs including: – elevated shelf platform above 50 m depth – drowned submerged linear reefs at 50, 55, 80, 90, 100 and 130 m water depths – Holocene pinnacle / patch reefs – Holocene (modern) coral reefs with coral communities	• Bridge *et al.* 2011a • Beaman *et al.* 2012 • Beaman *et al.* 2008 • Harris and Davis, 1989

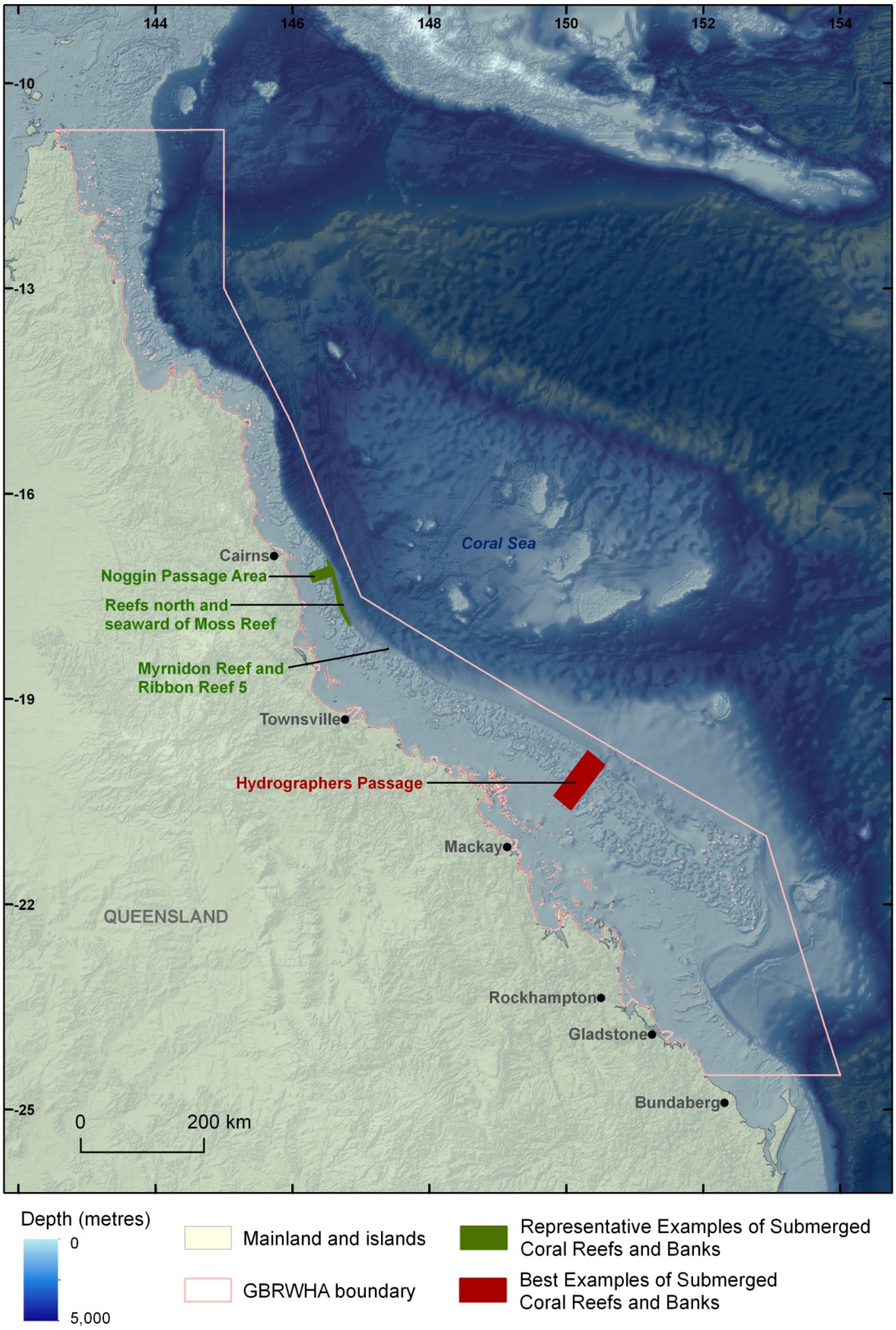


Figure 6.13 Selected examples of submerged reefs and banks in the GBRWHA.

6.8 Carbonate Reef Islands (excluding Low Wooded Islands and Mangrove Islands)

6.8.1 Description

Carbonate reef islands are deposits of carbonate sediment mostly composed of the skeletal remains of reef organisms. They form as reef sediment is swept by waves around and over the reef to a focal point on a reef flat where deposition occurs. On the GBR there are around 300 reef islands formed on reef platforms that have reached sea level after the mid-Holocene. A consequence of this history is that reef islands on the GBR (and generally elsewhere too) are very young geological features. Reef islands on the GBR are morphologically diverse, varying in factors such as size, shape, composition, location on the reef platform, elevation, age structure, occurrence and extent of consolidation/cementation, and the extent to which they have been colonised by vegetation. Various classifications of reef islands exist, but that of Hopley (1982) based on an island’s sediment type (sand or shingle), location on the reef platform (windward or leeward), shape (compact or linear), and stage of vegetation cover (vegetated or unvegetated) is most widely applied on the GBR. Typically reef islands composed of sand are deposited toward the lower energy, leeward platform margin, while reef islands dominated by coarser sediments accumulate nearer the higher energy, windward rim. Mixed sand and shingle islands on the GBR mainly form when storms deliver coarse clastic sediment from coral reefs to predominantly sandy islands. Island shape is strongly controlled by reef platform morphology and its impact on surface hydrodynamics, with compact cays usually developing on more circular reef platforms, and linear islands typically developing over elongate reefs. Vegetated reef islands tend to be more stable and mature than unvegetated reef islands, with the proportion of the island ‘footprint’ over the reef flat that supports vegetation being a good indicator of island stability. Unvegetated cays are very dynamic and may in some cases be ephemeral, so the exact number of reef islands of any type can vary over time. Within the GBRMP it has been estimated that there are around 213 unvegetated cays and only 43 vegetated cays, with an additional 44 islands classified as low wooded islands (see Section 6.10).

As indicated above, the reef islands of the GBR are morphologically diverse, reflecting the range of environmental conditions (wave energy, tide range, storm history, relative storm history, etc) to which they may be exposed. Their deposits and structure can also preserve a history of major events such as cyclones. Their distribution is strongly controlled by the availability of planar or near planar reefs with sufficient area at sea level. For example, there are no vegetated cays between Green Island and Bushy Island – a distance of 600 km, and no unvegetated cays between Wheeler Cay, offshore of Townsville, and the northern Pompey reefs – a distance of more than 325 km (Hopley *et al*. 2007). This distribution has been attributed to the deeper shelf and relatively delayed rise to sea level for many reefs through this region, in combination with exposure to greater cyclone wave energy and higher storm surges and tidal ranges (Hopley *et al.* 2007). In contrast, vegetated cays are most common in the far north and far south of the GBR, and low wooded islands are limited to the inner shelf north of Cairns.

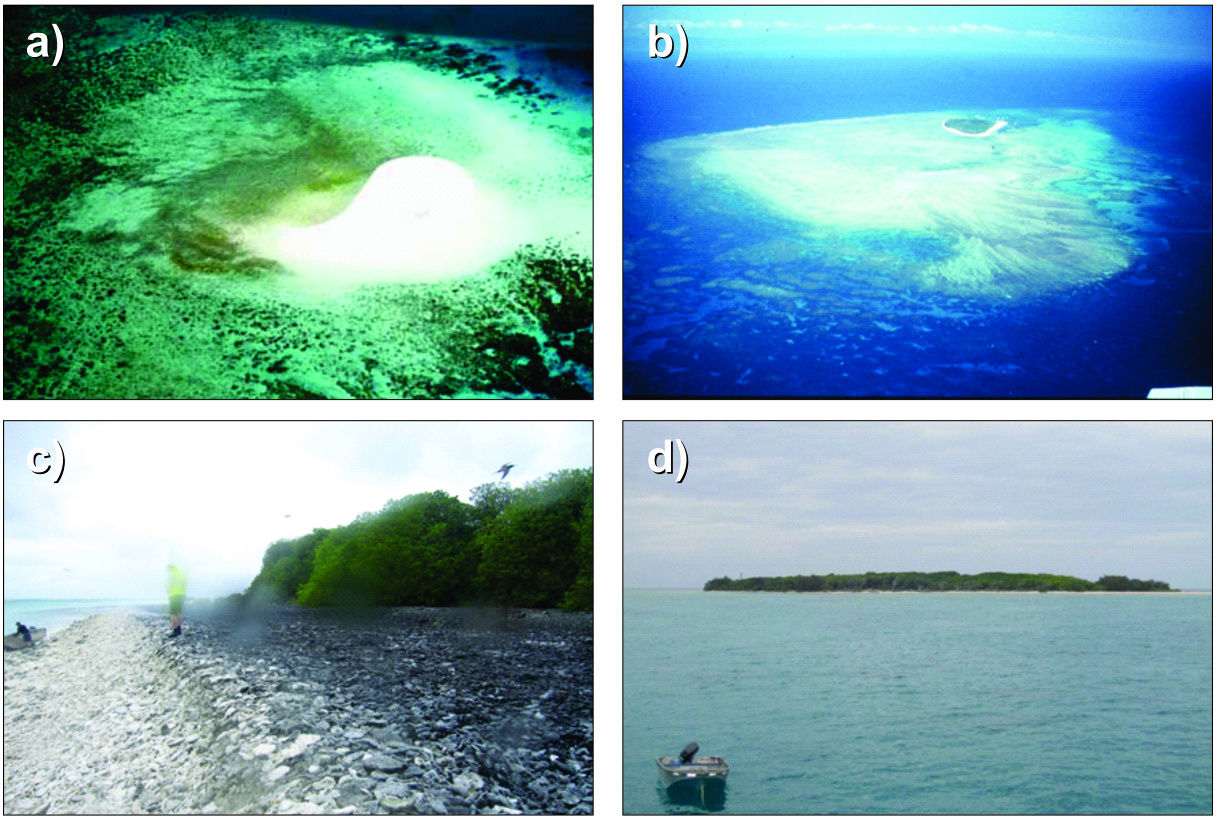


Figure 6.14 Carbonate Reef Islands a) Wheeler Cay (Photograph: D Hopley), b) Green Island (Photograph: D Hopley), c) Fairfax Island (Photograph: S Smithers) and d) Lady Musgrave Island (Photograph: S Smithers).

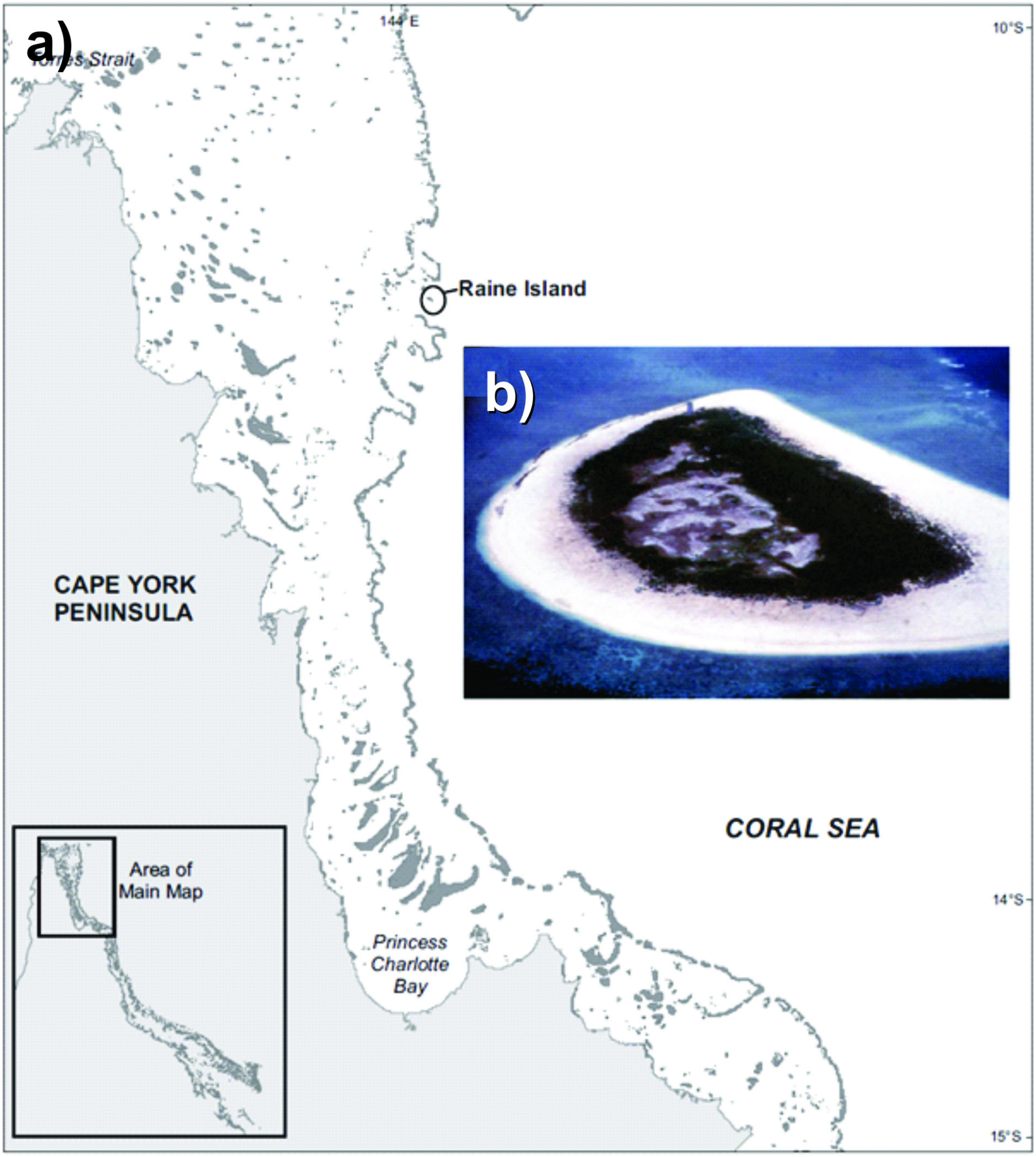


Figure 6.15 a) Location of Raine Island on the outer northern Great Barrier Reef. b) Oblique aerial photograph of Raine Island, viewed from the north-west towards the south east (photograph: D Hopley).

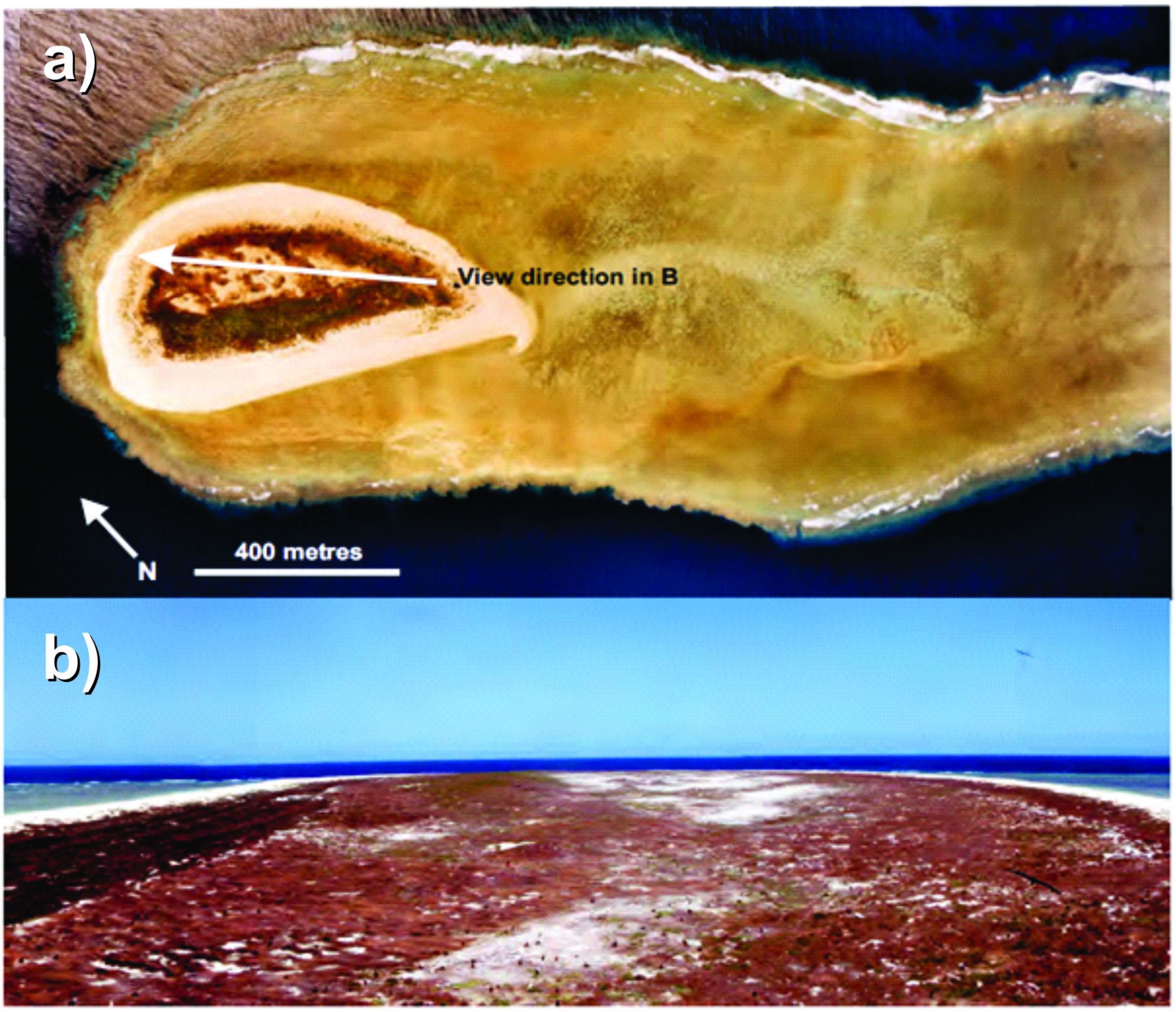


Figure 6.16 a) Aerial photograph of Raine Island and reef flat. b) Photograph from top of tower looking across phosphate cap toward the southeast (photograph: J Dawson).

6.8.2 Description of OUV

Carbonate reef islands:

- Form a diverse range of reef island types that are not matched anywhere else in the world (Hopley, 1979) (*criteria viii*).
- Preserve in their collective formation chronostratigraphic information critical to understanding the formation and evolution of reef islands under a variety of environmental conditions (*criteria viii*).
- Record in their sedimentary deposits histories of reef organism composition and productivity (*criteria viii*).
- Provide in their sediments evidence of important processes such as reef sediment cementation and lithification that enhance island stability (*criteria viii*).
- Record in their morphology histories of major environmental events (such as cyclones) and changes (*criteria viii*).
- Provide critical terrestrial habitats for many key species (*criteria x*).

*Table 6.8 Selected examples of carbonate reef islands with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.17)*

Feature	Outstanding Universal Values	References
Raine Island**	• Linear vegetated sand cay on detached reef platform on northern GBR. • Key nesting site for range of bird and turtle species • Cultural significance – Indigenous and European. • Sea level, reef growth, carbonate productivity, reef island evolution and morphodynamics. • Reef island with modern beach dominated by foraminiferans. • Intrinsic scientific significance due to location on detached reef, and unusual occurrence of phosphate rock development without *Pisonia* forest.	• Stoddart *et al.* 1978 • Gourlay and Hacker, 1991 • Hopley *et al.* 2007 • Dawson *et al.* 2010 • Dawson *et al.* 2012
Sandbank 7	• Small-medium unvegetated sand cay on ribbon reef, northern GBR. • Intrinsic scientific significance due to location on exposed ribbon reef – can improve understanding of cay formation and dynamics in very high-energy settings. • Important turtle nesting site.	• Aston, 1995 • Hopley *et al.* 2007
Stapleton Island	• Medium-sized linear vegetated sand cay on northern GBR • Good data available on cay compared to others from this region. • Important bird nesting site. • Well-developed sand dunes on island. • Island has elevated inner core, and lower periphery possibly reflecting pulsed sediment delivery to island. • Intrinsic scientific significance as mapped by 1973 Royal Expedition and dates available on sediments. Terraced morphology also informs understanding of relationship between sediment production, supply to island, and island evolution.	• Hopley 1982 • Stoddart *et al.* 1978 • Hopley *et al.* 2007
MacGillivray Reef	• Compact unvegetated shingle cay on northern GBR. • Rare on the GBR and globally.	• Hopley 1982 • Hopley *et al.* 2007
Green Island	• Large linear vegetated cay on northern GBR • Large cay developed to east of zero isobase (i.e. where no evidence of higher mid-Holocene sea levels exist). • Sediment delivery and budget research conducted, noting shift through time in dominant carbonate sediment producers. • Foraminiferans dominate contemporary sediment supply. • Reef flat / Reef island interactions examined on this reef. • Historical changes in shoreline position known from aerial photographs. • Last vegetated cay for more than 600 km until Bushy Islet off Mackay.	• Hopley, 1982 • Hopley, 2008 • Hopley *et al.* 2007 • Yamano *et al.* 2000
Pandora Reef	• Small unvegetated linear shingle cay • Rare on the GBR and elsewhere	• Hopley 1982 • Hopley *et al.* 1989 • Hopley *et al.* 2007
Wheeler Cay	• Small compact unvegetated sand cay central GBR • Ephemeral and highly mobile cay • Cays generally rare on central GBR • Good data available on cay mobility and morphodynamic response to weather events.	• Hopley 1982 • Hopley *et al.* 2007

Feature	Outstanding Universal Values	References
Sandpiper Cay	• Small unvegetated sand cay, Pompey Complex, GBR. • Unvegetated cays in the Pompey Complex tend to be small and ephemeral. • When disturbed by storms recovery can be protracted as complex reef morphologies impede refraction of waves to well-defined focal point, and thus slow accumulation of dispersed sediments.	• Hopley *et al.* 2007
North West Cay	• Large linear vegetated sand cay on southern GBR • Largest reef island on the GBR (>1.6 km long, 0.75 km wide). • Relatively stable • *Pisonia* forest • Phosphatised sediments • Important nesting site. • Cultural importance.	• Flood, 1977, 1984 • Hopley 1982 • Hopley *et al.* 2007
Tryon Island	• Small linear vegetated sand cay on southern GBR • Effects of cyclones and changes in wind direction documented • Mobile vegetated cay, with relatively small vegetated area as a proportion of total island footprint.	• Flood 1984
Fairfax Islands	• Multiple islands on a single reef flat – windward linear vegetated shingle cay and leeward linear vegetated sand cay, southern GBR. • Developed due to sorting of bimodal sediments on reef flat. • Rare on GBR – just two examples, both in the Capricorn Bunker Group. • Shingle cay contains ridges that preserve storm history.	• Flood 1984 • Hopley 1982 • Hopley *et al.* 2007
Lady Musgrave	• Vegetated mixed sand and shingle cay on lagoonal reef, southern GBR. • Mixed cay developed on leeward reef flat whilst shallow lagoon remains • Repeated historical surveys suggest relative stability • Mature *Pisonia* forest and phosphatized soils • Mixed sediment classes attributed to storm influx of gravels over ambient delivery of sands.	• Steers, 1938 • Flood, 1977 • Hopley 1982

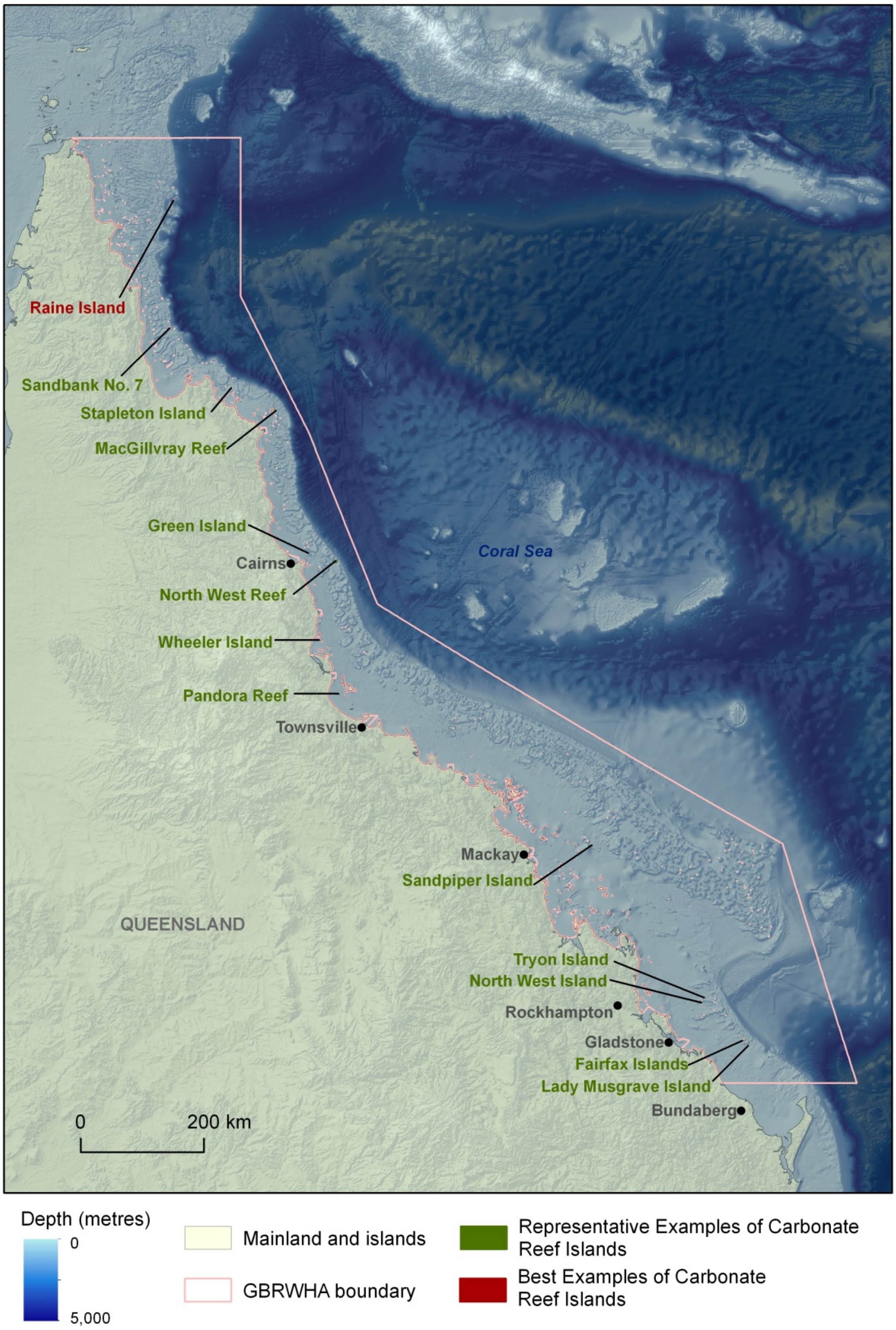


Figure 6.17 Selected examples of carbonate reef islands in the GBRWHA.

6.9 Gravel and Shingle Ridges

6.9.1 Description

Gravel and shingle ridges usually occur as a sequence of low-amplitude shore-parallel deposits of coarse reef sediment, deposited during the mid-late Holocene. Where these ridges are best preserved they tend to be composed of coral fragments, especially shingles of branching corals. The ridges form as coral fragments are transported onshore by wave run-up and overwash during cyclones and storms. While individual ridges may form over multiple events, units of sediment deposited during single events can be distinguished within ridges. Over time, multiple ridges usually form as the deposits prograde seawards (Nott, 2006; Chappell *et al.* 1983; Chivas *et al.* 1986; Hayne and Chappell, 2001; Nott and Hayne, 2001). Gravel and shingle ridges are best formed and preserved in the lee of spits at the ends of islands where coral reefs occur immediately adjacent to the shore (e.g. Cucaroa Island, Figure 6.18), and on reef islands where coarse material is eroded from the surrounding reef (e.g. Lady Elliot Island).

Figure 6.18 Gravel and shingle ridges on Curacoa Island (Photograph: D Hopley).

6.9.2 Description of OUV

At locations where the sediment can be reasonably assumed to have been derived from living coral reefs rather than reworked older material, radiometric ages of coral fragments from within gravel and shingle ridges and across ridge sequences can be used to reconstruct storm histories (Chivas *et al.* 1986; Hayne and Chappell, 2001; Nott and Hayne, 2001; Zhao *et al.* 2009). Analysis of the elevation of ridges and modelling of the associated storm surge also allows reconstruction of storm strength (Nott and Hayne, 2001). Consequently, these features contribute to the OUV of the GBR by:

- Providing long-term histories of storm/cyclone frequency and severity that extend well beyond the historical period (*criteria viii*).

- Contributing to our knowledge of climate variability over time, especially past climate fluctuations (*criteria viii*).
- Recording the disturbance regime reefs have experienced during the mid to late Holocene (*criteria ix*).

*Table 6.9 Selected examples of gravel and shingle ridges with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.19).*

Feature	Outstanding Universal Values	References
Curacoa Island **	• Sequence of 22 ridges paralleling the leeward island shore behind a spit. Ridges are contiguous over several 100 m, and rise to more than 5 m above mid-tide level. • Record of cyclone intensity and frequency extending back to the mid-Holocene. • Indicates a recurrence interval for severe cyclones averages around 280 years, and suggests that this interval has not significantly changed over time. • Allows carbonate productivity of nearshore reef to be calculated.	• Hopley *et al.* 2007 • Nott, 2006 • Hopley, 1968 • Hayne and Chappell, 2001 • Nott and Hayne, 2001
Fairfax Island	Shingle ridges preserved over surface of windward shingle island at south of the GBR.	• Hopley *et al.* 2007
East Hoskyn	Shingle ridges preserved over surface of windward shingle island at south of the GBR.	• Hopley *et al.* 2007
Lady Elliot Island **	• Oval shaped island exhibits near concentric ridges of shingle, coral rubble and phosphate rock clasts. • Lady Elliot is a rare shingle cay solitary island (only 3 in the GBR (Hopley *et al.* 2007). • Good record of Holocene environments from 6ka. • Most southerly cay of the GBR • Well preserved ridge chronology used to reconstruct storm and cyclone history and sea level change since the mid-Holocene.	• Chivas *et al.* 1986 • Hopley *et al.* 2007 • Nott and Hayne, 2001

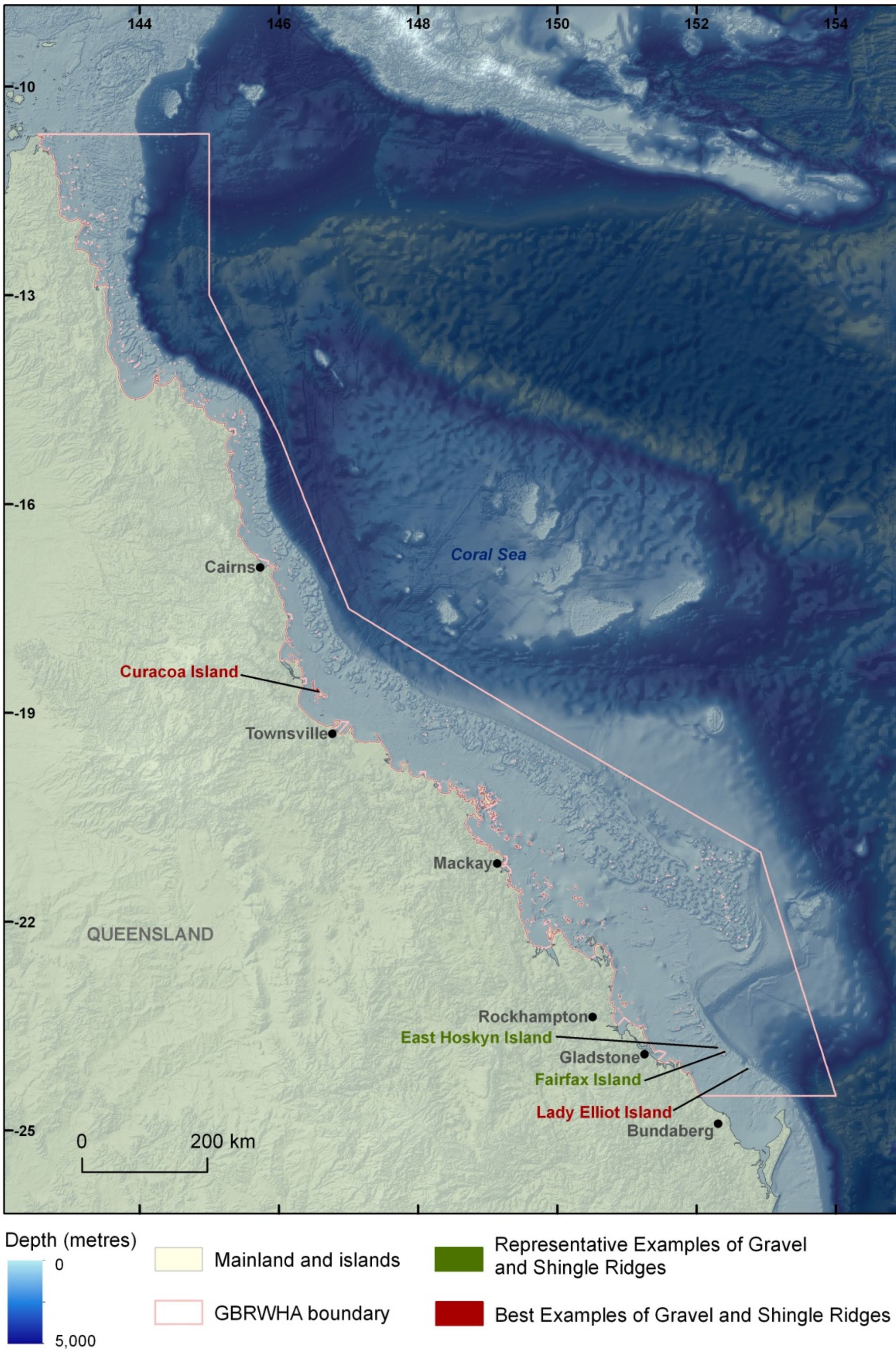


Figure 6.19 Selected examples of gravel and shingle ridges in the GBRWHA.

6.10 Mangrove Shorelines, Mangrove Islands and Low Wooded Islands

6.10.1 Description

The word mangrove describes the coastal vegetation community (or habitat) dominated by 'mangrove' plants; trees and palms that normally grow around the intertidal zone of tropical marine coastal environments and estuaries (Duke, 2006). Mangroves usually consist of a range of species distributed along shore parallel zones, often in muddy settings, but also on sand, gravel and even rock platforms. These zones reflect the intertidal elevation of the substrate and the tolerance of the plants to tidal inundation and emergence. Mangrove occurs along the shoreline of the mainland and in the intertidal environments associated with islands and reef platforms. Islands fully covered by mangroves are known as mangrove islands. Mangroves occurring on the top of reef platforms where no carbonate reef islands have formed, and on reef platforms in association with leeward sand and windward shingle coral cays, are collectively referred to as low wooded islands.

Figure 6.20 Examples of mangrove Islands a) Narrows behind Curtis Island, and b) mangroves in Hinchinbrook Channel (Photographs: S Smithers)

The coast of tropical Australia has extensive mangroves, with the highest mangrove biodiversity extending from Torres Strait to Hinchinbrook Island (39 species). Mangrove dominated shorelines on high islands, such as Hinchinbrook Island and Orpheus Island, occur throughout the GBR and are best developed in sheltered locations such as embayments, leeward coasts (Spenceley, 1982) and behind emergent reef. Mangrove islands (fully covered by mangroves), in contrast, are rare on the GBR, with Murdoch Island (14°37'S) being the only example. At Murdoch Island there is no windward shingle ridge to dissipate wave energy but *Rhizophora stylosa* mangroves nevertheless cover almost the entire seaward reef platform. Steers (1938) and others (Hopley *et al.* 2007) have speculated that an elevated reef platform may provide enough shelter to allow mangroves to initially colonise and then flourish across this particular reef. There are 44 low wooded islands on the GBR, which comprise a windward shingle rampart and/or gravel ridge, a leeward sand cay (or cays), and a central reef flat at least partially covered by mangroves (Hopley *et al.* 2007; Kench, 2011). Together these three biogeomorphic zones usually cover between 25-50% of the reef top, but can cover as much as 79% as they do at Bewick Island in the Howick Group. All low wooded islands on the GBR are located on the inner shelf north of Cairns, with 94% located within 20 km of the mainland coast.

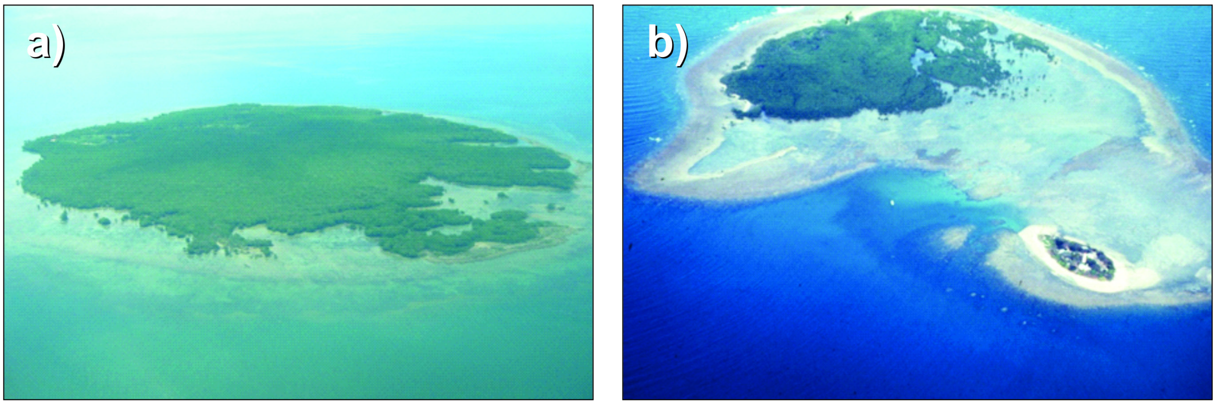


Figure 6.21 : Examples of Low Wooded Islands a) Hannah Island (Photograph: S Smithers), and b) Low Isles (Photograph: D Hopley)

The depositional environments associated with various mangrove settings result in the development of particular sedimentary facies that can be recognized in the stratigraphic record. In sheltered locations these facies are usually organic muds, often including the shells of various molluscs that inhabit mangrove habitats. In more exposed settings mangrove facies may comprise mangrove peats, which when buried can be preserved and in which mangrove plant structures can be recognized. Recognition of these deposits allows reconstruction of palaeoenvironmental conditions (Grindrod and Rhodes, 1984; Grindrod *et al.* 1999), and as mangroves grow in the intertidal zone these sedimentary facies can also be used to infer past sea level positions (Bunt *et al.* 1985; Larcombe *et al.* 1995; Hopley *et al.* 2007; Smithers, 2011).

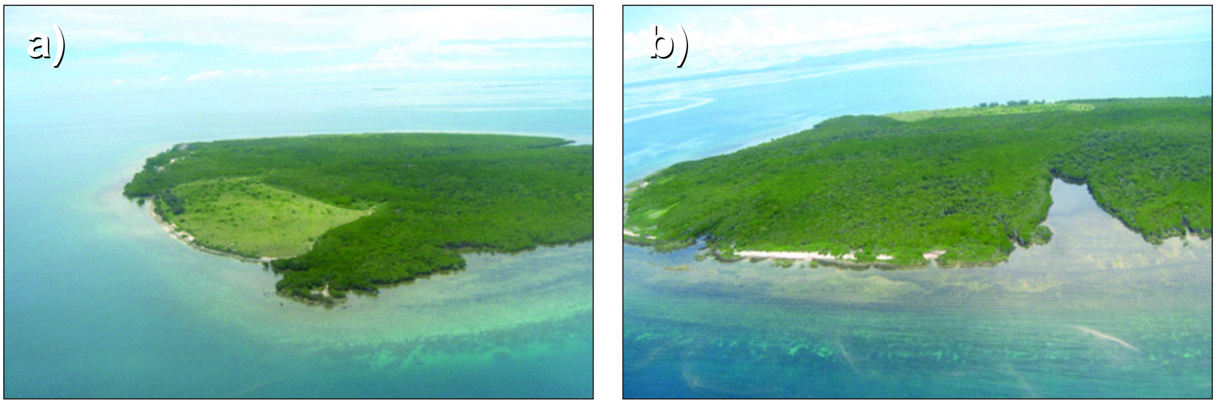


Figure 6.22 One of the exemplar low wooded islands; Bewick Island with a) grassed cay on left, and b) from windward to leeward – grassed cay at top of photograph. Shingle ridges occur on the shoreline. (Photographs: S Smithers.)

6.10.2 Description of OUV

Mangrove shorelines, islands, and low wooded islands (Table 6.10):

- Have unique sedimentary facies that can preserve records of past sea level and environmental conditions (*criteria viii*).
- Mangrove islands, in particular, are rare (*criteria viii*).
- Mangroves protect shorelines from erosion (*criteria ix)*.

- Mangrove deposits are distinctive and where exposed can be used to identify areas that have experienced shoreline erosion and coastal retreat.
- Low wooded islands of the inner northern GBR are unique in their regional abundance (*criteria viii*).
- Mangrove habitats are important ecologically as nurseries for many fish species including threatened species (GBRMPA, 2006) (*criteria ix)*.

*Table 6.10 Selected examples of mangroves and mangrove islands with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.23).*

Feature	Outstanding Universal Values	References
Murdoch Island **	Only mangrove island on the GBR. • Extremely rare • Formation and dynamics yet to be fully investigated and understood.	• Hopley *et al.* 2007
Bewick Island ** (Howick Group)	Type example of a mature low wooded island located on the northern GBR. • Mangroves, shingle and sand cay occupy almost 80% of platform area – the most of any low wooded island on the GBR (usually these make up between 25-50% of a low wooded island). • Reef and reef island evolution investigated by 1973 Royal Society Expedition and by Kench *et al.* 2012. • Supports fossil microatolls which preserve a record of the higher mid-Holocene sea level (the oldest of which is 6.5 ka). • Provides the first evidence that islands build over reef flats • Shingle and sand cays are joined by continuous mangroves, and for this reason Stoddart *et al.* (1978) notes that Bewick Island is a 'type example' of a '*low wooded island with reef top mangroves extending between windward shingle and leeward cay'*. • Has organic mangrove mud deposits up to 2 m thick, • Is in a mature planer reef stage in the classification of reefs.	• Steers and Kemp, 1937 • Stoddart and Fosberg, 1991 • Hopley *et al.* 2007 • Kench *et al.* 2012 • Stoddart *et al.* 1978
Low Island	Low wooded island at southern end of range on GBR • Research station with long history of research and available historical data. • Potentially exposed to pressures (catchment/tourism) so valuable example to examine changes. • Cultural significance.	• Marshall and Orr, 1931 • Moorehouse, 1933, 1936 • Fairbridge and Teichert, 1947, 1948 • Stoddart *et al.* 1978 • Johnston, 1995 • Frank, 2008 • Frank and Jell, 2006
Hinchinbrook Island ** (Particularly Hinchinbrook channel and Missionary Bay)	Mangrove habitats of significant extent and diversity in lee of large continental island in wet tropics, northern GBR. • Chronostratigraphic studies undertaken (Grindrod and Rhodes, 1984). • Extent, diversity, and complexity of system • The total mangrove area is 164 km^2 with the mangrove islands making up to 37 km^2 of this area • Mangrove sediments record past sea level change and indicate that the islands formed in the late Holocene (post ca. 2 ka) during a period of sea level regression.	• Grindrod and Rhodes, 1984 • Duke, 1997 • Ebert 1995

Feature	Outstanding Universal Values	References
Orpheus Island	Mangrove communities in drowned rias (coastal inlet, partially submerged), along embayed reef flat shorelines, and in tidal inlets behind Holocene coastal deposits. • Excellent examples of mangrove fringes exist along the beach base at the back of many embayed reef flats on Orpheus, including Pioneer Bay and Cattle Bay. • Infilled rias exist on the leeward northern coast of Orpheus – these settings have great potential in their sediments to record sea level changes and changes in erosion on the island associated with climate and anthropogenic use.	• Hopley, 1983 • Slocombe, 1981
Curtis Island 'Narrows'	• Large area of mangroves in the lee of a large continental island. • Large mangrove system at the southern end of the GBRWHA.	

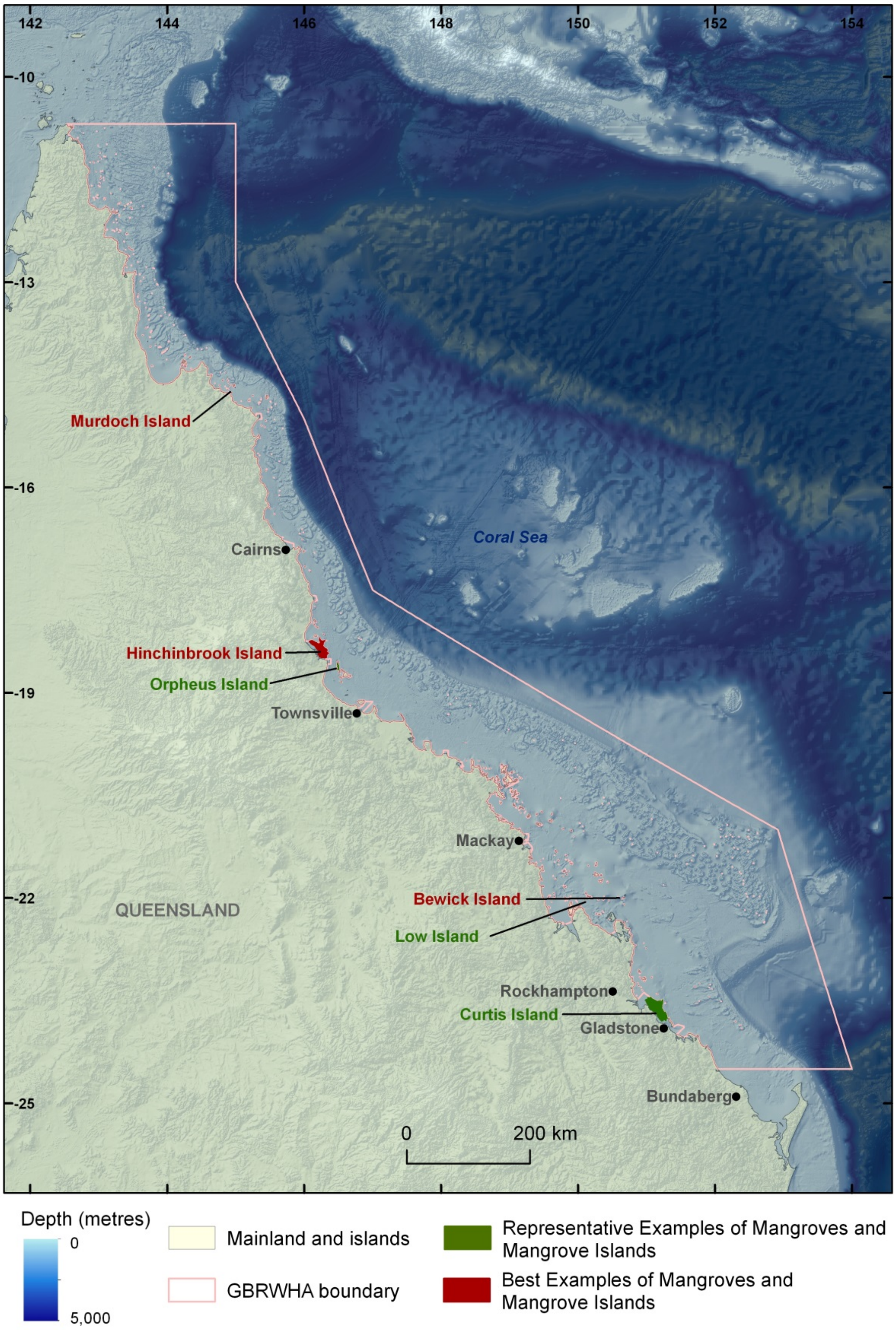


Figure 6.23 Selected examples of mangroves and mangrove islands in the GBRWHA.

6.11 Halimeda Banks, Bioherms and Meadows

6.11.1 Description

Halimeda is a genus of benthic green algae that produce calcified deposits in a plant-like form (Drew, 1983). *Halimeda* grow preferentially in the photic zone of warm, clear, nutrient rich, tropical oceans (Abel and Drew, 1985; Drew, 1983). *Halimeda* deposits in the GBRWHA commonly occur on banks (areas of the seafloor over which the depth of water is relatively shallow), meadows (extensive expanses of *Halimeda* beds) and bioherms (mound-like forms of built-up organic deposits of marine invertebrates such as corals, calcareous algae etc.).

In the GBR, *Halimeda* occur from north of Port Douglas to the Pandora Entrance and are most extensive between 11*o* 50' and 15*o* 35'S. It is estimated that 26% of the GBR northern shelf area has *Halimeda* sediments (Orme and Salama, 1988), and the associated *Halimeda* communities forms the second largest living structure of the reef, after coral reefs (Hopley *et al.* 2007). *Halimeda* form preferentially on the lee (coastal) side of shelf reef systems (particularly the ribbon reefs), where tidal jets flowing between shelf edge reefs provide nutrients to the shelf from upwelling ocean bottom waters (Wolanski *et al*. 1988; Hopley *et al*. 2007). *Halimeda* banks and bioherms do not form in the lee of every inter-reef channel, and Drew (2001) speculates that this is because only narrow inter-reef channels with a specific depth range permit strong, shallow-water currents that bring clear deeper waters to the surface.

Halimeda banks form on Pleistocene substrate and comprise clay and carbonate minerals and gravel-size *Halimeda* plates within a mud matrix (Orme and Salama, 1988; Hopley *et al.* 1997). They have a general north-south orientation and are flat topped, up to 150m long and 100m wide. Numerous *Halimeda* species have been identified in the GBR, the most prevalent being *H. copsia* (26%) and *H. hederacea* (48.4%).

The growth rates, thickness and age of *Halimeda* banks vary across the GBR. *Halimeda* meadows in the northern GBR have been calculated to have high vertical accumulation rates of up to 14 m/ka (Hopley *et al.* 1997). Orme (1985) describes 18.5 m thick banks at Petricola Shoal (near Lizard Island in the northern reef), but these have an age of 10,070 ± 180 years (based on peat samples overlying the Pleistocene basement). Further work by Marshall and Davies (1988) found that the accumulation rate for Petricola Shoals was approximately 1.7 m/ka, much slower than the meadows. Searle and Flood (1988) undertook similar studies for Swain Reef (southern GBR) and recorded accumulation rates of 2-3.4 m/ka. Searle and Flood (1988) also note that *Halimeda* banks commenced growth in the southern GBR at 5 ka, much later than the northern GBR. In some locations, Holocene *Halimeda* banks overlie older Pleistocene *Halimeda* deposits where it is believed that *Halimeda* commenced growth earlier than the corals on the GBR (Marshall and Davies, 1988).

6.11.2 Description of OUV

The *Halimeda* beds on the GBR are some of the most extensive, actively accumulating *Halimeda* deposits in the world. These deposits extend back to the pre-Holocene, preserving evidence of global climate change, glaciations and sea level changes, often prior to coral colonisation as the earlier Holocene conditions were more conducive to *Halimeda* than coral *(criteria viii)*. *Halimeda* beds are therefore particularly important for understanding the history of reef development in the GBR *(criteria viii and ix)*.

*Table 6.11 Selected examples of Halimeda beds with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order. These features have not been mapped).*

Feature	Outstanding Universal Values	References
Petricola Shoal	• Northern example of *Halimeda* banks (older and thicker). • Analysis of cores show that a succession of marine environments have occurred, preserving an excellent stratigraphic sequence of intertidal, near shore and outer shelf environments during the Holocene.	• Orme, 1985 • Marshall and Davies, 1988
Swain Reef	• Only southern example of *Halimeda* banks (younger and not as thick as in N GBR). • Not associated with fringing reefs, but still associated with upwelling of nutrient rich waters where the Coral Sea and Capricorn Channel currents meet.	• Rees *et al*. 2007 • Lucas *et al.* 1997 • Searle and Flood, 1988
From second three-mile entrance to Quoin Island.	• Largest extent of *Halimeda* in the GBR	• Lucas *et al.* 1997
Leeward Myrmidon Reef	• Corals found at 150 m water depth and *Halimeda* at 125 m depth due to exceptional water clarity	• Hopley 1989
Seaward Bowl Reef	• Meadows at deeper depths • Unique species composition	

6.12 Seagrass Beds

6.12.1 Description

Seagrasses are angiosperms (flowering plants) that grow predominantly in seawater. In locations where conditions are suitable (usually sheltered shallow coastal waters) seagrasses will grow extensively forming meadows and beds. There are 68 species of seagrass globally, of which 15 are found in Queensland (Lee Long, 1993). A gradient from high species richness in the northern GBR to low species richness in the southern GBR (Lee Long, 1993) is thought to be a result of the distance from the central diversity hotspot in Southeast Asia (Ooi Lean-Sim et al, 2011). Coles *et al.* (2003) note that tropical seagrass beds have a higher diversity, but biomass is lower than the temperate seagrass beds. Also of importance is the presence of *Amphibolis sp.* in the GBRWHA, which are endemic to Australia. These are thought to have been extensive in the Palaeogene (between 65.5 and 23.03 Ma), but are now restricted to a more confined distribution along the east coast of Australia (Coles *et al.* 2003).

The biological component of the seagrass habitat is not described in this section as the focus is on the geomorphological features and habitat complexes that result from the combination of location and species colonisation. Coles et al (2003) identifies the physical setting as a component of complex interactions that control species assemblage and location of the seagrass beds. In the GBR this setting often occurs in the lee of islands and headlands, protected from prevailing south-easterly winds. However, seagrass habitats have also been mapped more widely in less protected shallow shelf zones (Pitcher *et al.* 2007). Seagrass beds are generally found in shallow waters (< 10m), particularly in areas with high sediment and nutrient availability, such as close to the mainland, although they have been found in water depths of up to 60 m (Lee Long *et al.* 1993; Coles *et al.* 2003; Mellors *et al.* 2005).

Seagrass habitats stabilise the seabed by binding the surface sediments with their roots, decreasing current velocity and permitting suspended sediment to fall out of suspension (Merlin, 2011; Coles *et al.* 2003). They also provide habitat and food for a range of species including epibiota, fish, prawns, green turtles and in particular, dugongs, within the GBRWHA. Merlin's, (2011:p975) statement '*If seagrass beds were not in place, widespread marine areas in the world would have environments with unstable, shifting sand and mud*' highlights the importance of seagrass habitats for stability of the seabed.

Sediments within seagrass beds can be used to quantify the time and rate of seagrass growth and sediment accumulation (Ryan *et al*. 2008; Mateo *et al.* 1996). Although numerous studies have been undertaken on surficial sediments in seagrass habitat in the GBRWHA (Cavanagh *et al.* 1999; Haynes *et al.* 2000a, 2000b; Preen *et al.* 1995), no studies of the longer sedimentary record that is often preserved in seagrass beds (e.g. Ryan *et al*. 2008; Skene *et al.* 2005) were found. A number of large seagrass depositional environments in the GBR have been mapped and it is likely that they include relatively thick sediment deposits that preserve a Holocene record of seagrass extent and growth rates, as well as changes in sea level and temperature. Seagrass banks located within the pathway of river flood discharge also likely provide sedimentary records of changes in these depositional environments from recent changes in land use practices in the coastal hinterland.

6.12.2 Description of OUV

Seagrass Beds (Table 6.12):

- Control the local seabed geomorphology through stabilisation and trapping of sediment which provides habitat for unique and unusual compositions of flora and fauna (*criteria x*).
- Record Holocene climate and sea level changes (*criteria viii*).
- Record local sediment transport and yield, as well as long-term sediment flux (*criteria viii*).
- Record Holocene seagrass habitat development, including the distribution of key seagrass species (*criteria viii*).
- Support fisheries and feeding grounds for key species such as dugongs (*criteria x*).

*Table 6.12 Selected examples of seagrass beds with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order. These features have not been mapped).*

Feature	Outstanding Universal Values	References
Barrow Point to Lookout Point	• Extensive area of seagrass cover • Diverse Species • Deep water seagrass meadows (at Barrow Point) • Area of seagrass banks includes 1,566 km^2	• Lucas *et al.* 1997 • Lee Long *et al.* 1993
Dunk Island and coast region	• Diverse species	• Lucas *et al.* 1997
Roberts Point (North Princess Charlotte Bay)	• Extensive area of seagrass	• Lucas *et al.* 1997 • Lee Long *et al.* 1993
Bathurst Bay (East of Princess Charlotte Bay)	• Extensive area of seagrass	• Lucas *et al.* 1997 • Lee Long *et al.* 1993
Shoalwater Bay, including Port Clinton	• Extensive (estimated to be >7,000 ha in Port Clinton alone) • Highest seagrass diversity in GBR	• Lucas *et al.* 1997 • Lee Long *et al.* 1993

6.13 Karstic Channels and Blue Holes

6.13.1 Description

Karst landforms are chemically weathered formations created when slightly acidic fresh water from rainfall passes over soluble rock surfaces, weathering the bedrock into unique and unusual features. Karst landforms in the GBRWHA, such as channels, sink holes and dolines, developed when limestone reefs were sub-aerially exposed (above sea level) during periods of reef emergence. ‘Blue holes’ are deep circular depressions in the reef with steep sides that have been interpreted as submerged, collapsed dolines (Backshall *et al.*, 1979). Sea level is one of the strongest controls on coral reef development and morphology, including karst morphology. During periods of high sea level (highstands) the reef is in a constructional phase, and during periods of low sea level (lowstand) the reef is exposed to the destructive processes of sub-aerial weathering and erosion (Purdy, 1974). The global processes controlling sea level change are largely driven by glacial and interglacial climate cycles, together with local and or regional tectonics, and during the Late Quaternary have resulted in sea level changes of as much as 130 m. During the lowest sea levels associated with the Last Glacial Maximum (ca. 20 ka), the entire GBR would have been emergent. During the 500 ka during which much of the GBR is thought to have developed, periods of emergence account for around 80% of the time (Hopley, 1982).

Hopley (1982, 1997) attributed the deep, steep-sided passages between Darley Reef (19°12’S, 148°15’E), Gould and Cobham Reefs (19°28’S, 148°49’E), between Hook and Hardy Reefs (19°46’S, 149°14’E), and those that cut across many areas of the Pompey Complex in the southern GBR, as karstic in origin (Figure 6.24; Figure 6.26). Blue holes are a rare type of karstic expression on reefs, both on the GBR and globally. On the GBR there are just 3 identified examples, all excellent representations of blue hole morphology (Backshall *et al.* 1979). All are located in the Pompey Complex – at Molar Reef (20°38'S, 150°48'E), Cockatoo Reef (20°45'S, 151°02'E) and at an unnamed reef located at 20°57'S, 151°27'E. This last example is the deepest of the three, with an explored depth of 90 m and one of the best examples in the world (Hopley, 1997). Backshall *et al.* (1979) described blue hole geomorphology at Molar and Cockatoo Reef as roughly circular, partially surrounded at the surface by living coral rims, and flat bottomed. At 40 m the blue hole at Cockatoo Reef is around 10 m deeper than that at Molar Reef. The GBR blue holes were described as '*prominent examples'* of these features in a recent review (Gischler, 2011:164).

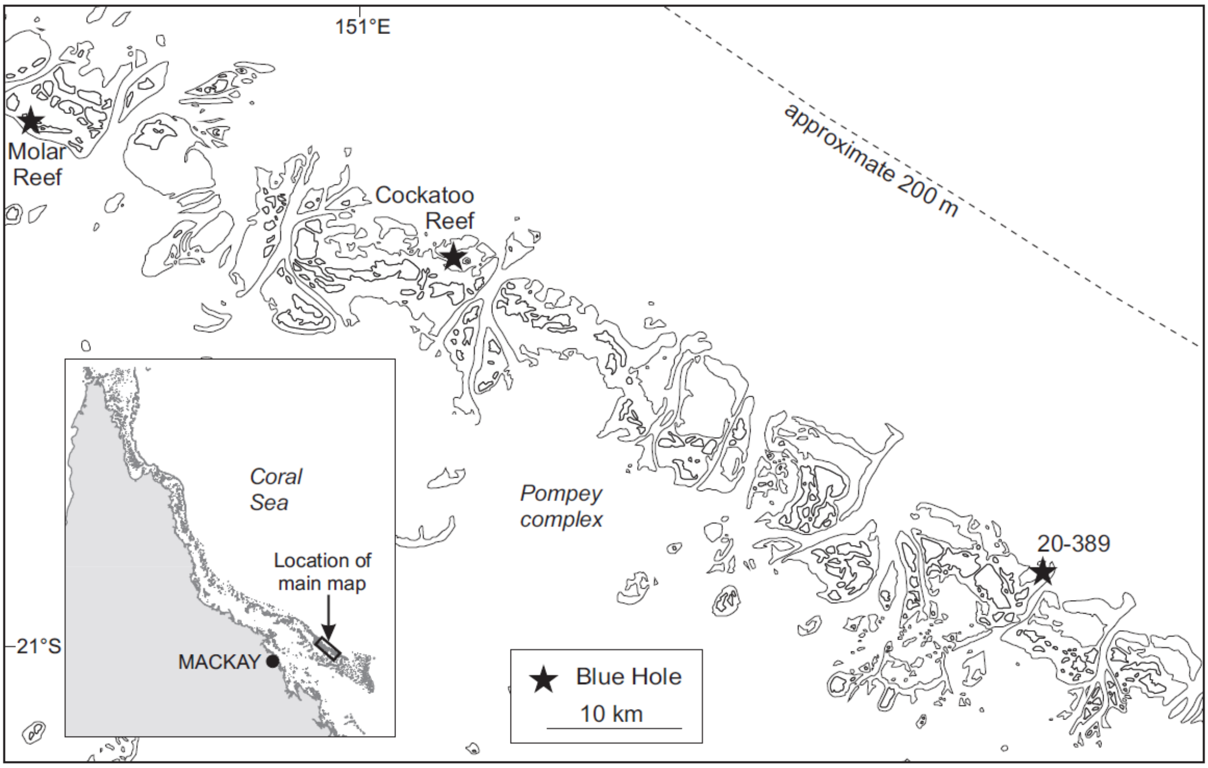


Figure 6.24 Map showing locations of the Blue Holes known from the Pompey Complex (Source: S Smithers).

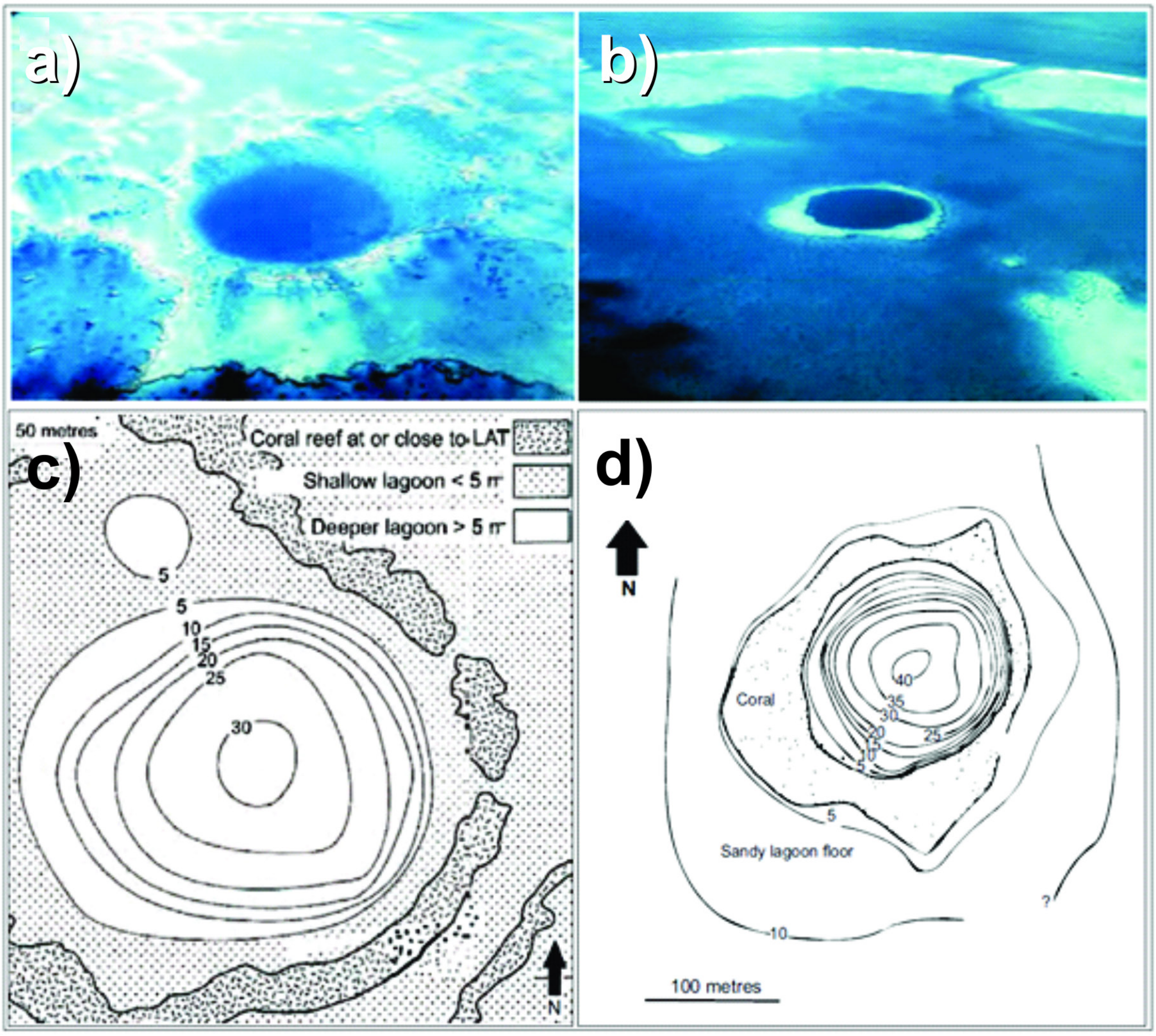


Figure 6.25 a) & c) Oblique aerial photograph and morphological diagram for Molar Reef; b) & d) Oblique aerial photograph and morphological diagram for Cockatoo (photographs: D Hopley. Morphological diagrams after Backshall et al. 1979).

6.13.2 Description of OUV

Karstic channels including blue holes (Table 6.13):

- Preserve evidence of karst erosion during past low sea levels and reef construction during higher sea levels (*criteria viii*)
- Record past fluctuations in sea level, reef growth and erosion during glacial and interglacial cycles (*criteria viii*).
- Comprise potential archives of storm history in sediments accumulated at the bottom of blue holes (*criteria viii*).
- The blue holes are rare geomorphic features within the GBR and represent globally significant examples (*criteria viii*).
- The evolution of karstic channels on the GBR can inform the understanding of shelf hydrodynamics and subaerial processes that occurred during glacial lowstands (*criteria viii*).

*Table 6.13 Selected examples of karstic channels and blue holes with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.26).*

Feature	Outstanding Universal Values	References
Steep and Deep Karstic channels between Darley Reef, Gould and Cobham reefs, and between Hook and Hardy Reefs	• Meandering deep channels with steep sides and deep bases that pass between major reef structures presumed to be karstic in origin. • Record of important processes influencing reef growth and structure that occurred during sea level lowstands. • Record of relative influence of lowstand erosional processes and highstand reef growth processes in determining reef morphology • Channels are locations of hydrodynamic focus, with very high velocity streams common in these features – as such the physical features structure the hydrodynamics of habitats that are relatively rare across the GBR.	• Lucas *et al.* 1997 • Hopley, 1982 • Hopley *et al.* 2007
Blue holes (Pompey Complex) ** • Molar Reef (32.5 m deep) • Cockatoo Reef (40 m deep) • Reef 20-389 (approx. 90 m deep)	Blue Holes are rare worldwide and in the GBR • These blue holes are considered globally ‘prominent’ examples (Gischler, 2011). • Record in their stratigraphy and formation histories of sea level change and storm impact.	• Byron, 1985 • Lucas *et al.* 1997 • Backshall *et al.* 1979 • Hopley 1982 • Hopley *et al.* 2007

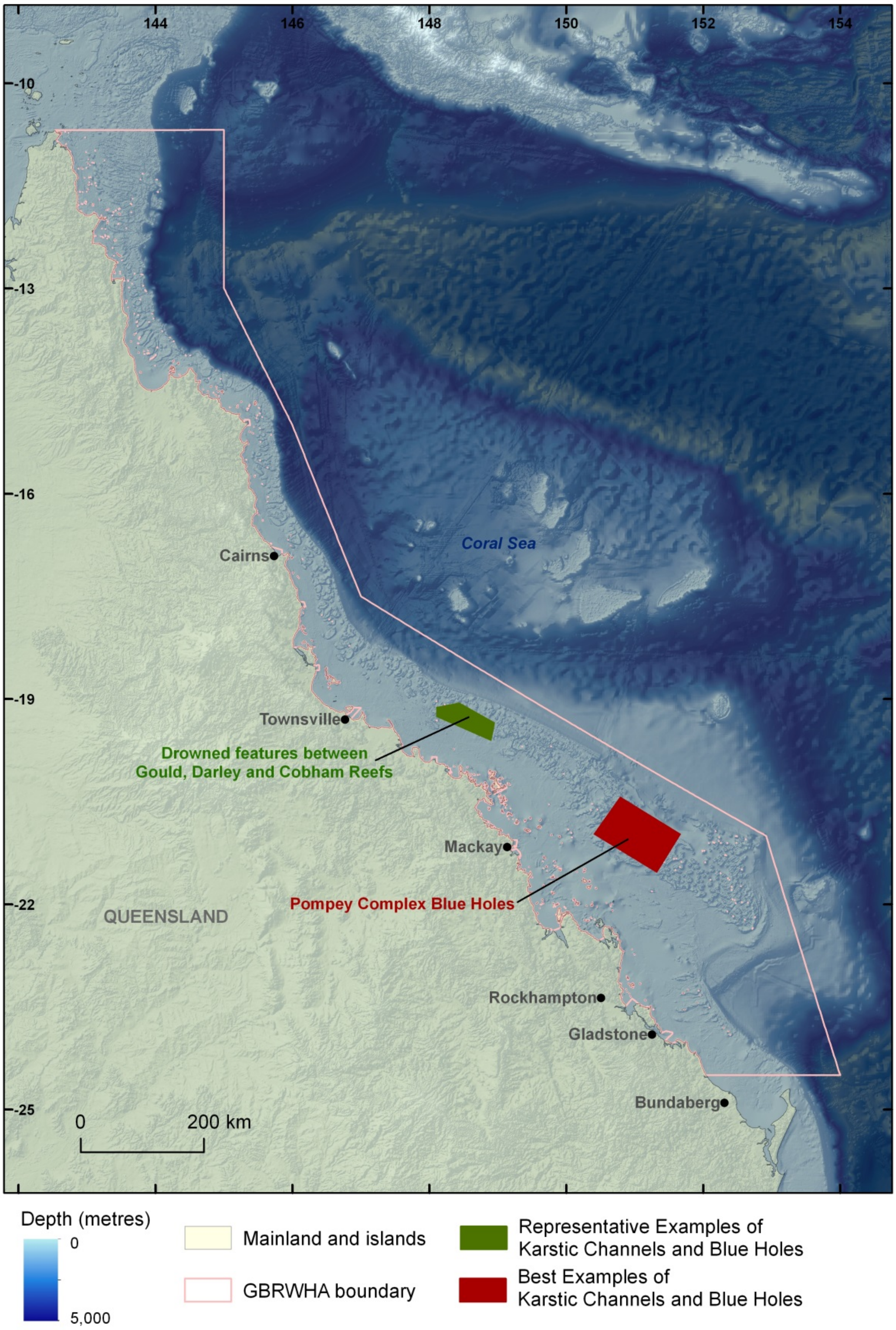


Figure 6.26 Selected examples of karstic channels and blue holes in the GBRWHA.

6.14 Palaeochannels

6.14.1 Description

Palaeochannels are abandoned ancient river channels or, in the case of marine environments, river channels that are now inundated by the ocean and often completely infilled by marine sediment. Palaeochannels include not only the channel depression but also the associated sedimentary features deposited by the former river (e.g. point bar deposits).

Thirty-eight major mainland catchments connect with the GBR lagoon (GBRMPA, 2009), including the two very large catchments of the Burdekin and Fitzroy rivers. During periods of low sea level, these rivers flowed across the exposed continental shelf to the low shoreline – a distance of between 50 km and 200 km (Ryan et al. 2007). Preservation of large palaeochannel features such as the Burdekin River palaeochannel (Fielding et al. 2003, 2005) and Fitzroy River palaeochannel (Ryan et al. 2007) are well documented, with studies that show the path of these rivers across the continental shelf during the Last Glacial period of much lower sea level. Smaller rivers of the GBR coast also flowed across the exposed shelf at this time (e.g. Herbert R., Hopley et al., 2007) but most of their former pathways are either not preserved or have not been identified, likely being well buried by marine sediment. As sea level rose to its present high position, coastal waves and currents reworked sediment deposited on the exposed shelf and lowstand coastlines and transported it offshore to the continental slope (Dunbar et al. 2000; Dunbar and Dickens, 2003a; Johnson et al. 1982).

6.14.2 Description of OUV

Palaeochannels are an important element of the OUV of the GBR because they:

- Record the past pathway and direction of flow of rivers during the last sea level lowstand, which is important for understanding the evolution of the continental margin (Fielding *et al.* 2003) (*criteria viii*).
- Provide a record of past climatic conditions, such as the volume and source of water flowing from a river, for example through measurements of channel width that indicate past stream power and discharge. Furthermore, palaeochannels record the response of coastal rivers to major changes in sea level that occurred over the last glacial cycle (*criteria viii*).
- Form a distinctive seabed habitat and a depositional environment that preserves a record of terrestrial sediment accumulation on the continental shelf (e.g. Fitzroy River palaeochannel) (*criteria viii and x*).
- Provide pathways for catchment-derived fresh groundwater to flow offshore. Groundwater discharges from depressions in the seabed (known as 'wonky holes') that mark connectivity between the lagoon environment of the GBR and palaeochannel aquifers. This process of submarine discharge of fresh groundwater from underlying palaeochannels occurs on the inner and middle shelf along, for example, the Burdekin River palaeochannel (Stieglitz, 2005) (*criteria viii and ix*).

*Table 6.14 Selected examples of palaeochannels with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.27).*

Feature	Outstanding Universal Values	References
Fitzroy River Palaeochannel **	The Fitzroy palaeochannel is a well preserved example on the southern GBR, providing also a reference for past climates as it '*records the response of alluvial and estuarine depositional environments to sea level change'* (Ryan *et al.* 2007). • Longest river draining into the GBR • Extended across the entire shelf in the Last Glacial Maximum lowstand • channel ranges from 800–1,000 m wide, and incises up to 20 m into the surrounding seabed • Possible mechanism for cross shelf sediment transport • Connectivity of ground water between the coast and shelf	• Ryan *et al.* 2007 • Hopley *et al.* 2007 (p178)
Burdekin River Palaeochannel **	The Burdekin River has a well mapped palaeochannel that extends across the bed of the GBR lagoon: • Well preserved example of a palaeochannel on the central GBR; • Records the lowstand flow paths in relict sediment deposits and a Pleistocene surface horizon	• Hopley *et al.* 2007, (p175) • Harris *et al.* 1990 • Fielding *et al.* 2003
Herbert River – Rib Reef off Townsville	The palaeochannel contains good records of past river flow, erosion and sediment accumulation.	• Hopley *et al.* 2007 (p175)

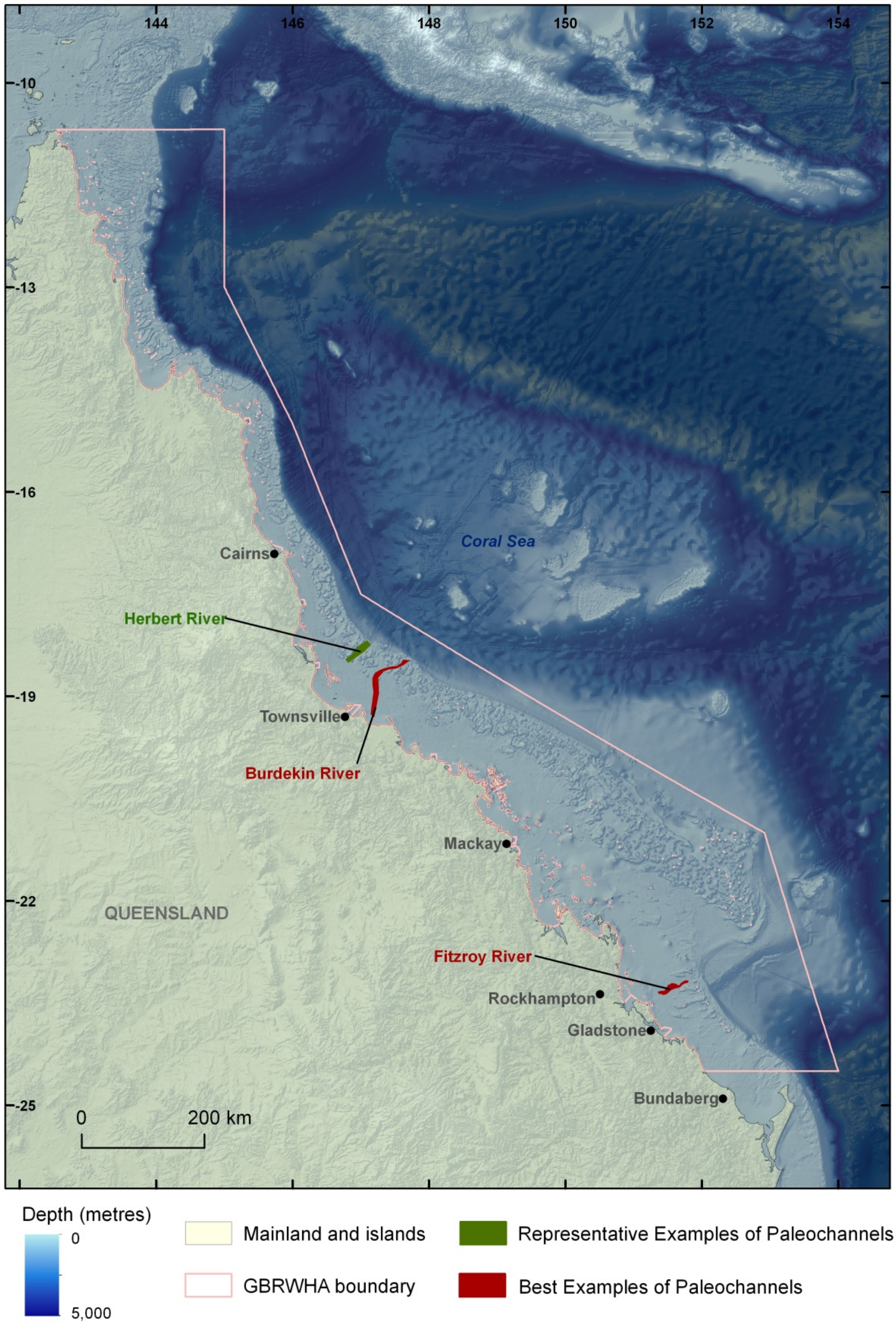


Figure 6.27 Selected examples of palaeochannels in the GBRWHA.

6.15 Continental Islands

6.15.1 Description

Continental islands are islands that were once part of the continental land mass but are now separated from the mainland by the sea. They can be formed when sea level rises, leaving only the highest areas above water, or through marine erosion that removers softer rock and sediment and leaves only hard outcrops exposed. In some locations, over much longer timescales, continental islands also form when tectonic processes break off fragments of continent and move them away from the coast.

The GBRWHA contains more than 600 continental islands composed of continental rocks and regolith that were isolated from the mainland during the post-glacial marine transgression (Thom and Chappell, 1975; Stoddart, 1978; Thom and Roy, 1983; Hopley *et al.* 2007). The continental islands exhibit a range of topographies and morphologies similar to that observed along the mainland coast which, in part, reflects their lithology and structure (Stoddart, 1978). A range of rock types are represented, including most of the major lithologies found on the mainland coast. Felsic igneous rocks, such as granites and volcanic equivalents, were emplaced during the Late Palaeozoic (330-270 Ma) and Cretaceous (120-100 Ma) and dominate the geology of around 70% of the continental islands on the GBR (Henderson, 1997). The remaining 30% of rock types comprise a range of metamorphic, sedimentary and other igneous rocks (Henderson, 1997). Examples of islands dominated by granite include Lizard, Hinchinbrook and Magnetic islands and the Palm and Whitsunday groups of islands. Dunk Island comprises granite intrusions in a basement of metamorphic rocks. Islands composed of sandstone are less common, the Flinders Island group being an excellent example.

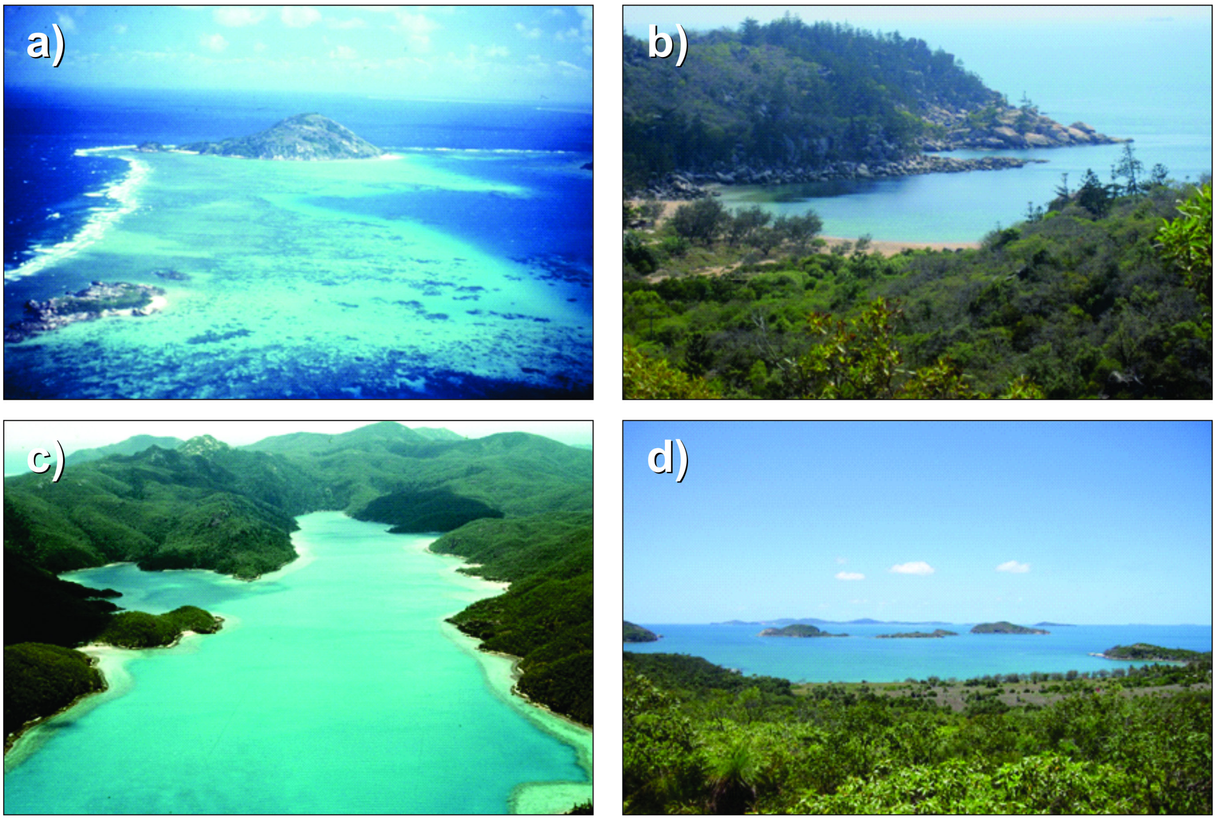


Figure 6.28 Examples of Continental Islands a) Lizard Island (Photograph: S Smithers), b) Magnetic Island (Photographs: S Smithers.), c) Nara Inlet – Whitsunday Islands (Photograph: D Hopley) and d) Keppel Island Group (from N. Keppel Island Lookout) ((Photograph: S Smithers).

Several continental islands within the GBRWHA are unusual or unique in their geological composition: South Repulse Island includes a combination of mafic volcanic rocks and fossiliferous limestones which are unrepresented on the mainland; South Percy Island contains pillow basalts and rare serpentinite rocks not found elsewhere on the GBR; Wild Duck Island is an excellent sample of an island composed of Cretaceous sedimentary rocks, and the Cretaceous volcanics of the Whitsunday coast are widely considered the best place to examine these rocks, critical to understanding the tectonic evolution of Australia and the adjoining basins at that time (Henderson, 1997).

Geological structure is also an important control on the geomorphology of the continental high islands, and thus is a key factor influencing landscape development and processes, and the diversity, distribution and traits of habitats. For example, the spectacular geomorphology on Hinchinbrook Island, which includes Mt. Bowen – at 1121 m one of the highest peaks in Queensland – together with steep cliffs, incised valleys, gorges and waterfalls is largely a function of its geology and geomorphological processes. The location and morphology of archipelagos such at the Palm and Whitsunday groups of islands are similarly a function of the geological composition and structure of these areas

6.15.2 Description of OUV

The geology and geomorphology of the continental high islands in the GBRWHA:

- Preserve evidence of the geological evolution of Australia's eastern margin (*criteria viii*).
- Record long-term geological processes and past environmental conditions in sedimentary structures and fossil assemblages (*criteria viii*).
- Preserve evidence of long-term sea level, climate, and environmental changes (*criteria viii*).
- Provide major control on terrestrial and coastal habitat diversity and distribution within the GBRWHA (*criteria ix and x*)
- Are excellent examples of unusual or unique geological features unrepresented elsewhere (*criteria viii*).
- The number and diversity of continental islands within the GBR that are protected is unmatched in other reef provinces (*criteria viii*).
- They are a fundamental element of the aesthetic value of the GBRWHA (*criteria vii*).
- Are culturally important to past and present indigenous communities as they are habitable (*criteria iii*).

*Table 6.15 Selected examples of continental islands with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.29).*

Feature	Outstanding Universal Values	References
Flinders Island Group **	Excellent examples of sandstone continental islands – northern GBR. • Relatively rare on GBR. • Bedding structures develop landforms unusual on GBR islands. • Marine sandstone units deposited ~120 Ma on Flinders Island group are a lateral extension of sandstones exposed in the mainland Bathurst Range. • This sandstone unit are particularly resistant to weathering and which has contributed to the islands resistance to erosion. • These strata preserve evidence of palaeoenvironmental conditions at the time of deposition and subsequent environmental change and represent the only rocks of Cretaceous age preserved in the region. • Culturally important	• Maxwell, 1972 • McConachie *et al.* 1997
Lizard Island	Excellent example of granitic continental high islands – northern GBR. • Excellent fringing /barrier reef development. Lizard Island almost is completely surrounded by well-developed fringing reefs. • The lagoonal system formed within a complex of continental islands is very unusual in the Great Barrier Reef Region. • Unusual assemblage of islands and reef morphology and relatively close to the shelf margin - the continental shelf edge is just 20 km east. • Culturally important	
Hinchinbrook Island **	Large granitic continental high island in a wet tropical setting – central GBR. • Spectacular landform/landscape development. Large in size and elevation. The largely mountainous island covers 39,000 ha and includes a chain of high peaks, culminating in Mt Bowen at 1,142 m high. • composed of 260 million year old Almaden Granites with significant variation in composition across the island. • Close to the mainland coast. • Culturally important.	• Ewart, 1978

Feature	Outstanding Universal Values	References
Palm Islands	Archipelago of small to large continental high islands composed of granitic and felsic volcanic rocks – central GBR. • High geomorphic diversity supports high habitat diversity • Culturally important	• Henderson, 1997
Magnetic Island**	Granitic continental high island in seasonal wet/dry climate – central GBR.	• Lucas *et al.* 1997
Whitsunday Islands **	A group of continental high islands predominantly composed of Cretaceous granites (~120-100 million years in age). • These igneous rocks provide valuable evidence in understanding the Cretaceous geological evolution of Australia's eastern margin. • Rocks of the Whitsundays form part of a felsic large volcanic province dominated by several large caldera centres and record temporal changes in eruptive styles and compositions and facilitate understanding of the timing and physical processes of continental breakup of eastern Gondwana over a time span of >35 Ma. • Development of the archipelago has provided habitat and environmental diversity that structures ecological richness. • The Whitsunday Islands are recognised as the best site on the east coast of Australia to study Cretaceous volcanics, which are of broad significance to the geological evolution of the eastern margin of the continent.	• Henderson, 1997 • Ewart *et al.* 1992 • Bryan *et al.* 1997
South Percy Island **	Continental high island with unusual geological assemblage. • Occurrence of ultramafic rocks – largely serpentinised together with pillow basalts – unique in GBR • South Percy Island provides the best known exposure of the Northumberland Serpentine, contrasting with the Palaeozoic granites and felsic volcanics which dominate the geology of the surrounding area. • Unique fossil biota associated with rare serpentine rocks • Unique record of geological processes significance for understanding the evolution of Australia's eastern margin.	• Leitch *et al.* 1994 • Bruce and Niu, 2000
South Repulse Island **	Continental high island with unusual geological assemblage. • This island is composed predominantly of volcanic rocks of Middle Devonian to early Carboniferous age, which can be correlated with extensive volcanic successions across the region, including on the adjacent mainland. • Well exposed occurrences of rare sedimentary layers within the Campwyn Volcanics on South Repulse Island. • Unique association of mafic volcanics and fossiliferous limestone.	• Fergusson *et al.* 1994 • Henderson *et al.* 2010 • Jensen *et al.* 1966 • Clarke *et al.* 1971
Wild Duck Island **	Continental high island with unusual geological assemblage. • Cretaceous sediments. • Two separate outcrops (maximum elevation 103 m) joined by sandy tombolo. • The base geology of the island is Cretaceous quartz sandstone, a rare rock type for a continental island in this region and contrasts to the geology of nearby Avoid and Red Clay Islands. • Part of the Styx Coal Measures, composed of quartzose sandstone, mudstone, conglomerate and coal deposited in a coastal plain/swamp environment. • The Styx Coal Measures on Wild Duck Island are also noted to support an acacia woodland ecosystem, not found extensively elsewhere in the GBRWHA.	• Henderson, 1997 • Pollock, 2007 • Ewart *et al.* 1992

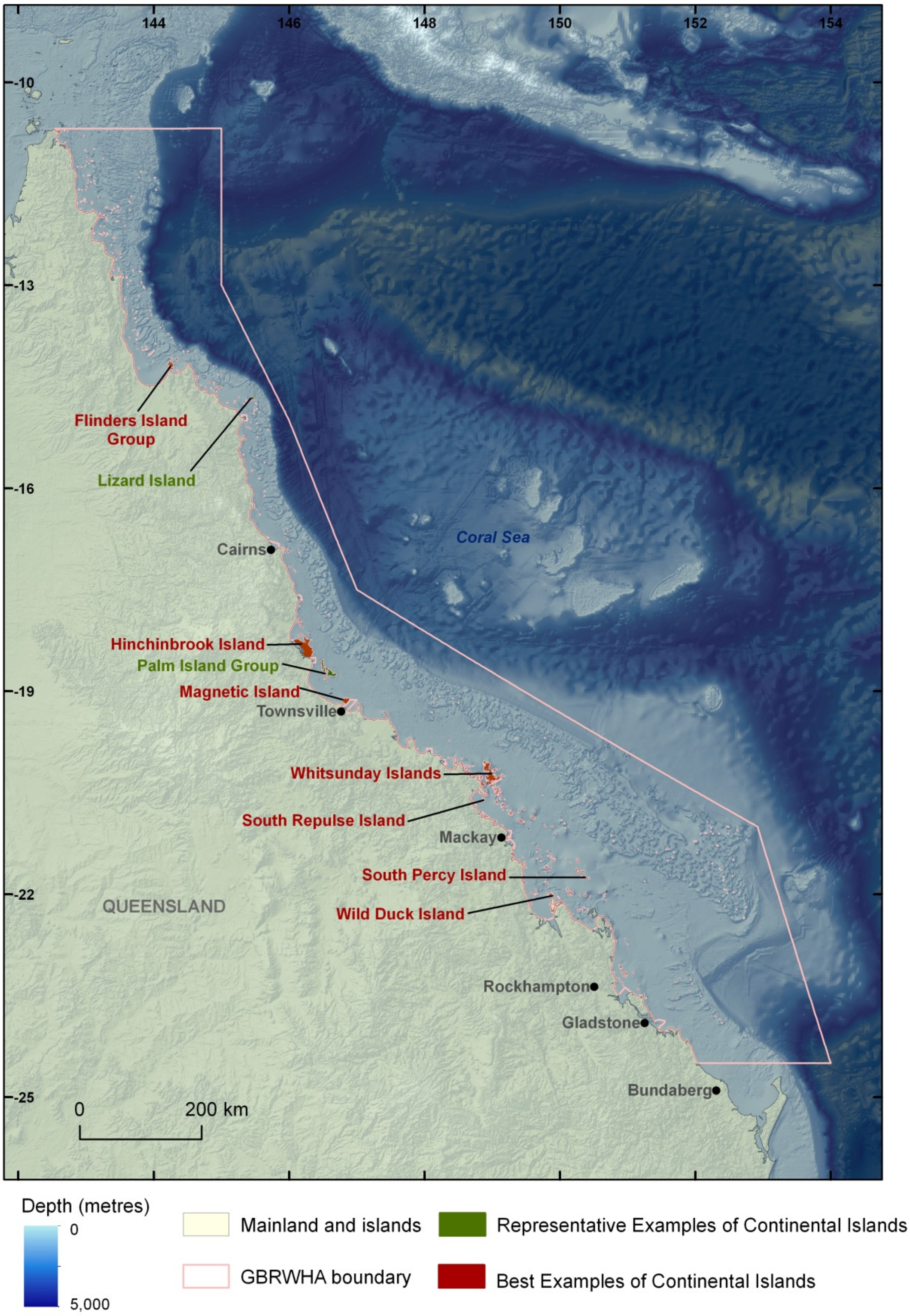


Figure 6.29 Selected examples of continental islands in the GBRWHA.

6.16 River Deltas

6.16.1 Description

Deltas are sedimentary landforms and seabed structures at the mouths of rivers that are composed of terrestrial sediment deposited by the rivers (Chernicoff, 1995). Deltas are commonly classified into three processes-based types; wave, tide and river dominated (Galloway, 1975 as modified in Walker and James, 1992). River-dominated deltas usually have a characteristic fan shape created as a result of river discharge transporting sediment directly out over the delta front and onto the continental shelf. Wave-dominated deltas have eroded delta fronts that form convex bays with cuspate connections. In areas with relatively high wave energy, barrier sand islands form at the front of and parallel to the delta front as a result of wave erosion and longshore transport of the river sediment. Tide-dominated deltas are usually channel controlled, often with sand islands and intertidal and subtidal sand bars perpendicular to the front of the delta (Galloway, 1975 as modified in Walker and James, 1992).

Approximately 30 rivers and several hundred smaller, often ephemeral, streams drain into the GBR lagoon (Furnas, 2003). Many of these rivers and streams transport significant loads of terrestrial sediment to the coast and shelf, including bedload sediments (medium sands and coarser) and suspended sediment (fine sand and mud), that accumulate to form a range of deltaic habitats. The combination of relatively high sediment yields and relatively low ambient wave energy (except during cyclones) due to the protection created by the outer barrier reefs, has enabled significant deltas to form at the mouths of many rivers in the GBRWHA, especially the Barron, Herbert, Burdekin and Fitzroy rivers. At river mouths exposed to relatively high wave energy and tidal currents, some of the river sediment is transported alongshore, generally northwards, and back into the river channel. This process has played an important role in the development of significant coastal and offshore geomorphological features, including both the deltas (and their associated subaerial and subtidal structures) and the depositional landforms and seabed sedimentary features that form downdrift from the river-mouth sediment source (e.g. subaqueous dunes, sandbanks, mudflats, beaches, spits, beach ridges and dune fields), for example offshore and north of the mouth of the Fitzroy River (Ryan et al., 2007; Brooke et al., 2008).

At more than 600 km^2 the Burdekin River has the best developed cuspate delta in Australia, with an intertidal zone of approximately 27 km^2 and around 54 km^2 of subtidal environment that extends offshore to approximately the 10 m isobath (Goh, 1992). The Burdekin delta is widely recognized as a globally important example of a wave and drift-dominated delta (Hopley, 1997). The development and geomorphology of the Burdekin delta has been well described by Hopley (1970), with later studies examining sediment delivery to the coast and the development of deltaic landforms (e.g. Belperio 1978, 1983; Pringle 1984, 1991, 1995; Fielding *et al*. 2006; Alexander *et al*. 1996). The Burdekin delta exhibits classic cuspate morphology, with the main channel in the delta shifting position several times during the past 3000 years, from the north, near the base of Cape Bowling Green, south to its present position (Hopley, 1970; Fielding *et al.* 2006). Former large channels now function as distributaries during overbank floods only (e.g. Sheepstation, Kalamnia and Plantation Creeks). Stream flow in the Burdekin River is highly seasonal and strongly affected by cyclones and climatic cycles associated with El Nino Southern Oscillation (ENSO) conditions, and a large degree of interannual variation occurs in both stream flow and sediment discharge to the coast (Alexander *et al.* 1999, Pringle, 2000; Lough, 2007). Belperio (1978) calculated that on average around 450,000 tonnes of sand were exported from the Burdekin River, representing approximately 10% of the average annual sediment yield (suspended sediment the remaining 90%).

Figure 6.30 Burdekin River delta (Photograph: D Hopley).

Deltas are dynamic geomorphological features, with the position of the mouth varying through time (e.g. Bostock et al., 2007). As a consequence, sediments deposited near to former delta mouths can remain important sediment sources for ongoing coastal processes, well after the stream mouth has shifted to another location. This includes deposits that have been drowned by the Holocene transgression and are now subtidal. For example, Hopley (1970) argued that relict deltaic deposits have fed the development of Australia's largest sand spit - Cape Bowling Green – which extends more than 18 km north of the main Burdekin delta area around Kalamnia Creek. Based on detailed examination of the morphology and stratigraphy of the delta and shorelines near the base of Cape Bowling Green, Hopley (1970) proposed that the growth of Cape Bowling Green was originally supplied by sediments delivered to near its current base by Kalamnia Creek when it was the primary Burdekin River channel around 3,000 years ago. Since that time the main channel mouth has progressively shifted south, diminishing this sediment source.

A smaller, but also wave-dominated delta is the Barron River Delta, north of Cairns. The annual net longshore transport of sediment is predicted to be in the order of 10,000-30,000 m^3 / year, whereas the net fluvial transport of sediment to the Barron River mouth is in the order of 23,000 m^3 / year (Barron River Steering Committee in Robinson et al. 1980). Hence there is a net annual loss of sediment to wave action and longshore drift, which creates a barrier sand island extending northwards from the river mouth (Manders, 2010).

6.16.2 Description of OUV

River deltas in the GBRWHA (Table 6.16):

- Preserve a record of fluvial drainage on the northeastern margin of Australia that better informs our understanding of global tectonic processes during the Cenozoic (*criteria viii*).
- Preserves evidence of climate change, relative sea level change, coastal morphodynamics, and sediment yields from coastal catchments during the last several thousand years (*criteria viii*).

- Represent contemporary and relict sediment sources that supply sediment to modern coastal sediment systems, including beaches, dunes and spits, and provide important habitats that underpin critical ecosystem services (*criteria viii and ix*).

Table 6.16 Selected examples of river deltas with OUV in the GBRWHA (Note: Features are listed in no particular order. These features have not been mapped).

Feature	Outstanding Universal Values	References
Barron River Delta	Dynamic wave-influenced delta at the mouth of a wet tropics river • Sediment source for coastal landform development and change • Provide a range of important sub-tidal habitats.	• Pringle, 1991 • Lucas *et al.* 1997
Burdekin River Delta (including Bowling Cape Green)	World-class example of a large wave-influenced delta in seasonally dry tropical setting. • Large feature with long history of development. • Stratigraphy and sedimentological features preserve evidence of sediment yields, shifts in channel and shoreline position. • Preserves evidence of climate and sea level change. • Provides contemporary and relict sediments sources critical to the maintenance of important coastal features. • Provide a range of subtidal habitats and sediment delivery supports the development and maintenance of a range of ecosystems and ecosystem services.	• Lucas *et al.* 1997 • Hopley 1970 • Belperio 1978, 1983 • Pringle 1984, 1991, 2000 • Fielding *et al.* 2006 • Alexander *et al.* 2007

6.17 Dune Systems

6.17.1 Description

In locations where strong onshore winds occur (greater than 5 m/sec) beach sediment can be swept to the back of the beach, become trapped in vegetation and lead to the formation of coastal dunes. The most impressive coastal dunes in tropical Australia occur along the coastline adjacent to Cape Grenville (12°07'S, 143°07'E - 400 km^2), and between Cape Bedford and Cape Flattery (15°03'S, 145°17'E - 700 km^2). Together these two dune fields account for more than 60% of the total dune field area on Cape York. The location of these dune fields coincides with the availability of sand-size sediments weathered from the Mesozoic sandstones and an orientation of the coast that allows the higher-energy south-easterlies that prevail during winter to mobilize the sands. It is of particular relevance to the GBRWHA that the relatively small number of dune ages available indicate that the dune fields are largely formed from sand blown onshore from the exposed continental shelf during periods of low sea level in the Late Pleistocene (Pye, 1982; Pye and Bowman 1984; Lees, 2006). This is clearly evident where the trailing arms of some of the larger elongate parabolic dunes have been truncated at the shoreline but clearly extended further offshore when sea level was lower than present (Pye, 1982). Terrigenous sandy sediments dominate the inshore seafloor of these systems (Maxwell, 1968), but at present there is negligible sand being transported from the beach to the dune field (Pye, 1982). The scale, geomorphological diversity, and degree of landform preservation of the tropical dune field at Cape Flattery and Cape Grenville are globally rare.

Smaller dune systems exist elsewhere within the GBRWHA that are also of significance, including dune systems at Ramsay Bay, Hinchinbrook Island; at Whitehaven Bay, Whitsunday Island; at Shoalwater Bay-Byfield; and at Cape Capricorn on Curtis Island. At Ramsay Bay a dune complex exists that forms a barrier linking a bedrock outlier with the main body of Hinchinbrook Island. This tombolo is up to 700 m wide and around 9 km long, and is aligned to the NNE-WSW so that it is well exposed to the prevailing SE trade winds on the eastern shore. Elongate parabolic dunes with long axes broadly aligned with the prevailing SE winds have developed over the tombolo, reaching heights of up to 60 m at the northern more exposed end of the bay (Pye, 1982). Most of these dunes are vegetated and appear stable at present, but some blowouts are evident. Pye and Rhodes (1985) investigated the sedimentology of sands in the dune field and identified distinctive sediment traits that coincide with particular landforms – the parabolic dunes were composed of the finest sands, and were found to be well to moderately sorted. In contrast, foredune sands are well-sorted medium to fine sands. Coring revealed that aeolian sands extended to at least 30 m below contemporary sea level, indicating that the dunes were initially formed during lower sea levels. Radiocarbon dating of organics within the barrier sequence identify two major periods of dune activity; the first coincides with the early transgression and is speculated to be associated with destabilization related to rapid shoreface erosion, and the second phase occurred at 0.9-1.0 ka, the cause of which is currently unclear (Pye and Rhodes, 1985). The morphology and dynamics of the dunes at Ramsay Bay identify it as an episodic transgressive dune barrier that was partly drowned *in-situ* by the postglacial marine transgression. In the lee of the dunes an extensive mangrove forest with large areas of upper and supratidal mud flats has developed.

Figure 6.31 A large dune barrier and extensive mangroves have formed behind the beach at Ramsay Bay, Hinchinbrook Island (Photograph: D Hopley).

Whitehaven Beach is located on the east coast of Whitsunday Island, the largest island in the Whitsunday Group. Whitehaven Beach is composed of very fine white silica sands (approximately

98% pure silica) and is recognized as one of the most aesthetically stunning beaches in the world. The spectacular snow-white sands that compose the beach are, however, not derived from the local geology and are interpreted as being weathered and transported from distant rocks a long time ago, to form parabolic dunes where they accumulated against the bedrock outcrops. These parabolic dunes are aligned from the southeast toward the northwest – coincident with the prevailing southeast tradewinds. They are well vegetated, and are estimated to be of at least Late Pleistocene age based on the degree of soil development. The modern beach is approximately 7 km in length and faces toward the northeast. It is exposed to afternoon northeasterly sea breezes which have entrained sand and developed small foredunes behind the modern beach.

6.17.2 Description of OUV

Coastal dunes in the GBRWHA (Table 6.17):

- Preserve in their composition, stratigraphy and morphology evidence of past environmental conditions, including the aeolian transport of large volumes of shelf-derived sand and the long-term development of soil, that are linked to Quaternary global climate cycles. They also record short-term and more recent changes in coastal climate (*criteria viii*).
- Preserve evidence of shelf sediment transport processes and pathways associated with phases of both low and high sea level (*criteria viii*).
- Provide globally rare examples of large parabolic dunes in a wet tropical setting (*criteria viii*).
- Have significant aesthetic value, for example Whitehaven Beach (*criteria vii*).

*Table 6.17 Selected examples of dune systems with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.32).*

Feature	Outstanding Universal Values	References
Hinchinbrook Island – Ramsay Bay	Unusual example of an episodic transgressive parabolic dune assemblage developed in wet humid tropical setting. • Stratigraphy indicates past episodic dune activity. • Formation began during lower sea levels but dunes also became active as sea levels rose. • Sedimentary facies record palaeoenvironmental conditions. • Dune fields have resulted in the formation of other important habitats such as leeward mangroves and salt flats.	• Pye, 1982 • Pye and Rhodes, 1985
Whitsunday Islands - Whitehaven Bay	High purity very fine silica sands (~98%) forming an iconic white beach and dune landscape on the eastern shoreline of Whitsunday Island. • Local geology is not the source of the sands. • Vegetated dunes and adjoining beach composed of sands of this type are rare on the GBR. • Lithology and sedimentology of dunes informs our understanding of their development, including the importance of processes during sea level lowstands. • Morphology of dunes and the chronology of periods of dune stability and instability informs our understanding of environmental change. • High aesthetic value.	• Lucas *et al.* 1997 • Pye 1982
Shoalwater Bay – Townshend Island	Excellent and rare example of unmodified tropical relict cliff-top parabolic dunes. • Morphology of dunes and assessment of phases of stability and instability can inform understanding of environmental changes. • Significant parabolic dune development occurs along the mainland coast in this region, and is also found on Townshend Island at the far north of Shoalwater Bay. • The upwind end of the dunefield does not extend from the rocky coastline, indicating the dunes are now isolated from their original sediment source. • Most of the dunes are elongate and the maximum length as much as 4 kilometres. • The sand dunes in the Shoalwater Bay Training Area are highly significant in a national context.	• O'Neil *et al.* 2008
Curtis Island	A large field of parabolic dunes on the eastern coast, south of Cape Capricorn, extends from the shoreline to the southern end of Blackhead Beach. • These dunes are significant due to the range of important habitats they provide, their relative uniqueness at the S end of the GBR, on the largest continental island of the GBRWHA, and their aesthetic value.	*(no detailed published description found)*

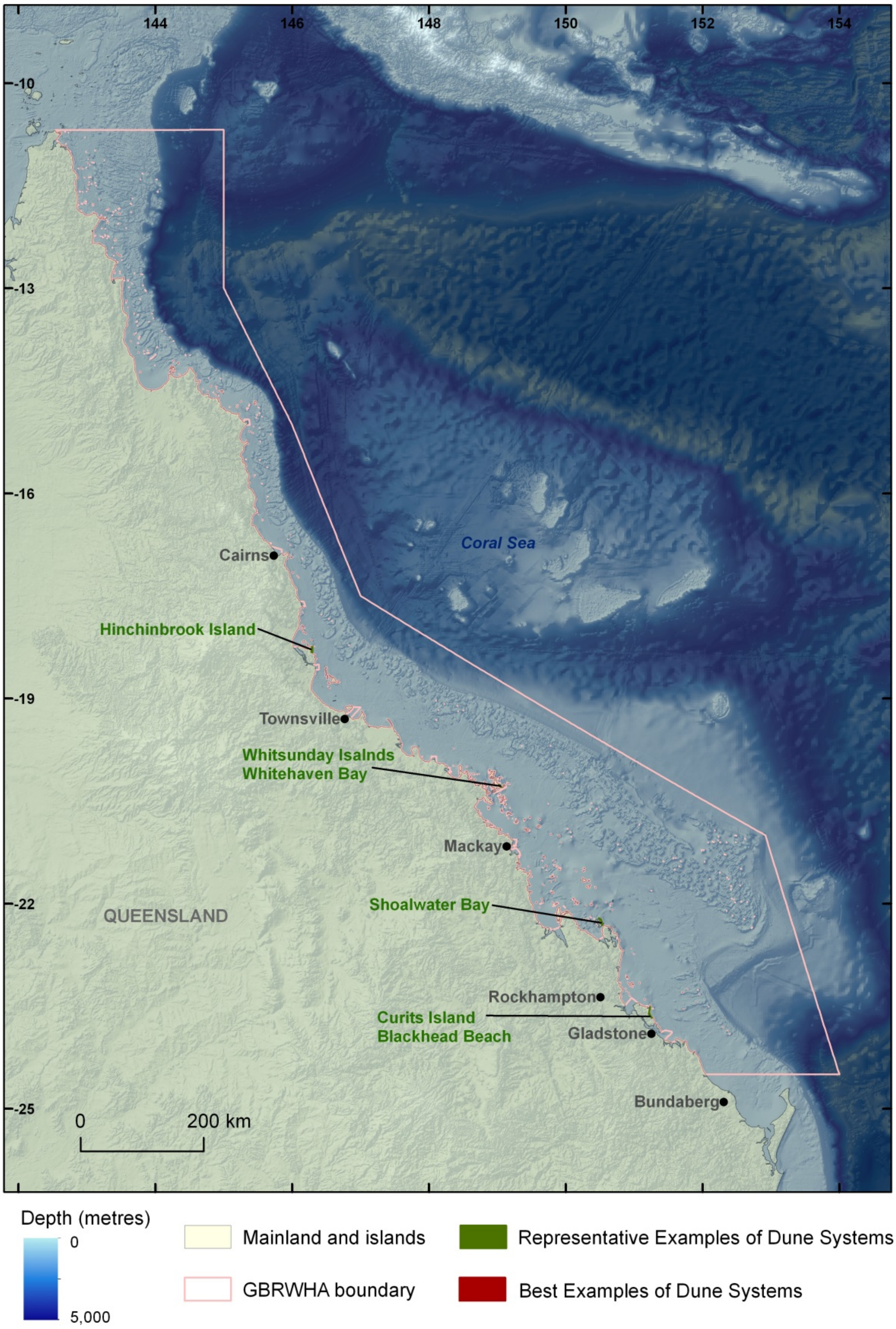


Figure 6.32 Selected examples of dune systems in the GBRWHA.

6.18 Submarine Canyons and Turbidite Deposits

6.18.1 Description

Submarine canyons are undersea valleys that cut into the outer edge of the continental shelf (termed the continental slope). Some canyons extend into the continental shelf proper and are termed shelf-incising canyons. Associated with submarine canyons are turbidite deposits, which form when sections of the continental slope collapse causing a gravity flow of sediment and water down to the deep abyssal plain. These deposits are characterised by sediment with a mix of grain sizes, often including relatively coarse grains, that fine upwards as as a consequence of fine sediment settling out of suspension after a turbidity flow.

Over the past decade improvements in multibeam acoustic seabed mapping and data processing technologies have revealed fine-scale geomorphic features in the GBRWHA that were previously poorly described or unknown (Beaman, 2011). A key product from this mapping has been 3-dimensional terrain models of shelf-edge and deep water environments (e.g. Beaman *et al.* 2008; Abbey *et al.* 2011; Bridge *et al.* 2011), which when combined with other seabed data have enabled detailed images of benthic habitats to be produced. This information has proven invaluable for the interpretation of the development and dynamics of seafloor processes and structural features and to highlight their geological and biological significance (Puga-Bernabeu *et al.* 2011; Webster *et al.* 2012; Puga-Bernabeu *et al.* in review). While submarine canyons are relatively common on continental margins (Harris and Whiteway, 2011; Puga-Bernabeu *et al.* in review) those identified within the GBRWHA are exceptional because they:

- are representative of mixed siliciclastic-carbonate systems (deposits of terrestrial and marine-derived sediment), which are poorly understood compared to better studied modern and ancient equivalents in siliciclastic settings (Puga-Bernabeu *et al.* 2011);
- are of impressive size and extent (Beaman, 2010);
- display a varied morphology along the shelf edge (Puga-Bernabeu *et al.* 2011; in review).

Submarine canyons are also important because they represent the major conduits for the exchange of water between the deep ocean and the shelf, shelf to basin sediment transport, and influence the location of distinctive sediment gravity flow deposits. In other settings where they have been well studied, the deposits formed by these flows have been shown to preserve information on across-shelf sediment yields, tectonic movements, sea level changes (e.g. Henrich *et al.* 2010; Pierau *et al.* 2010; 2011), and to host deep-water benthic ecosystems. Importantly, submarine canyons may significantly modify shelf-edge oceanographic processes to produce upwellings (Puga-Bernabeu *et al.* in review, and references therein).

Detailed maps recently produced by Beaman (2010) provide a unique overview of the nature and distribution of submarine features along the GBR shelf margin (see http://www.deepreef.org/biography/robs-blog/116-coralsea-geo.html). Around Ribbon Reefs and Noggins Passage most submarine canyons are between 5,000 and 20,000 m long, have average widths ranging between 900 and 8,000 m, and maximum incision depths of between 144 m and 815 m (Puga-Bernabeu *et al.* 2011; in review). The largest submarine canyon is Bligh Canyon, which begins approximately 200 km east of the Lockhart River mouth and extends out across the GBRWHA and into the Coral Sea Marine Reserve. Bligh Canyon is more than 200 km long, almost 10 km wide, and has incised as much as 300 m into the sea bed (Beaman *pers. comm.*). It is a major seafloor geomorphological feature in the GBRWHA, capturing sediment from a vast area of the continental shelf. The Fraser canyons occur at the very southern end of the GBRWHA, and comprise a collection of more than 35 features up to 300 m wide and 40 m deep, which extend from the outer shelf at around 150 m depth into the deep water of the shelf edge (Boyd et al., 2008). These features are important conduits that channel northward moving sand from the shelf into the deep ocean. The diversion of this mobile coastal sand at the southern margin of the Great Barrier Reef is likely to have been an important control on reef initiation and growth.

Submarine canyons are morphologically classified as either shelf-incised or slope confined. These different primary morphologies likely indicate distinctly different current and sediment transport pathways, with much greater connectivity between the shelf and slope environments where canyons incise the shelf. Importantly, recent research in the GBRWHA has revealed significant morphological variability in the Ribbon Reef Canyons compared to those examined near Noggin Passage, near Cairns, which likely reflects distinct spatial variations in current regimes and sediment transport processes (Puga-Bernabeu *et al.* in review).

Submarine canyons have a major influence on continental shelf-edge sedimentary processes. Webster *et al*. (2012) note the recently revealed distribution of submarine canyons on the GBR shelf margin and the associated landslide and turbidite deposits, are providing unique new information on the long-term formation and dynamics of the GBR, and the response of its continental shelf and reefs to global changes in sea level. Results from an analysis of a turbidite deposit east of Cape Flattery (Webster *et al.* 2012) show siliciclastic sediments dominated the deposit prior to around 31 ka, but not during the glacial sea level lowstand. Most of the off-shelf sediment flux occurred during Marine Isotope Stage 3 (56 – 29 ka), when sea level fluctuated by up to 50 m over thousands of years, between depths of around 50 and 100 m, repeatedly inundating and exposing the shelf break. A shift to carbonate sediments is evident in the top of the deposit associated with carbonate reef production during the mid-Holocene sea level highstand. Ages obtained for cores from the deposit indicate the submarine canyon actively exported sediment from the shelf during the Late Pleistocene until approximately 1.2 ka.

Importantly, recent research has identified areas of the northern GBR shelf edge prone to collapse and possibly capable of generating large (7 - 11 m) tsunami in the northern GBR (Puga-Bernabeu *et al.* 2012). Records of these events can be preserved in associated submarine landslide/turbidite deposits. In addition to the catastrophic impacts such events can have on coastal populations, they also from major disturbances for shelf reef ecosystems and benthic habitats.

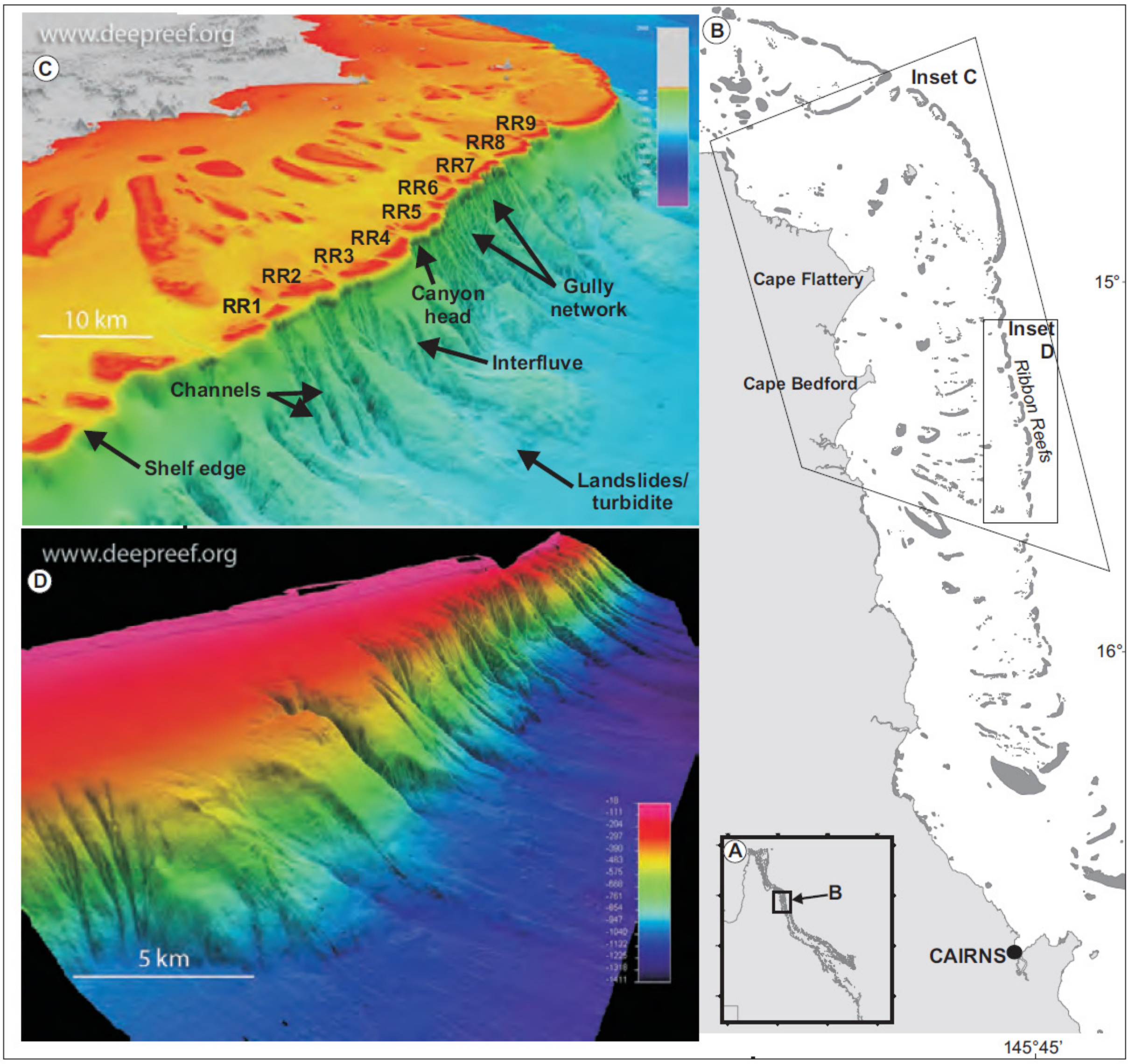


Figure 6.33 a) location of inset B. b) Section of northern Great Barrier Reef showing the location of Ribbon Reefs and submarine canyons and turbidites shown in multibeam swathe images - insets C and D. c) Shelf edge morphology showing canyons, landslides and turbidites adjacent to the Ribbon Reefs, numbered from Ribbon Reef 1 (RR1) to Ribbon Reef 9 (RR9). d) Close up of the section adjacent to Ribbon Reefs 1 to 7. Images shown in C and D made available by Dr R Beaman (www.deepreef.org)

6.18.2 Description of OUV

Submarine canyons and turbidite flows in the GBRWHA (Table 6.18):

- Represent geological and geomorphological features of extraordinary scale (*criteria viii*).
- Are outstanding examples of a tropical mixed siliciclastic-carbonate shelf–edge setting (*criteria viii*).
- Providing new and potentially ongoing insights on major geological processes of shelf to basin sediment transfer (*criteria viii*).

- Comprise outstanding and unique natural archives of environmental change and events in earth history, such as sea level and climate change, tectonic processes and catastrophic events (*criteria viii and ix*).
- Provide important habitats for benthic communities (*criteria x*).

*Table 6.18 Selected examples of submarine canyons and turbidite deposits with OUV in the GBRWHA. Those identified as the best examples are indicated ** (Note: Features are listed in no particular order and are mapped in Figure 6.34*

Feature	Outstanding Universal Values	References
Submarine canyons and turbidite deposits – Ribbons to Cairns.	Canyons and turbidite flows associated with steep shelf break. • Geological and geomorphological features of extraordinary scale. • Insights on basic geological processes of shelf to basin sediment transfer. • Natural archives of environmental changes and events in earth history, such as sea level and climate change, tectonic events catastrophic natural events.	• Webster *et al.* 2012 • Hopley 1982 • Dunbar and Dickens, 2003b • Puga-Bernabeu *et al.* 2011 • Beaman, 2010; 2012 • Beaman *et al.* 2008
Submarine canyons and turbidite deposits – Noggins to Hydrographers Passage	Canyons and turbidite flows associated with lower gradient shelf break. • Geological and geomorphological features of extraordinary scale. • Insights on basic geological processes of shelf to basin sediment transfer. • Natural archives of environmental changes and events in earth history, such as sea level and climate change, tectonic events catastrophic natural events.	• Puga-Bernabeu *et al.* 2012 • Puga-Bernabeu *et al.* in review • Dunbar and Dickens, 2003b • Abbey *et al.* 2011 • Bridge *et al.* 2011 • Beaman, 2010
Submarine Canyons offshore and N of Fraser Island	• Geological and geomorphological features of extraordinary scale. • Insights on basic geological processes of shelf to basin sediment transfer. • Natural archives of environmental changes and events in earth history, such as sea level and climate change, tectonic events catastrophic natural events. • Significant biodiversity value.	• Beaman, 2012

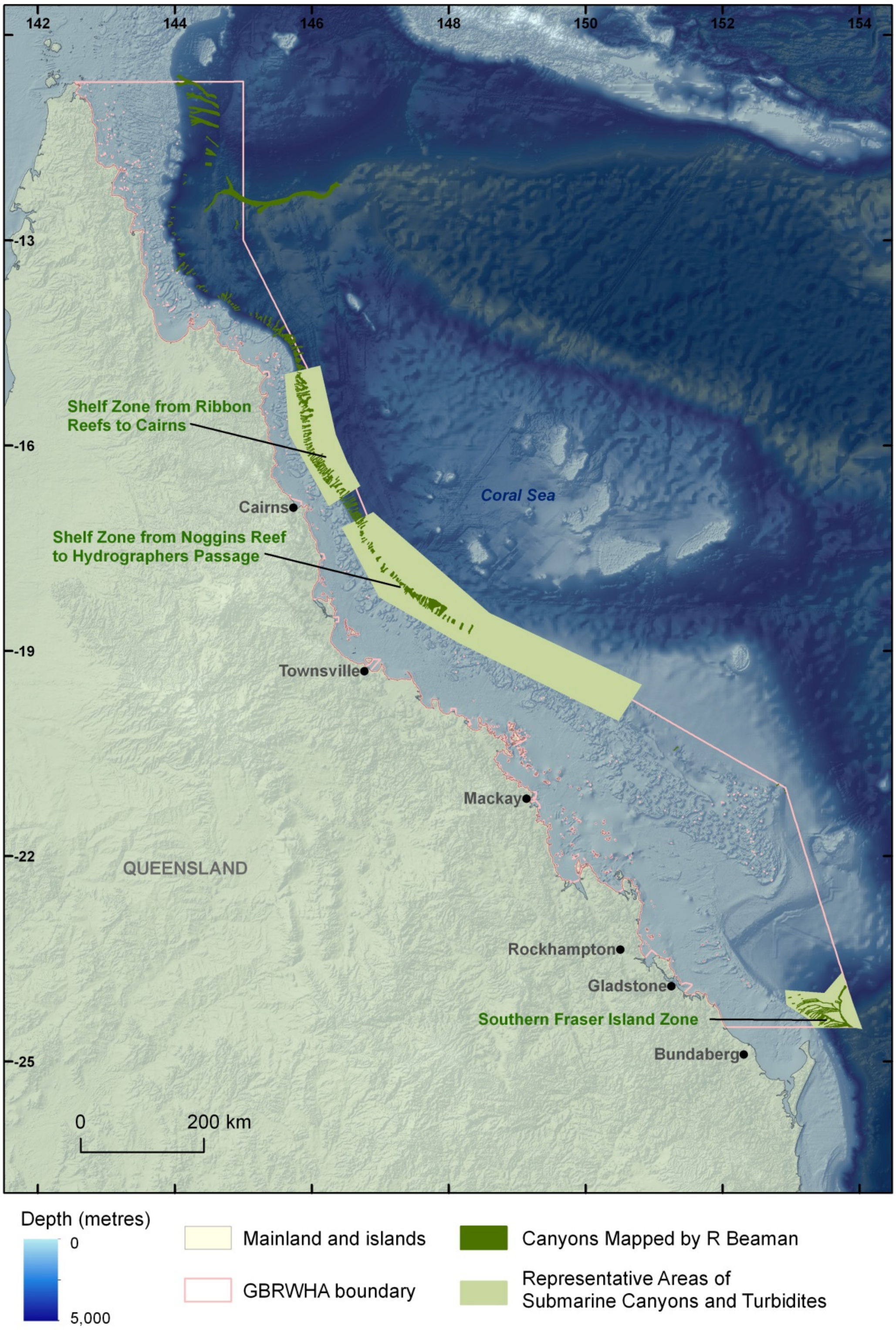


Figure 6.34 Selected examples of submarine canyons and turbidite deposits in the GBRWHA (Data Source: Beaman, 2012).

7 Pressures on geological and geomorphological features with OUV – an overview

The report 'State of the Environment Queensland 2011' (http://www.ehp.qld.gov.au/state-of-the-environment/report-2011/) identified regional issues that threaten the state's marine environment. This built upon the report by Lucas *et al.* (1997) that identified threats to the condition of the GBR, and the GBRMPA 2009 Outlook Report that identified 41 threats to the GBR ecosystem. A more focussed assessment of the potential vulnerability of geomorphic features to the impacts of climate change was undertaken by Smithers *et al.* (2007).

In 2011 the World Heritage Committee considered the state of conservation of the GBRWHA, expressing concern about the potential impacts on the OUV of the GBRWHA of recent and proposed developments. In 2012 representatives from the UNESCO World Heritage Centre and the IUCN visited the GBRWHA and a range of stakeholders to review the reef's condition, the pressures it is facing, and the management arrangements available to protect its OUV.

The World Heritage Centre's 2012 report on 'State of conservation of World Heritage properties inscribed on the World Heritage List' concludes that the OUV of the GBRWHA is threatened and decisive action is required to secure its long-term conservation. Concerns were raised regarding the possible impacts of the rapid increase of coastal developments in the past decade and declining water quality. The report noted that a number of proposed developments, should they proceed, may instigate consideration of whether the GBRWHA should be added to the List of World Heritage in Danger. It was recommended that the OUV should be regularly assessed, with specific consideration of the long-term viability of OUV, critical threats, and the effectiveness of protection and management. Strategic assessments of the impacts of actions on the values of the GBRWHA are presently underway to identify the values of the GBR that need protecting, the threats to those values and best practice ways of managing them.

In this report the potential pressures and impacts on key geological feature types are reviewed, with a focus on the largest threats identified in the 2009 Outlook Report (GBRMPA, 2009):

- **Climate Change**: increasing sea surface temperature, ocean acidification, increasing cyclonic activity and rising sea level
- **Catchment Runoff:** sediments and contaminants, including nutrients, pesticides and herbicides)
- **Coastal and Marine Development:** including changes to sediment transport pathways, dredging and spoil disposal and developments
- **Direct Use:** including shipping, trawling, mining, grazing and the impact of introduced pests.

There is wide overlap between the threats to ecosystems identified by GBRMPA and the threats to geological and geomorphological features. In many cases impacts on the condition and resilience of ecosystems will also impact geomorphic features because the '*geomorphology and ecology of the GBR are strongly interdependent'* (Smithers *et al.* 2007; pp 668), especially as geomorphic and geological features provide habitat structure for biological communities.

Compared to ecological response times, there is likely to be a lag in the response of geological / geomorphic features to many of the threats identified. Many of the threats will have an immediate impact on ecological / biological components of the reef. For example, the death /degradation of coral and associated species as a result of sea temperature rise. However, the death of coral may not begin to impact on the overall reef structure for much longer periods (e.g. months to years), or until the dead coral begins to erode.

7.1 Climate change

Sea level rise, increased sea surface temperature, increased cyclone activity and ocean acidification could directly influence the stability of geomorphic features in the GBRWHA (Smithers *et al.* 2007).

7.1.1 Sea level rise

Global sea level has been rising at a rate of 1.8 +/- 0.5 mm per year from 1961 to 2003, and since 1993 this has accelerated to about 3 mm per year (Church and White, 2006; IPCC, 2007). The Intergovernmental Panel on Climate Change (IPCC) predicts that sea level will rise between 18 and 59 cm by 2100, which is approximately a 2-6 mm per year rise. On the eastern Australia coast, it is possible that sea level may rise more than in other areas because of a change in ocean circulation, with a possible strengthening of the eastern Australian ocean currents having the potential to raise sea levels a further 10 cm above the global average (CSIRO, 2007).

Sea level rise may positively impact on reefs through increased availability of new surfaces for reef-building organisms. Conversely, rising sea level has the potential to 'drown' reefs if they cannot grow fast enough to remain in a suitable light range. However, Smithers *et al.* (2007) suggest that healthy reefs will be able to maintain growth at a rate equivalent to sea level rise because coral growth rates are commonly around 10-12 mm per year, which is well above the predicted 3 mm per year rise in sea level.

However, the morphology of other GBR features may be negatively impacted, for example due to erosive action on features not previously exposed to waves (Smithers *et al.* 2007) or exposed to less wave energy. Island beaches and spits exposed to higher sea level with less wave attenuation may be more susceptible to increased wave energy. This may take the form of erosion, but also may result in changes to beach morphology, for example changes to the rate of longshore sediment transport and the location of sediment deposition. Continental islands subject to higher seas and greater wave power may be eroded more rapidly, particularly those composed of softer rocks (e.g. sandstone and mudstone).

7.1.2 Rising sea temperatures

The oceans absorb heat from the atmosphere, with an estimated 80% of heat from the atmosphere absorbed since 1961 (Levitus *et al.* 2005). CSIRO (2007) suggests that by 2030 sea surface temperatures around much of Australia, including Queensland, will increase by 0.3 to 0.6^{o}C.

Rising sea temperatures are expected to have an extensive and extreme impact on coral reefs, including coral bleaching. Coral bleaching is a process where coral expels its symbiodinium (zooxanthellae) when environmental conditions prevent it from supporting them (such as in high temperatures) (Berkelmans and Oliver, 1999; Baker *et al.* 2008). As the zooxanthellae provide the coral colour, the corals become white or bleached when they are expelled. Coral bleaching can lead to coral mortality (Baird and

Marshall, 2002) and also impacts on coral reproduction (Ward *et al.* 2000) and fecundity (Baker *et al.* 2008) resulting in a relative increase in the rate of erosion of the reef structure.

The GBR has already been subject to coral bleaching events caused by multiple concurrent days of high sea surface temperatures, and these events will negatively impact reef growth. Bleaching events have occurred in 1980, 1982, 1987, 1992 and 1994 (Berkelmans and Oliver, 1999), and more recently mass bleaching events have occurred in 1998 and 2002 (Berkelmans and Oliver, 1999; Berkelmans *et al.* 2004). In both recent mass beaching events, warm water along the eastern Australian margin caused extensive and severe coral bleaching of inshore reefs. The 2002 event was the more extensive, extending beyond the continental shelf and impacting on shelf-edge corals as well as inshore corals. The 2002 event was also more severe with sea surface temperatures in many areas exceeding 33^{o}C (Berkelmans *et al.* 2004).

7.1.3 Increased tropical cyclone activity / changed rainfall patterns

Modelled responses to climate change by CSIRO (2007) suggest that the average rainfall in the far north of Australia may change little, but deceases of between 2 – 5% may occur elsewhere along the Queensland coast. CSIRO (2007) also suggest that tropical storm activity and intensity will increase as the climate changes, and cyclone and intense storm activity is likely to increase in frequency and intensity throughout the GBR.

The impact of cyclone activity on geological and geomorphological features is varied, not only because of individual susceptibility to a cyclone, but also because of variability in cyclone intensity and landfall. Cyclones can be highly destructive, with the erosion of reefs and reworking of pre-existing sediment deposits. Coral banks on islands such as Lady Elliot (Chivas *et al.* 1986; Hopley *et al.* 2007) and Curacoa (Hopley *et al.* 2007; Hopley, 1968; Hayne and Chappell, 2001; Nott and Hayne 2001) are evidence that cyclones erode living coral and transport it considerable distances onshore. In particular, shoreline and shallow subtidal features are likely to be impacted the most. In deeper water settings wave attenuation will reduce impact on seabed features in these areas. Features such as continental islands and islands with some fringing vegetation and reefs are also likely to be better protected / preserved (e.g. Berwick Island, Hopley *et al.* 1997).

Cyclone-generated currents in the GBR can radically reshape the seabed. Currents associated with tropical cyclones can mobilise as much as the upper 1–2 m of seabed sediment, resulting in the formation of distinctively structured storm beds known as ‘tempestites’ (Harris and Heap, 2009). Cyclone-generated currents can also profoundly influence the overall distribution of sediment in the GBR lagoon. Widely distributed accumulations of reef sediment are attributed to sediment mobilisation under currents generated by tropical cyclones. The orientation of these deposits is indicative of a consistent, along-coast transport pathway. An explanation for this pattern is that currents generated by the passage of a cyclone are asymmetric in plan view, such that stronger flows are generated between the eye of the cyclone and the coast, giving rise to sediment transport along hundreds of kilometres of coast. The result of the passage of many cyclones over geological time-scales is a consistent force for the net along-coast sediment transport on the inner to mid-shelf, possibly extending throughout the lagoon. As cyclone intensity and frequency change, these sediment deposits and associated seabed habitats could be significantly rearranged, eroded or destroyed.

7.1.4 Ocean Acidification

Ocean acidification is a process that results from a combination of increasing atmospheric CO_2 and warming oceans, leading to increasing absorption of CO_2 which makes the ocean more acidic. The atmospheric CO_2 concentration for the year 2100 is forecast to range from 500 to 1,200 parts per million (ppm), a value significantly higher than pre-industrial levels of 280 ppm (Smithers *et al.* 2007; CSIRO, 2007). At atmospheric concentrations of 500 ppm, calcifying organisms in the ocean can no longer access carbonate ions required to produce calcium carbonate (Byrne, 2011) and therefore coral reef production and the formation of calcium carbonate sediment by a wide range of organisms (e.g. foraminifera, *Halimeda*) may be compromised.

As the oceans acidify, the rate at which features composed of calcium carbonate sediment (e.g. coral reefs, *Halimeda* banks, seagrass meadows, deep water or ‘drown’ reefs) form will decrease. Erosional processes may dominate, and features that are protected by reefs may be indirectly impacted. As protective reef barriers erode, wave action across the reef may increase resulting in enhanced shoreline erosion.

7.2 Catchment runoff

River flow, and the associated impacts of sediment and nutrient discharge into the Great Barrier Reef lagoon from its 38 river catchments, is highly variable over time and space (Devlin and Brodie, 2005; Bostock *et al.* 2007). The level of impact depends on the flood volume of the coastal river (Alongi and McKinnon, 2005), the geomorphology of the shoreline and adjacent seabed and the prevailing oceanographic conditions.

Dissolved nutrient input from the GBR catchments has increased greatly since pre-European settlement and is now ‘*two to five times greater for nitrogen and four to ten times greater for phosphorus’* (Brodie, 2007 in GBRMPA, 2009). The top three rivers delivering nutrients to the GBR, in order of decreasing nutrient discharge, are the O’Connell (south of Proserpine), Barron (north of Cairns), and North Johnstone (south of Cairns) Rivers (GBRMPA, 2009). During a flood event, dissolved nutrients are delivered to the GBR lagoon and can result in the proliferation of macroalgae in coastal waters. Once a section of reef is invaded by macroalgae, it may become unavailable for the settlement of coral larvae, and erosional processes on the reef may become dominant (Pandolfi *et al.* 2005). The added impact of high pesticide concentrations (herbicides, insecticides and fungicides) as a result of increased intensity of agriculture can also reduce the productivity of corals and marine plants (Lewis *et al.* 2009).

Sediment inflow to the GBR has also increased dramatically since settlement, rising to approximately 2 to 4 times the pre-European input. An average of approximately 14-28 Mt/y now reaches the GBR lagoon (Alongi and McKinnon, 2005), with 70% of the total sediment flux coming from only 20% of the more degraded catchments (Brodie *et al.* 2003). The largest contributors to the GBR terrestrial sediment flux are the Fitzroy (the largest point source of sediment (Smith *et al*, 2008), Burdekin and Herbert rivers, all of which discharged more than 200,000 tonnes of sediment into the GBR lagoon in the 2005/2006 wet season (GBRMAP, 2009). Around 63% of sediment reaching the lagoon comes from catchment surface erosion, and a much smaller proportion comes from gully and bank erosion (Brodie *et al.* 2003).

Currently, a large proportion of this sediment load is trapped by river flats and modern mangrove forests associated with the river deltas (Alongi and McKinnon, 2005; Bostock *et al.* 2007), however large volumes of suspended sediment appear to be exported to coastal waters during high flow, flood events. The combination of increasing storm frequency and severity (CSIRO, 2007), and increasing coastal development (GBRMPA, 2009) may significantly increase the flux of sediment that reaches the middle shelf and outer reefs. An increased frequency and load of suspended sediment reaching these reefs has the potential to decrease the health of reef ecosystems (e.g. smothering and lower photosynthetic rates, Przeslawski *et al.* 2008) and increase their susceptibility to erosional processes.

Increased concentrations of contaminants and suspended sediment can compromise the stability of features, for example with the decline in coral health and a subsequent reduction in the protective capacity of reefs. Increased sediment delivery to the nearshore and inner shelf may result in the burial of submarine features and habitats, either completely changing the visual aspects of the feature (for example if a reef or *Halimeda* bank is buried) and in the case of seagrass banks, changing the extent and long-term stability of the banks.

7.3 Coastal and marine development

Coastal development is defined by GBRMPA (2009) as '*all development activities within the GBR catchment, such as rural land use, mining and industry, population growth, urban infrastructure and port development*' and includes tourism and coastal urban development. Since the settlement of Europeans in the GBR catchment in the 1850s there has been steady urban development, in particular along the coastal margins. The population has increased to 1,000,000 in 2003, and is expected to increase to 1,390,400 by 2026 (GBRMPA, 2009). By 2021 it is expected that four times more people will live in the coastal zone than inland.

For geological and geomorphological features of OUV, the key impacts of continued development and population growth are wide-ranging and include changes to coastal sediment transport pathways and reductions in marine water quality.

7.3.1 Sediment transport pathways

Sediment transport in the GBR coastal zone is dominated by waves and nearshore wind and tide-generated currents, which in turn are strongly influenced by the topography of the nearshore seabed and adjacent shelf. Tidal flats, mangroves and seagrass beds slow water velocity and trap sediments and organic materials in a disproportionate amount to their size (Alongi and McKinnon, 2005; Bostock *et al.* 2007).

Changes to the coastal morphology have the potential to impact on the distribution of sediment and associated benthic habitats along the coastline. The development of coastal structures have long been known to change sediment transport patterns (Brayshaw and Lemckert, 2012; Castelle *et al.* 2009). Coastal developments on island in the GBR have the potential to modify sediment pathways, and impact on the long-term stability of seabed and shoreline sedimentary features.

7.3.2 Dredging and spoil disposal

Dredging has been undertaken in the GBRWHA to improve shipping access to major ports such as Cairns, Townsville, Mackay, Hay Point and Gladstone (GBRMPA, 2012c). Continued and increased dredging is proposed at a number of locations along the GBR coast to expand the capacity of current ports, and to create new ports. These include:

- Port Curtis
- Keppel Bay
- Hay Point
- Princess Charlotte Bay (Cape York)
- Dalrymple Bay
- Abbot Point

Geological and geomorphological features of OUV may be impacted by dredging due to:

- The removal of sediment that makes up a feature of OUV (e.g. sediment from a palaeochannel, or seagrass bank),
- The deposition of resuspended sediment on local features of OUV, such as nearby fringing or deep reefs, and
- seabed erosion as a result of destabilisation of the seabed biological communities (e.g. loss of seagrass cover) and local changes in seabed currents due to dredging or the dumping of spoil.

The resulting changes to the seafloor can be extensive but can be assessed and monitored using acoustic methods (Skene *et al.* 2004).

7.4 Direct Use

The GBRWHA is also under pressure from direct use (often associated with coastal and marine development) including shipping, trawling and the introduction of pest species.

7.4.1 Trawling

Queensland's commercial trawl fishery supports about 600 vessels with an annual production of about $110 million per year (QLD DAFF, 2013). Trawling is generally undertaken in shallow waters to 300 m depth (beyond which it becomes too deep to trawl), depths at which there is a wide diversity of biota, habitats and geomorphic features (Pitcher, 1995).

Trawling has had a large impact in particular on the biota of the GBR with over 16,000 tonnes of mixed species caught, but only about 3,000 tonnes retained, the rest being by-catch (GBRMPA, 2009). Burridge *et al*. (2003) investigated the impact of repeated prawn trawls (13 runs) and found substantial impacts on biomass including reductions in benthic biota such as ascidians, sponges, echinoids, crustaceans and gorgonians of up to 86%. In later work, Pitcher *et al*. (2009) found that the impact of a single prawn trawl was much lower at an overall loss of seabed biomass of 3%, ranging for specific species from 0% to 20% loss of biomass.

The recovery of biomass (and hence the ongoing stability of the underlying geomorphic features) is variable depending on the type of trawling undertaken (Foden *et al*. 2010), species composition (Pitcher *et al*. 2008), and the frequency of trawling events (Pitcher *et al.* 2009; Burridge *et al.* 2003). Generally, harder substrates recover slower (Foden *et al*. 2010), and softer substrates often recover faster as they are more likely to be disturbed naturally (Pitcher *et al*. 2008). Although in the GBR this pattern may not hold as the dominant fishery in Queensland (the prawn fishery) often focus their efforts on soft sediment habitats where prawns predominantly occur (Gribble, 2007), and usually harder substrates such as corals are avoided to ensure nets are not caught.

The extent and level of impact on geomorphological and geological features in the GBRWHA is difficult to quantify. There have been no specific studies undertaken on these pressures, however it is likely that regular trawling, and high-disturbance trawling (such as scallop dredges) will have a greater impact on geomorphic and geological features. About 7 % of the GBRMP is trawled more than once per year (Grech & Coles 2011), and there is likely to be redistribution of sediment and some disturbed hard substrates associated with these trawls.

7.4.2 Shipping

Shipping is a major activity undertaken in the GBR, and is a key contributor to the Queensland economy, contributing $720 million to the local economy (GBRMPA, 2012b). The number of shipping movements in the GBR has been steadily increasing, and is expected to continue to increase as new port facilities are developed (e.g. Abbot Point, Curtis Island; GBRMPA, 2009).

Risks to the stability of geological and geomorphological features produced by the impact of shipping related activities include:

- vessel groundings and the related physical impacts on the seabed,
- chemical spills and associated impact on biogenically formed calcareous features,
- wash related erosion of shorelines,
- vessel wastage discharge that reduces water quality and the health of seabed communities (e.g. reefs, seagrass beds), and
- anchoring and related physical impacts on the seabed, such as the erosion of coral and seagrasses.

The GBR has been designated a ‘particularly sensitive area’, which has allowed for the implementation of additional measures to protect the reef from shipping activities (SEWPaC, 2012). The potential risk associated with shipping activities is directly influenced by vessel size, with large vessel incidents considered unlikely but with potentially major/widespread impact, while small vessel incidents are more likely but with localised damage (GBRMPA, 2009). Strict requirements on vessel speed are maintained in shipping zones to reduce the potential impact of wash. However, some key shipping routes align with areas known to have features with OUV (Figure 7.1), including:

- Hydrographers Passage
- Grafton Passage
- Palm Passage
- Hay Point
- Cape Melville

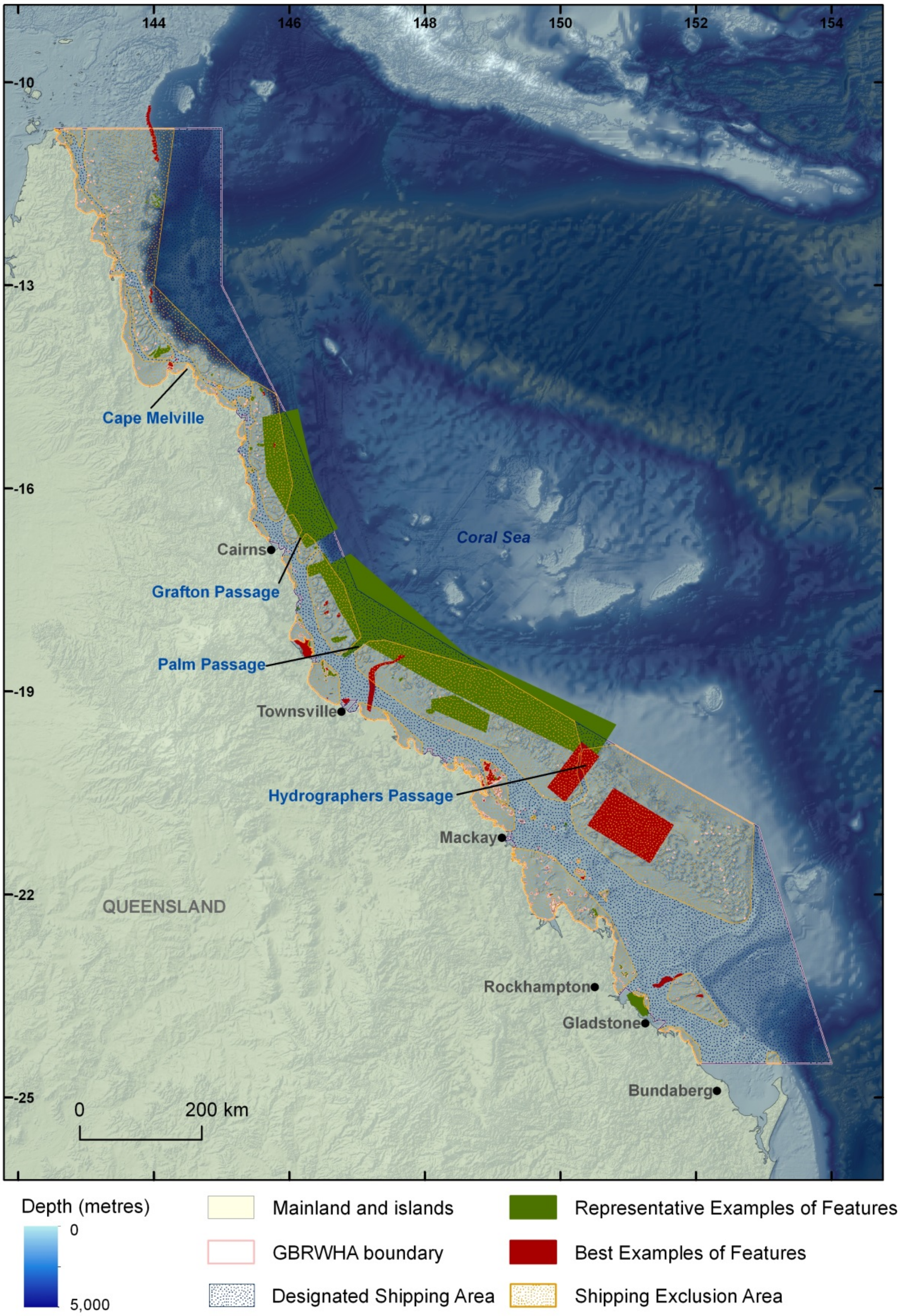


Figure 7.1 Designated shipping areas in the GBRWHA, and areas of overlap with representative and 'best example' feature types identified in this report (Data source: GBRMPA - shipping lane dataset).

7.4.3 Mining

Prior to its declaration as a Marine Park and later as a World Heritage Area, the GBRWHA was an area in which mining for guano was undertaken on a number of islands including (Daley, 2005):

- Raine Island
- North-west Island
- Fairfax Island
- Lady Musgrave Island
- Lady Elliot Island

The damage from this mining was localised but significant, causing severe erosion (Daley, 2005) and loss of entire depositional features (Chivas *et al.* 1986). Mining is now not permitted in the GBRWHA.

7.4.4 Grazing

Grazing no longer occurs in the GBRMP, however, past livestock and feral animal grazing on islands in the GBR has caused extensive damage as a result of the removal of stabilising vegetation and the subsequent erosion of soil. Those islands in the GBR that have been grazed, or have had feral ruminant populations in the past include (Daley, 2005):

- Long Island
- South Molle Island
- Lindeman Island
- Brampton Island
- Repulse Island
- Keppel Island
- Fairfax Island
- Lady Musgrave Island
- Lady Elliot Island

There are feral animals such as rabbits on some islands (SEWPAC, 2010), which have the potential to impact on the stability on features of OUV.

7.4.5 Introduced / Plague marine species

Species introduced via shipping and other anthropogenic activities may negatively impact reef ecosystems and associated geomorphic and geological features (Przeslawski *et al.* 2008). In addition, range shifts due to climate change or population increases of native species may also affect corals. For example, the crown-of-thorns starfish (*Acanthaster planci*) feed on corals, and their population outbreaks are one of the biggest short-term threats to corals and coral reefs in the Great Barrier Reef. Major outbreaks of the crown-of-thorns starfish have been recorded since the 1960s and may be linked to catchment runoff (Brodie *et al.* 2005). Enhanced sedimentation also significantly lowers the rate of survival of young corals and thus the capacity to recover from this type of disturbance.

8 Pressures on feature types with geological and geomorphological OUV

The following section provides an outline of pressures and impacts on the environmental condition of a feature and the associated sensitivity and risk. Risk refers to the likelihood of a pressure impacting on the condition of a feature. Sensitivity refers to how easily and how much a feature might be impacted by a pressure. Literature reviews and professional opinions, including observations during field surveys, were used in the development of this section. The values attributed to the sensitivity and risk assessment (low, moderate and high) are a qualitative indication designed to provide guidance on what pressures might have an impact on a feature of OUV, and to help identify features that may have significant sensitivity to a pressure.

It is important to note that in combination, the impacts from multiple pressures may cause more extensive and intensive damage to a geological / geomorphological feature. For example, Gretch (2011) discusses the importance of cumulative impacts on seagrass stability, where increasing coincidence of pressures on individual seagrass habitats cause progressively greater levels of damage. The pressures and associated impacts below do not include a consideration of cumulative impacts, which was outside the scope of this report.

8.1 Fringing Reefs

Table 8.1 Pressures on fringing reefs, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level rise • changed storm regimes	Increasing SST will produce changes in reef community composition and productivity. These shifts in reef ecology will affect the geomorphology and geology of these systems by modifying the potential for reef growth and structural maintenance. Ocean acidification may affect the durability of skeletons and sediments produced, also reducing net carbonate production as well as making the reef structure potentially more vulnerable to erosion during storms. Most fringing reefs on the GBR have large senescent back reef areas as a result of emergence caused by hydro-isostatically driven relative sea level fall since the mid-Holocene (Smithers et al. 2006; Hopley et al. 2007). Rising sea levels will inundate some of these substrates, and in some cases it is possible that coral communities will recolonise the presently moribund surfaces. If this occurs reef flats may begin to grow upwards (vertically accrete) toward the new confining water level (Hopley, 1996). Changed storm regimes will have variable impacts, but it is probable that weakened skeletons will be more vulnerable to breakage. Also, increased cyclone-associated flood plumes are likely to exacerbate the problems related to sediment and contaminant export from coastal catchments.	Moderate/Moderate

Pressure	Impact(s)	Sensitivity / Risk
Catchment Runoff • sediment export • nutrients • contaminants	The geographic position of fringing reefs adjacent to terrestrial coasts means that they are highly exposed to catchment run-off (Hopley et al. 2007). It is also true, however, that most have developed under conditions of episodic sediment influx, with the community assemblages dominated by species, forms and genotypes adapted to these conditions (e.g. Pastorak and Bilyard, 1985). However, increases in both the amount of run-off (due to catchment clearing), the amount of nutrients and contaminants, and potentially the number of delivering events (due to changed storm intensity and frequency) are likely to be problematic for many fringing reefs adjacent to developed parts of the coastline (Fabricius, 2005).	Moderate/moderate
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Modification of coastal habitats may impact on some fringing reefs by removing a buffer zone between catchment and fringing reef habitats, in which sediments and other contaminants shed from coastal catchments may be trapped. Wetland infill and development of aquacultural enterprises in adjacent areas may occur and increase nutrient loads. In the past channels have been dredged through fringing reefs to allow all-tide access to island infrastructure (e.g. Hayman Island, Orpheus Island), and reclamation over reef flats has occurred for airstrip construction (e.g. Heron, Hayman and Orpheus islands) but it is unlikely that this would occur now. Fringing reefs at Rattlesnake Island and Herald Island are regularly impacted by military ordinances during training.	High/Variable
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	In the past limestone has been mined from some fringing reefs – e.g. King Reef (Daley, 2005) but this is no longer allowed, and it is unlikely that new activities would be allowed.	Moderate/Moderate

8.2 Inshore Turbid Zone Reefs

The geographic location of inshore turbid zone reefs close to the mainland coast and therefore close to human activities means that they are exposed to some of the direct pressures identified in the 2009 Outlook Report. It is also clear from many cores taken through these reefs, however, that they have always grown in ‘marginal’ turbid conditions compared to clear water reefs further offshore. Furthermore, based on rapid rates of vertical accretion and structural resilience, many appear to be well adapted geomorphologically to coping with high levels of turbidity and sedimentation. The potential geomorphological impacts of contaminants are not fully known, but it is likely that changes in carbonate production and net carbonate productivity will lower reef growth rates on some reefs.

Table 8.2 Pressures on inshore turbid reefs, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	As geomorphological features and geological structures inshore turbid zone reefs are unlikely to be directly impacted by increased SST and ocean acidification, but because reef geomorphology and ecology are so inextricably linked they will be indirectly impacted by declines in reef productivity, calcification, and durability of carbonates produced by reef organisms affected by these pressures (e.g. see Perry et al. 2012). It is possible that higher SSTs will result in more bleaching more often with a reduction in cover and carbonate production, with a shift in species possibly also accompanied by changed reef construction and fabrics. For example, if massive corals remain but branching and plate corals are far less common, rates of reef growth and the style of reef accretion may change. Ocean acidification may affect the durability of carbonate sediments and framework produced on the reef, with implications for net calcification reef growth rates. Many turbid zone reefs are sea level confined or close to it because they have generally initiated over substrates at shallow depth and thus have only a narrow depth window to grow through to reach the surface. As a consequence, the upper surfaces of many reefs are no longer vertically accreting. This is especially the case for fringing reefs that reached sea level in the mid-Holocene and have since experienced relative sea level fall and emergence due to hydo-isostatic flexure (upward) of the inner shelf (see Lambeck and Nakada, 1992). In these locations it is possible that rising sea levels may invigorate coral growth over these currently dead reef flat surfaces, with some modelling indicating that more rapid rates of sea level rise will be more beneficial than slower rates (Hopley, 1996). Possibly due to high turbidity and reduced light penetration even at shallow depth, binding coralline algae are relatively uncommon on many of the inshore turbid zone reefs examined on the GBR (see Smithers and Larcombe, 2003; Perry and Smithers, 2006; Perry et al. 2007; Palmer et al. 2010; Perry and Smithers, 2011). Coring through many of inshore turbid zone reefs reveals stratigraphic units of biogenic reef clasts, sometimes clasts are supported, but often matrix supported (e.g. see Figures; Perry and Smithers, 2011). Such reefs have been argued to achieve rigidity by overgrowth, with the implication being that it is the healthy coral community growing over the detrital accumulation that provides resistance to wave erosion (Hopley et al. 2007). If coral reef condition is compromised, and if more frequent severe cyclones occur into the future, the physical resilience of these systems may be challenged. Although concentrations of coral rubble can often be encountered on sandy shores that may reflect the demise and disassembly of these inshore systems by storms, it is important to also note that some turbid zone reefs have remained intact for millennia (Cape Tribulation Reefs – Partain and Hopley, 1989), and recent surveys following TC Yasi showed some damage but not devastation (Perry et al. in review).	Variable

Pressure	Impact(s)	Sensitivity / Risk
Catchment Runoff • sediment export • nutrients • contaminants	It has been suggested that high turbidity can protect corals on inshore turbid zone reefs from impacts such as bleaching due to UB-B penetration (Hopley et al. 2007), and it has been shown that acclimation to higher levels of turbidity is possible on some reefs (Pastorok and Bilyard, 1985). These impacts may be beneficial to reef geomorphology by increasing calcification and reef growth. Coring also shows that most of these reefs have experienced muddy conditions since initiation, and that muddy sediments deposited as both matrix sediments and as distinct units in some reefs comprise a significant component of the reef structure. Episodic increases in sedimentation and turbidity are likely to occur on inshore reefs associated with floods and storms, and it may be expected that these events may affect live coral cover and carbonate production on affected reefs, at least temporarily. Regional scale declines in reef growth have also been noted (Perry and Smithers, 2011), but it has also been shown that these reefs were able to re-establish. Rates of rapid vertical accretion have recently been established for Middle Reef, just offshore from Townsville, with average rates of vertical accretion exceeding those known from clear water reefs further offshore (Perry et al. 2012). The high rapid rates of vertical accretion were attributed to higher rates of net productivity as sedimentation buries framework quickly and thus limits bioerosion. It has been argued that turbidity and sedimentation on the inshore reefs is energy rather than supply limited (Woolfe and Larcombe, 1999). More frequent storms may increase the frequency of high turbidity and sedimentation events, affecting carbonate production and reef growth dynamics. A shift to more tolerant species and growth forms may also affect the geomorphology of these systems, but it is likely that these effects will be patchy, reflecting the spatial distribution of episodic severe cyclones, rather than regional. An increase in nutrients may affect the geomorphology of these systems by increasing algal cover, with the possible result of increased deposition of fine sediments due to baffling. Higher rates of bioerosion may also be encouraged, reducing net carbonate production and reef growth potential. Pesticides and other contaminants may affect the geomorphology of these systems by reducing the productivity and survival of sensitive biota. Although it is known that these reefs can be exposed to these contaminants (see various papers in Marine Pollution Bulletin Special Issue 65 (4-9)), the details of their geomorphological response(s) are not known.	Variable and strongly debated
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	As indicated above and discussed in Section 6.2, turbidity is generally considered to be energy rather than supply limited, and thus although modifications of coastal catchments may increase sediment yields to the inshore GBR the impact on turbidity will likely be limited. Of course, coastal development also typically results in the export of nutrients and contaminants, the impacts of which have been covered above. Inshore reefs are particularly exposed to port construction, channel dredging and even shipping accidents due to their proximity to these activities. As noted above, Middle Reef off Townsville is an inshore reef that is exposed to some of these pressures. At present it is difficult to detect any significant impact of on the reef's geomorphology, or geomorphological processes and performance (Browne et al. 2010; Perry et al. 2012)	Although these reefs are relatively highly exposed to these pressures due to their geographic proximity to the coast, it appears that many have developed under conditions of high turbidity and sedimentation. The geomorphic impacts of contaminants are not known, but are likely to be deleterious.

Pressure	Impact(s)	Sensitivity / Risk
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Possible exposure to shipping accidents as traffic increases through both inner GBR shipping channels and passages linking export ports and the open ocean.	Low/Low

8.3 Shelf Reefs (Excluding Fringing, Ribbon and Inshore Turbid Reefs)

Table 8.3 Pressures on shelf reefs, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	Increasing SST may cause coral bleaching, lowering productivity, calcification, and reef growth. Ocean acidification may affect the durability of coral skeletons, diminishing net reef growth and the structural resilience of coral reefs as wave-resistant landforms (Hoegh-Guldberg *et al.* 2007). Structural complexity may also be reduced, and a shift in reef construction such that framework becomes less volumetrically important and detrital deposits more so. Rising sea levels are likely to have limited geomorphological impacts on submerged shelf edge reefs, and only minor impacts on those with reef flats near sea level. In these cases reef flats where upward growth is constrained by subaerial exposure may re-initiate a phase of new vertical accretion. Increased intense storm frequency may shift coral community composition toward more robust forms and species, affecting the nature of both the reef framework and detrital facies.	Moderate/Moderate
Catchment Runoff • sediment export • nutrients • contaminants	Most shelf reefs are located well offshore or adjacent to relatively undeveloped sections of the mainland coast.	Low/Low
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Most shelf reefs are located well offshore or adjacent to relatively undeveloped sections of the mainland coast.	Low/Low
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Possible exposure to shipping accidents as traffic through both inner GBR shipping channels and passages linking export ports and the open ocean increases.	Low/Low

8.4 Ribbon Reefs

Table 8.4 Pressures on inshore ribbon reefs, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	The long-term implications of the changing climate are the largest risk to the stability of ribbon reefs. Periods of high sea surface temperature causing mass bleaching events are currently having the most impact on the near-shore zone, but these events may extend to the outer shelf more frequently as temperatures increase. Increasing ocean acidification may slow down reef growth, allowing the reef to become more susceptible to other risks. Sea level rise has the capacity to drown reefs unable to grow fast enough to maintain their specific photic zone, although it currently believed that reefs are capable of growing faster than the rates at which the sea level is predicated to increase (Smithers *et al.* 2007). In a more immediate timeframe, the impact of increasing cyclone frequency and intensity is important. The location of the ribbon reefs on the edge of the continental shelf leaves them exposed to high energy waves that build up in the Coral Sea. The deep water associated with the steep slope to east of the ribbon reefs results in limited attenuation of incoming swell. In high energy periods the reefs are highly vulnerable to the high energy waves. For example, in 1991, Cyclone Ivor (a relatively small cyclone) caused large amounts of erosion, cutting down the windward reef edge by 1.5 m (Done *et al.* 1991 in Hopley *et al.* 2007).	High / high
Catchment Runoff • sediment export • nutrients • contaminants	The outer shelf and shelf-edge location of these reefs means that they are rarely if ever exposed to catchment runoff pressures. However, as noted for shelf-edge canyons, very large floods, which may become more common into the future, may occasionally extend out to the shelf edge (Brodie *et al.* 2012). It is therefore possible that the exposure of the ribbon reefs to catchment runoff may increase in the future. It is unclear what the impacts on these reefs may be, but the weight of evidence from other reef settings suggests reef condition, geomorphological/geological resilience and performance may be compromised (e.g. see various papers in Marine Pollution Bulletin Special Issue 65 (4-9).	Sensitivity is not known. Risk is probably low due to geographic location
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Likely to have negligible impact due to distance offshore.	moderate / low
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Overall, there is likely to be negligible impact due to direct uses due to the distance offshore. These reefs are also within a shipping exclusion lane, so there is likely to be minimal impact from shipping activities.	Low / low

8.5 Deltaic Reefs

Table 8.5 Pressures on deltaic reefs, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	The long-term implications of the changing climate are the largest risk to the stability of deltaic reefs. Sea level rise has the capacity to drown reefs unable to grow fast enough to keep in their specific photic zone. Periods of high sea surface temperature causing mass bleaching events are currently having most impact on the near-shore zone, but these events may extend to the outer shelf more frequently as temperatures increase. Increasing ocean acidification may slow down reef growth, allowing the reef to become more susceptible to other risks. In a more immediate timeframe, the impact of increasing cyclone frequency and intensity is important due to the exposed location of the deltaic reefs on the edge of the continental shelf.	High / high
Catchment Runoff • sediment export • nutrients • contaminants	The outer shelf and shelf-edge location of these reefs means that they are rarely if ever exposed to catchment runoff pressures. However, as noted for shelf-edge canyons, very large floods, which may become more common into the future, may occasionally extend out to the shelf edge (Brodie *et al.* 2012). It is therefore possible that the exposure of the ribbon reefs to catchment runoff may increase in the future. It is unclear what the impacts on these reefs may be, but the weight of evidence from other reef settings suggests reef condition, geomorphological/geological resilience and performance may be compromised (e.g. see various papers in Marine Pollution Bulletin Special Issue 65 (4-9).	Sensitivity is not known. Risk is probably low due to geographic location.
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	The outer shelf and shelf-edge location of these reefs means that they are rarely if ever exposed to catchment runoff pressures. However, as noted for shelf-edge canyons, very large floods, which may become more common into the future, may occasionally extend out to the shelf edge (Brodie *et al.* 2012). It is therefore possible that the exposure of the deltaic reefs to catchment runoff may increase in the future. It is unclear what the impacts on these reefs may be, but the weight of evidence from other reef settings suggests reef condition, geomorphological/geological resilience and performance may be compromised (e.g. see various papers in Marine Pollution Bulletin Special Issue 65 (4-9).	Moderate / low
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Overall, there is likely to be negligible impact due to direct uses due to the distance offshore. However, Hydrographers Passage is of particular concern as a major shipping lane traverses the complex. As noted, extensive regulation is in place to minimise the impact of shipping activities. However, as developments and activity in shipping lanes increase, further attention should be given to ensuring these regulations continue to protect the reef.	Low / low

8.6 Northern Detached Reefs

Table 8.6 Pressures on northern detached reefs, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	The long-term implications of the changing climate are the largest risk to the stability of northern detached reefs. Sea level rise has the capacity to drown reefs unable to grow fast enough to keep in their specific photic zone. Periods of high sea surface temperature causing mass bleaching events are currently having most impact on the near-shore zone, but these events may extend to the outer shelf more frequently as temperatures increase. Increasing ocean acidification may slow down reef growth, allowing the reef to become more susceptible to other risks. In a more immediate timeframe, the impact of increasing cyclone frequency and intensity is important due to the exposed location of the northern detached reefs on the edge of the continental shelf.	High / high
Catchment Runoff • sediment export • nutrients • contaminants	The outer shelf and shelf-edge location of these reefs means that they are rarely if ever exposed to catchment runoff pressures. However, as noted for shelf-edge canyons, very large floods, which may become more common into the future, may occasionally extend out to the shelf edge (Brodie *et al.* 2012). It is therefore possible that the exposure of the northern detached reefs to catchment runoff may increase in the future. It is unclear what the impacts on these reefs may be, but the weight of evidence from other reef settings suggests reef condition, geomorphological/geological resilience and performance may be compromised (e.g. see various papers in Marine Pollution Bulletin Special Issue 65 (4-9).	Sensitivity is not known. Risk is probably low due to geographic location.
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	The outer shelf and shelf-edge location of these reefs means that they are rarely if ever exposed to catchment runoff pressures. However, as noted for shelf-edge canyons, very large floods, which may become more common into the future, may occasionally extend out to the shelf edge (Brodie *et al.* 2012). It is therefore possible that the exposure of the deltaic reefs to catchment runoff may increase in the future. It is unclear what the impacts on these reefs may be, but the weight of evidence from other reef settings suggests reef condition, geomorphological/geological resilience and performance may be compromised (e.g. see various papers in Marine Pollution Bulletin Special Issue 65 (4-9).	Moderate / low
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Likely to have negligible impact due to distance offshore.	Low / low

8.7 Submerged Coral Reefs and Banks (Mesophotic Coral Ecosystems)

The geographic distribution of submerged and mesophotic coral reefs predominantly on the outer shelf and shelf edge effectively buffers them from many of the pressures identified in the 2009 Outlook Report. However, relatively little is known about the ecology and physical structure of these systems, including basics such as growth rates and degree of consolidation. It should also be noted that assumptions regarding exposure to parameters such as storm waves may not be as simple as assumed, as exemplified by the observation that deep mesophotic reefs near to Myrmidon Reef were severely damaged and stripped by waves and currents associated with TC Yasi. Based on present knowledge, the contributions of the geological and geomorphological attributes of submerged and mesophotic coral reefs to the outstanding universal value the GBR are not under significant threat.

Table 8.7 Pressures on submerged coral reefs and banks, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	Because they remain submerged and are often well below the sea surface, submerged and mesophotic coral reefs commonly endure relatively low levels of exposure to pressures such as higher sea temperatures and more frequent storm waves than shallow water counterparts. Those on the outer reef edge and slope may experience cold water upwellings that buffer the effects of elevated SSTs (Andrews, 1983; Fabricius *et al.* 2007). Rising sea levels are not an issue – even under rapid rates of sea level rise these reefs are unlikely to 'drown' as the absolute magnitude of the amount of sea level rise is relatively small relative to their depth. There has been speculation that these reefs may act as refugia for many reef species as a consequence of their relatively protected settings (Bridge *et al.* 2011, 2012). However, recent robotic surveys of the shelf edge mesophotic reefs off the Central GBR have revealed large areas stripped of live coral and sediment by severe TC Yasi, interspersed with patches that show little or no apparent impact (*pers. comm.* Dr Tom Bridge). Little is as yet known about the disturbance and recovery dynamics of these systems, but it is possible that a negative condition trend could develop if severe tropical cyclones become more common, as is projected (Knutson *et al.* 2010). The impacts of increased ocean acidification on these reef systems is not known, but colder deeper water can hold more dissolved CO2 in solution and can therefore be relatively acidic compared to warmer surface waters. More acidic waters may impede calcification, reduce the strength of skeletons and reef framework, and present a more aggressive environment for calcification products, possibly reducing reef growth rates (e.g. Hoegh-Guldberg *et al.* 2007).	Generally low sensitivity and low risk, but certainty is low due to lack of information on these systems.
Catchment Runoff • sediment export • nutrients • contaminants	The outer shelf and shelf-edge location of many of these reefs means that they are rarely if ever exposed to catchment runoff pressures. However, as noted for shelf-edge canyons above, very large floods, which may become more common into the future, may occasionally extend out to the shelf edge (Brodie *et al.* 2012). It is therefore possible that the exposure of submerged and mesophotic coral reefs to catchment runoff may increase in the future. It is unclear what the impacts on these reefs may be, but the weight of evidence from other reef settings suggests reef condition, geomorphological/geological resilience and performance may be compromised (e.g. see various papers in Marine Pollution Bulletin Special Issue 65 (4-9).	Sensitivity is not known. Risk is probably low due to geographic distribution.

Pressure	Impact(s)	Sensitivity / Risk
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Harris *et al.* (2012) notes that Hydrographers Passage is in pristine condition, it is however one of the major shipping lanes between the Coral Sea and the mainland (particularly for coal exports). Shipping pressures have been discussed as having a low to moderate risk dependent on vessel size. With the decree that the GBR is a 'particularly sensitive area' and subsequent increased management of shipping activity, there should be no reason that shipping and the reef should not coexist. However, if shipping activity continues to increase, particularly around this feature of interest, there may be reason to review shipping management plans to ensure they continue to protect the reef under increased pressure.	Low/Low
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Possible exposure to shipping accidents as traffic through both inner GBR shipping channels and passages linking export ports and the open ocean increases. Trawling may have an impact on these reef features as they provide habitat for many key fisheries species.	Low/moderate

8.8 Carbonate Reef Islands (Excluding Low Wooded Islands and Mangrove Islands)

Table 8.8 Pressures on carbonate reef islands, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	Increasing SSTs may cause bleaching of corals and foraminiferans, lowering productivity, calcification, and the production of sand for transport onto cays (see Dawson *et al*. 2012; Perry *et al*. 2012). Ocean acidification may affect the durability of sediments produced, particularly foraminiferans that have delicate tests, again diminishing net sediment delivery to cays (Hough-Guldberg et al. 2007). Over time both of these processes may reduce sands supply to cays (Perry et al. 2012). Rising sea levels and more frequent severe cyclones are likely to increase the dynamic nature of cay shorelines, as more energy reaches the beach due to greater depths across the reef flat. It is likely that sediments available to be transported with be washed by wave processes higher on the beach to form a more elevated berm, but it is also likely that the width of the berm will decrease as the sediment volume declines due to the decrease in supply. This decline will possibly be exacerbated by increased attrition of beach sand associated with abrasion on a more active (dynamic) shoreline. Although it is probable that vegetated cays will persist for some time, changes in their morphology, specifically the width and elevation of berms, and in the tempo of shoreline changes, may compromise some the ecosystem services that cays currently provide (such as nesting sites for green turtles on the beach berm, and separation of these sites from nesting sites for seabirds on the phosphate cap). Unvegetated cays are likely to be more dynamic and vulnerable to both changes and complete destruction due to higher sea levels and more intense storm regimes. Shingle cays may increase in size and elevation if the supply of shingle from *Acropora* thickets can be assured, however a general collapse of *Acropora* across parts of the GBR has been noted (Roff *et al.* 2012), and communities comparable with the large deposits evident on many reef flats are difficult to identify on reefs today. It would thus seem unlikely that significant shingle island formation will occur in the near future.	High/moderate

Pressure	Impact(s)	Sensitivity / Risk
Catchment Runoff • sediment export • nutrients • contaminants	Most carbonate reef islands are located well offshore or adjacent to relatively undeveloped sections of the mainland coast.	Low/Low
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Most carbonate reef islands are located well offshore or adjacent to relatively undeveloped sections of the mainland coast. Possible exposure to shipping accidents as traffic increases. Tourism on some cays, and activities associated with both the tourism activity and transit to and from the islands may be problematic.	Variable/Variabl e
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Several islands were formerly host to guano mining activities, but these have ceased.	Low/Low

8.9 Gravel and Shingle Ridges

Table 8.9 Pressures on inshore gravel and shingle ridges, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	In the 1989 coral bleaching event in the GBR, Curacoa Island was severely impacted with an estimated 30-50% of coral bleached (Berkelmans and Oliver, 1999). Although not directly impacting on beach ridge features, coral bleaching, and other effects of climate change, such as rising sea levels and more intense storms, have the potential to impact on the long-term stability of these features. If the fringing reef becomes degraded, the volume of sediment available to the beach system may eventually decline making island shorelines more susceptible to wave erosion.	Low/moderate
Catchment Runoff • sediment export • nutrients • contaminants	Changes to catchment runoff are unlikely to have any impact on the gravel and shingle ridges, except maybe adding an increased component of fine sediment to the composition of the ridges.	Low/low
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Severe degradation occurred on Lady Elliot Island as a result of guano mining (between 1863 and 1873) and the introduction of goats (from 1863) (Daly, 2005). These activities no longer occur on this island and are unlikely to re-commence.	Moderate / low

Pressure	Impact(s)	Sensitivity / Risk
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Unlikely to have any impact.	Low/low

8.10 Mangrove Shorelines, Mangrove Islands and Low Wooded Islands

A study of the mangroves in Missionary Bay (Hinchinbrook Island) found that this habitat was relatively stable – neither growing or receding, suggesting that the mangroves are old and likely to change only over long time scales in the absence of human activities (Duke 1997). However, as the extent and intensity of human activities grows (Alongi, 2002), mangroves in the GBR will be increasingly impacted by a wide range of pressures as identified by Goudkamp and Chin (2006):

- coastal development,
- declining water quality,
- shipping and oil spills,
- aquaculture,
- disturbance events,
- climate change, and
- human use.

Table 8.10 Pressures on mangroves and mangrove islands, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	Lying within the intertidal zone, mangroves are going to be impacted by both marine and atmospheric changes. Lovelock and Ellison (2007) note that there are a wide range of likely responses. Mangroves in areas with high tidal ranges with increased rainfall and sediment delivery may expand, and these may grow even further in response to warmer temperatures in southern latitudes and increased CO_2. However, mangroves can only keep up with sea level rise if they have suitable intertidal substrate on which to colonise. Backing supratidal flats will be suitable, while terrestrial substrate is usually steep, thus decreasing potential habitat (also known as 'coastal squeeze'). Intertidal flats can take centuries or millennium to develop. Mangroves not receiving or retaining enough sediment (such as those in low tidal ranges with reduced rainfall and runoff) may also reduce in area. Woodland mangroves may be less susceptible to some of the immediate impacts of climate change, as they are noted to be generally stable in the long-term and often develop in protected locations. Cyclone impact on Bewick Island was studied by Hopley *et al.* (2007) and was found to be negligible after one severe cyclone event. However, island woodlands flooded by rising sea level may not be able to retain sediment at a fast enough rate to remain above the sea level for transpiration.	Medium/Medium

Pressure	Impact(s)	Sensitivity / Risk
Catchment Runoff • sediment export • nutrients • contaminants	Increased rates of sedimentation may extend or shift the intertidal zone that mangroves inhabit.	Low/Low
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Duke (1997) notes that '*it is unfortunate that mangroves are often mostly prevalent in sites preferred for coast cities and industrial development*. Increasing development in the GBR will have an increasingly large impact on coastal mangroves, particularly those in areas identified for development. However, the low wooded islands may be impacted less as their size and height (often low) and their location (offshore) make them generally unsuitable for large scale developments.	Medium/Low
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Direct use activities are unlikely to impact on low wooded islands.	Low/low

8.11 Halimeda Banks, Bioherms and Meadows

Table 8.11 Pressures on Halimeda banks, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	The *Halimeda* beds are particularly reliant on the flux of nutrients from the deep waters off the shelf, through the fringing reef system, to the lagoon where they develop (Wolanski *et al*. 1987; Hopley *et al*. 2007). Changes to the hydrologic processes controlling this flux have the potential to change the productivity of the *Halimeda* beds or the location at which they form. Sea level change is a likely cause of changed ocean circulation. Ocean acidification is also a potential risk for *Halimeda* growth and stability because of their calcium carbonate structures.	Unknown / unknown
Catchment Runoff • sediment export • nutrients • contaminants	As water quality is such an important factor for the growth of *Halimeda,* increased sediment flux from the mainland, and potentially increasing flood frequency and intensity may start to impact on the extent and location of *Halimeda* beds. *Halimeda* beds are currently restricted to the outer shelf of the GBR (Rees *et al.* 2007) and as a result are not frequently impacted by turbid runoff from the mainland. The impact of sediment load can be seen from the examples of Princess Charlotte Bay and Bathurst Bay, where *Halimeda* deposits were expected to exist, but do not. It is hypothesised that *Halimeda* beds do not exist here because of the turbid water from the Normandy River (Searle and Flood, 1988; Hopley *et al.* 2007; Rees *et al.* 2007).	Moderate / moderate
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Coastal development is not likely to have a large impact on the outer-shelf based *Halimeda* beds.	Low / low

Pressure	Impact(s)	Sensitivity / Risk
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Direct uses are also unlikely to have any impact on the *Halimeda* structures.	Low / low

8.12 Seagrass Beds

There are two potential risks to the stability of seagrass beds;

- decreased productivity or death of seagrasses which maintain the stability of the trapped sediment, and
- destruction of the sediment and organic material layered in the seagrass bed through activities such as dredging.

Table 8.12 Pressures on seagrass beds, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	Climate change impact on seagrass has not been extensively tested. Work by Koch *et al.* (2012), indicates that seagrass photosynthesis and productivity may increase as atmospheric and dissolved CO_2 increases. However, it is likely that not all species of seagrass will be able to withstand the impact of increasing water temperatures (Connolly, 2009). There may be as a result, a switch in species to those that can withstand warmer sea temperatures. In terms of the sediment trapped in the seagrass beds, this will remain relatively stable unless increased storm activity causes more intense flooding and erosive activity along the coastal margins.	Unknown / Unknown
Catchment Runoff • sediment export • nutrients • contaminants	In a survey of experts in the field of seagrasses, Gretch (2011) found that they identified (in order of decreasing importance) agricultural, urban and industrial runoff to be the greatest threat to seagrass habitats. Water quality, particularly in coastal zones, is declining (Haynes *et al.* 2000a; Schaffelke, 2005). Eutrophication (increasing nutrients in the water column) is known to cause increased epiphyte growth on seagrasses, causing reduced light delivery. Increased sediment loads negatively impact seagrass health, also decreasing light attenuation to the plants (Dennison *et al*. 1993). In 1992, elevated turbidity in floods from the Mary and Burrum rivers resulted in light deprivation to seagrasses, destroying over 1,000 km^2 (24% of known Queensland) seagrass habitat (Preen *et al.* 1995). It has also been found that organochlorine compounds such as herbicides and pesticides from the land, accumulate in sediment and biota in the near shore. Seagrass beds have been shown in the Townsville and Cairns areas to have high concentrations of Diuron (one of the 3 most commonly used herbicides in Queensland that is long lived in water) (Haynes *et al.* 2000a, 2000b). At high concentrations Diuron impedes photosynthesis and growth of seagrasses.	High / high

Pressure	Impact(s)	Sensitivity / Risk
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Seagrass habitats in the GBR have increasingly come under pressure from human activities as coastal development expands (Kirkman, 1997). Reduction in area of seagrass beds is primarily caused by reduced light attenuation as a result of sedimentation, and in some cases as a result of dredging, and land reclamation such as at Townsville and Airlie Beach (GBRMPA, 2009). Dredging of seagrasses will directly impact on the stability of the sediment in the seagrass beds. Removal of even sections of the beds leaves exposed surfaces open to erosion by natural processes such as wave and current action. Intense flooding after dredging could result in mass erosion of these deposits. Hydrological changes as a result of developments can also extensively change the hydrodynamics which in turn can erode sediment deposits. While these deposits are held together by seagrass there may be little impact, but where seagrass health and cover is compromised the sediments may become susceptible to erosion.	High / high
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	As seagrass beds are generally located in shallow coastal waters, trawling is a threat to seagrass habitat stability. Although it has been noted that trawlers will avoid dense seagrass beds (as they clog up nets) and there is legislation in place to protect seagrass, there is a potential that trawlers may access seagrass areas (GBRMPA, 2012d). The impact of these trawlers is localised but intense.	Moderate / low

8.13 Karstic Channels and Blue Holes

Blue holes may experience minor changes in the geomorphology associated with the Holocene reefs that fringe their upper rims, or in the rates of infill associated with changed storm regimes. However, they are unlikely to undergo significant changes in their geomorphology as a result of pressures identified in the 2009 Outlook Report.

Table 8.13 Pressures on karstic channels and blue holes, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	Blue holes on the GBR are drowned dolines formed by destructive processes over long periods of time. Known pressures are not likely to significantly impact on their outstanding universal value.	Low/Low
Catchment Runoff • sediment export • nutrients • contaminants	Likely to have negligible impact due to distance offshore.	Low/Low
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Likely to have negligible impact due to distance offshore.	Low/Low

Pressure	Impact(s)	Sensitivity / Risk
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Unlikely to have any impact.	Low/Low

8.14 Palaeochannels

These relict features are unlikely to be significantly impacted by most pressures.

Table 8.14 Pressures on palaeochannels, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level changed storm regimes	Not likely to have any impact, although during cyclones currents may scour palaeochannel deposits.	Low / low
Catchment Runoff • sediment export • nutrients • contaminants	Many palaeochannels are predominantly already buried and additional sedimentation will not negatively impact on the sediment records they contain, however, greater sediment loads infill relict channels. Remnant channels, such as the Fitzroy palaeochannel (Ryan *et al.* 2006), still form extensive depressions in the seabed, but on the middle and outer continental shelf. These structures may act as flow pathways for cooler bodies of water, form freshwater aquifers and provide distinctive habitats.	Low / low
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Palaeochannel deposits may be removed/disturbed by dredging for shipping access, compromising the palaeoenvironmental record that they contain. The offset to this impact is that palaeochannels are often extensive, and dredging is likely to impact on only a small section of the channel deposit.	Moderate / moderate
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Not likely to have any impact.	Low / low

8.15 Continental Islands

The major considerations for these islands are their proximity to the mainland and coastal development.

Table 8.15 Pressures on continental islands, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	A threat to the shorelines of continental islands is sea level rise combined with increasing storm activity and intensity. Rising sea level and more intense storms can enhance shoreline erosion. For features comprising softer material (such as sandstone and mudstone) erosion may increase. Harder rock types are unlikely to be impacted.	Different for each feature / moderate
Catchment Runoff • sediment export • nutrients • contaminants	Not likely to have any impact.	Low / low
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	The development of tourist facilities on these stable islands is an activity that may compromise their resilience.	Different for each feature / moderate
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Not likely to have any impact.	Low / low

8.16 River Deltas

Table 8.16 Pressures on river deltas, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	Changes in sea level and storm regimes have the potential to rearrange delta morphology, impacting on the associated coastal and benthic habitats. Rising sea level will generate saline intrusion into the freshwater floodplains and wetlands. Floods will also achieve greater elevations owing to higher sea level.	Moderate/moderate
Catchment Runoff • sediment export • nutrients • contaminants	Enhanced sediment flux and associated contaminants have the potential to compromise the resilience of seabed habitats and their biological communities, however, these are generally relatively turbid environments.	Low /Moderate

Pressure	Impact(s)	Sensitivity / Risk
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Alterations to the hydraulics of channels in deltas due to dredging has the potential to lead to the rearrangement of sediment deposits and shorelines within the delta and the associated coastal and offshore sedimentary features and habitats that are part of the deltaic sediment system.	Moderate/low
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Not likely to have any impact.	Low / Low

8.17 Dune Systems

Table 8.17 Pressures on dune systems, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level • changed storm regimes	Changes in sea level and storm regimes have the potential to increase the erosion of sandy shorelines, which could lead to the destabilisation of some dunes.	Moderate / moderate
Catchment Runoff • sediment export • nutrients • contaminants	Not likely to have a significant impact on islands, other than changing the characteristics of sandy sediment that may ultimately be deposited in coastal dunes after being discharged by nearby rivers.	Low / Low
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	Developments that alter shoreline currents and rates of sediment delivery to shorelines have the potential to lead to shoreline erosion and the destabilisation of dunes.	Moderate / Low
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Unlikely to have impact however introduced pests such as rabbits, if present on an island, have the potential to destabilise dunes.	Low/Low

8.18 Submarine Canyons and Turbidite Deposits

Table 8.18 Pressures on submarine canyons and turbidite deposits, with indicative sensitivity and risk.

Pressure	Impact(s)	Sensitivity / Risk
Climate Change • increasing SST • ocean acidification • sea level changed storm regimes	Not likely to have any impact – too deep and too far offshore.	Low / low
Catchment Runoff • sediment export • nutrients • contaminants	Not likely to have any impact – too deep and too far offshore.	Low / low
Coastal & Marine Development • Changed sediment transport pathways • Dredging & spoil disposal	The disposal of spoil from dredging has the potential to reduce the integrity of these features.	Low / low
Direct Use • Shipping • Mining • Trawling • Grazing • Introduced pests	Not likely to have any impact – too deep and too far offshore.	Low / low

8.19 Summary of Sensitivity and Risk

A summary of the risk and sensitivity for each feature type identified is provided in Table 8.19. Risk refers to the likelihood that a type of pressure will impact on the feature. Sensitivity refers to how easily and how much a feature type might be impacted by a pressure.

The pressure identified as potentially impacting most of the feature types is climate change, followed by catchment runoff and coastal and marine development. Reef formations on the outer shelf and carbonate reef islands may be particularly susceptible to climate change impacts such as rising sea level, increasing coral bleaching events and increasing cyclone frequency and/or intensity. Seagrass beds may be particularly susceptible to the impacts of catchment runoff and marine development that result in a decline in water quality.

Table 8.19 Summary table for the sensitivity (S) and risk (R) for each listed feature. L = Low, M = Moderate, H = High, V = Variable, and ? = Unknown.

	Climate Change		Catchment Runoff		Coastal and Marine Development		Direct Use	
	S	R	S	R	S	R	S	R
Fringing Reefs	M	M	M	M	H	V	M	M
Inshore Turbid Reefs	V	V	V	V	?	?	L	L
Shelf Reefs	M	M	L	L	L	L	L	L
Ribbon Reefs	H	H	?	L	M	L	L	L
Deltaic Reefs	H	H	?	L	M	L	L	L
Northern Detached Reefs	H	H	?	L	M	L	L	L
Submerged Coral Reefs and Banks	L	L	?	L	L	L	L	M
Carbonate Reef Islands	H	M	L	L	V	V	L	L
Gravel and Shingle Ridges	L	M	L	L	M	L	L	L
Mangrove Shorelines, Mangrove Islands and Low Wooded Islands	M	M	L	L	M	L	L	L
***Halimeda* (banks, bioherms and meadows)**	?	?	M	M	L	L	L	L
Seagrass Beds	?	?	H	H	H	H	M	L
Karstic Channels and Blue Holes	L	L	L	L	L	L	L	L
Palaeochannles	L	L	L	L	M	M	L	L
Continental Islands	V	M	L	L	V	M	L	L
River Deltas	M	M	L	M	M	L	L	L
Dune Systems	M	M	L	L	M	L	L	L
Submarine Canyons and Turbidite Deposits	L	L	L	L	L	L	L	L

9 Summary

This report provides the first relatively comprehensive assessment of the types of geomorphological and geological features of the GBR whose intrinsic characteristics represent elements of the OUV of the World Heritage Area. The feature types described are:

- Fringing Reefs
- Inshore Turbid Reefs
- Shelf Reefs
- Ribbon Reefs
- Deltaic Reefs
- Northern Detached Reefs
- Submerged Coral Reefs and Banks
- Carbonate Reef Islands
- Gravel and Shingle Ridges
- Mangrove Shorelines, Islands and Low Wooded Islands
- Halimeda Banks
- Seagrass Banks
- Karstic Channels and Blue Holes
- Palaeochannels
- Continental Islands
- River Deltas
- Dune Systems
- Submarine Canyons

Specific examples of these features are described and an initial assessment made of the environmental pressures that they currently or in the future may experience. Importantly, the information compiled in this report improves our knowledge of an important set of physical and biophysical features in the GBRWHA with key natural heritage values and thereby has the potential to better inform the conservation and management of this unique region.

10 Recommendations

1. This report is not exhaustive and it is expected that there are additional types of geological and geomorphological features with OUV that were not documented, and the report is likely missing some additional important examples of the various types of features that have been listed. To enhance its utility, the report could be periodically revised and updated as new data and information become available. Future work should also include consultation with key stakeholders, including managers and a wider range of scientific experts and users of environmental information on the GBRWHA, especially in relation to the analysis of environmental pressures and impacts.
2. To improve the utility of the information provided in this report it is recommended that the information is moved into an authoritative spatial database of the key geological and geomorphological features in the GBRWHA, which is made available online. The database would include fundamental information on features (e.g. name, location, extent) as well as the descriptions of OUV and pressures. This would include the adoption of a consistent naming convention for feature types and individual features. It is also important to continue to capture legacy data and include them in the database, for example, descriptions and maps of some fringing reefs are held by individual researchers but not publically available.
3. The assessment of pressures and risk (Section 8) includes extensive professional opinion, as many of the features discussed have not undergone an explicit assessment of the pressure to which they are exposed. In particular, where the sensitivity and risk of features are considered medium or high (Section 8), a more detailed assessment is needed to improve our understanding of the degree of pressure on these features.
4. The assessment of the environmental condition or resilience of geological and geomorphological features of OUV would complement the information in this report and further inform the management of the GBRWHA. Remote sensing techniques (satellite imagery and aerial photography) coupled with available ground-truth information could be employed as an effective initial approach to identify change in the condition of features, and when the change occurred, since the inclusion of the GBR on the World Heritage List. A national Landsat satellite image database is now available that covers the GBRWHA, often with multiple scenes per month, and extends from 2012 back to 1987. There are also a number of sets of aerial photographs that date back to the 1950s. A pilot project could be developed to test the utility of this approach, focused on a few high-priority sites.
5. New satellite data (e.g. World View 2) is now available for the GBRWHA that has the spatial resolution and spectral range suitable for rapid, fine-scale assessments of changes in the environmental condition of reefs and coastal habitats and landforms. Importantly, this new imagery could be used to underpin environmental accounts, develop useful fine-scale environmental baseline information to enable the monitoring of key geological and geomorphological features and to better inform the assessment of the impacts of the pressures discussed in the Outlook Report (GBRMPA, 2009).
6. Cumulative impacts have not been addressed in this report, but are likely to be very important to the stability of both biotic and abiotic components of the GBRWHA. Further work is required to identify the geological and geomorphological features that are particularly susceptible to cumulative impacts.

References

Abbey E and Webster JM (2011) *Submerged reefs*, in Hopley, D., ed., Encyclopedia of Modern Coral Reefs: Structure, Form and Process. : Dordrecht, Netherlands, Springer- Verlag, p. 1058-1062.

Abbey E, Webster JM and Beaman RJ (2011) Geomorphology of submerged reefs on the shelf edge of the Great Barrier Reef: The influence of oscillating Pleistocene sea-levels: *Marine Geology*, v. 288, no. 1-4, p. 61-78.

Abel KM and Drew EA (1985) Response of {Halimeda} metabolism to various environmental parameters. 5: 21-26. In: *Proceedings of the 5th International Coral Reef Congress, Tahiti, 27 May-1 June 1985*. Antenne Museum-Ephe

Alexander J, Fielding C and Pocock G (1999) *Flood behaviour of the Burdekin River, Tropical north Queensland, Australia*, in Marriot, S., and Alexander, J., eds., Floodpalins: Interdisciplinary Approaches, Volume 163: London, Geological Society of London, p. 27-40.

Alongi DM (2002) Present state and future of the world's mangrove forests. *Journal of Environmental Conservation*; Vol 29; 03.

Alongi DM and McKinnon AD (2005) The cycling and fate of terrestrially-derived sediments and nutrients in the coastal zone of the Great Barrier Reef shelf. *Mar Poll Bull* 51:239-252.

Andrefouet S and Cabioch G (2011) *Barrier Reef (Ribbon Reef)*, in Hopley, D., ed., Encyclopedia of Modern Coral Reefs: Dortrecht, Springer, p. 102-107.

Andrews JC (1983) Thermal waves on the Queensland shelf.: Australian *Journal of Marine & Freshwater Research*, v. 34, p. 81-96.

Anthony KRN (2000) Enhanced particle-feeding capacity of corals on turbid reefs (Great Barrier Reef, Australia): *Coral Reefs*, v. 19, no. 1, p. 59-67.

Aston JP (1995) *The relative mobilities of coral cays on the Great Barrier Reef can be modeled* [M. Sc.: James Cook University, 267 p.

Backshall D, Barnett J, Davies P, Duncan D, Harvey N, Hopley D, Isdale P, Jennings J and Moss R (1979) Drowned dolines - the blue holes of the Pompey Reefs, Great Barrier Reef.: Bureau of Mineral Resources *Journal of Australian Geology and Geophysics*, v. 4, p.99-109.

Baird AH and Marshall PA (2002) Mortality, growth and reproduction in scleractinian corals following bleaching on the Great Barrier Reef, *Marine Ecology Progress Series* 237, 133-141.

Baker AC, Glynn PW and Riegl B (2008) Climate change and coral reef bleaching: An ecological assessment of long term impacts, recovery trends and future outlook: *Estuarine, Coastal and Shelf Science*, v. 80, pp435-471.

Barron River Delta Investigation Steering Committee, Report of Barron River Delta Investigation, Harbours and Marine Department, Brisbane (in preparation) in Robinson DA, Cook DJ and Barff JG (1980), 'Barron River Delta Investigation', *Proceedingsof the Seventeenth Conference on Coastal Engineering, Sydney Australia*, pp. 885-896.

Beaman RJ (2012) *Project 3DGBR: Great Barrier Reef and Coral Sea Geomorphic Features*. Marine and Tropical Sciences Research Facility (MTSRF) Project 2.5i.1a Final Report, MTSRF, Cairns, Australia.

Beaman RJ (2010) *Project 3DGBR: A high-resolution depth model for the Great Barrier Reef and Coral Sea*: Reef and Rainforest Research Centre.

Beaman RJ, Bridge T, Done T, Webster JM, Williams S and Pizarro O (2011) *Habitats and Benthos at Hydrographers Passage, Great Barrier Reef, Australia*. In: Harris, P.T., Baker, E.K. (Eds.), Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of Seafloor Geomorphic Features and Benthic Habitats. Elsevier, Amsterdam, Netherlands, pp. 425-434

Beaman RJ, Webster JM and Wust RAJ (2008) New evidence for drowned shelf edge reefs in the Great Barrier Reef, Australia: *Marine Geology*, v. 247, no. 1-2, p. 17-34.

Belperio A (1978) *Inner shelf sedimentation model for the Townsville region, Great Barrier* Reef.PhD]: James Cook University.

Belperio A (1983) Terrigenous sedimentation in the central Great Barrier Reef lagoon: A model from the Burdekin Region: BMR *Journal of Australian Geology and Geophysics*, v. 8, p. 179-190.

Berkelmans R and Oliver JK (1999) Large-scale bleaching of corals on the Great Barrier Reef. Coral Reefs 18: 55-60

Bird ECF (1971) The fringing reefs near Yule Point, North Queensland.: *Australian Geographical Studies*, v. 9, p. 107-115.

Bostock HC, Brooke BP, Ryan DA, Hancock G, Pietsch T, Packett R and Harle K (2007) Holocene and modern sediment storage in the subtropical macrotidal Fitzroy River estuary, Southeast Queensland. *Australia Sedimentary Geology*. 201(3-4).

Boyd R, Ruming K, Goodwin I, Sandstrom M and Schroder-Adams M (2008) Highstand transport of coastal sand to the deep ocean: a case study from Fraser Island, southeast Australia. *Geology* v. 36, p. 15-18.

Brayshaw S and Lemckert C (2012) Pitfalls of Shoreline Stabilisation – Tweed River Mouth, Gold Coast, Australia; *Coastal Research Library*, Volume 3.

Bridge T and Guinotte J (2012) *Mesophotic coral reef ecosystems in the Great Barrier Reef World Heritage Area: their potential distribution and possible role as refugia from disturbance. Great Barrier Reef Marine Park Authority, Townsville.*

Bridge TCL, Fabricius KE, Bongaerts P, Wallace CC, Muir PR, Done TJ and Webster JM (2012) Diversity of Scleractinia and Octocorallia in the mesophotic zone of the Great Barrier Reef, *Australia: Coral Reefs*, v. 31, no. 1, p. 179-189.

Bridge TCL, Done TJ, Beaman RJ, Friedman A, Williams SB, Pizarro O and Webster JM (2011a) Topography, substratum and benthic macrofaunal relationships on a tropical mesophotic shelf margin, central Great Barrier Reef, Australia. *Coral Reefs* 30:143-153

Bridge TCL, Done TJ, Friedman A, Beaman RJ, Williams SB, *et al.* (2011b) Variability in mesophotic coral reef communities along the Great Barrier Reef, Australia. *Mar Ecol Prog Ser* 428: 63–75.

Brinkman R, Wolanski E, Deleersnijder E, McAllister F and Skirving W (2002) Oceanic inflow from the Coral Sea into the Great Barrier Reef. *Estuarine, Coastal and Shelf Science* , 54 (4). pp. 655-668.

Brodie JE, Kroon FJ, Schaffelke B, Wolanski EC, Lewis SE, Devlin MJ, Bohnet IC, Bainbridge ZT, Waterhouse J and Davis AM (2012) Terrestrial pollutant runoff to the Great Barrier Reef: An update of issues, priorities and management responses: *Marine Pollution Bulletin*, v. 65, no. 4-9, p. 81-100.

Brodie J (comp) (2007) *Nutrient management zones in the Great Barrier Reef catchment: a decision system for zone selection: report to the Department of Environment and Heritage.* Australian Centre for Tropical Freshwater Research (ACTFR) report 06/07, James Cook University, Townsville, Australia.

Brodie J, McKergow LA, Prosser IP, Furnas M, Hughes AO and Hunter H (2003) *Sources of sediment and nutrient exports to the Great Barrier Reef World Heritage Area.* Australian Centre for Tropical Freshwater Research (ACTFR) report 03/11, James Cook University, Townsville, Australia.

Brooke BP, Harris PT, Nichol SL, Sexton J, Arthur WC, Haese RR, Heap AD, Hazelwood MC and Radke LC (2012) *Living on the Edge, in Shaping a Nation – A Geology of Australia*, R. Blewett (Ed), p. 275-331. Geoscience Australia, Canberra.

Brooke, BP, Ryan, DA, Pietsch, T, Olley, J, Douglas, G, Packett, R, Radke, L, Flood, P (2008) Influence of climate fluctuations and changes in catchment land use on Late Holocene and modern beach-ridge sedimentation on a tropical macro-tidal coast: Keppel Bay, Queensland, Australia. *Marine Geology* 251, 195–208.

Browne NK, Smithers SG and Perry CT (2010) Geomorphology and community structure of Middle Reef, central Great Barrier Reef, Australia: an inner-shelf turbid zone reef subject to episodic mortality events. *Coral Reefs*: online 10.1007/s00338-010-0640-3

Browne NK, Smithers SG and Perry CT (2012) Coral reefs of the turbid inner-shelf of the Great Barrier Reef, Australia: An environmental and geomorphic perspective on their occurrence, composition and growth: Earth-Science Reviews, v. 115, no. 1-2, p. 1-20.

Bruce MC and Niu Y (2010) Early Permian supra-subduction assemblages of the South Island terrane, Percy Isles, New England Fold Belt, Queensland, *Australian Journal of Earth Sciences*: 47:^, 1077-1085.

Bryan SE, Constantine AE, Stephens CJ, Ewart A, Schon RW and Parianos J (1997) Early Cretaceous volcano-sedimentary successions along the eastern Australian continental margin; implications for the break-up of east Gondwana. *Earth and Planetary Science Letters*, 153 (1-2), p. 85-102.

Bryan SE, Ewart A, Stephens CJ, Parianos J and Downes PJ (2000) The Whitsunday volcanic province, central Queensland, Australia; lithological and stratigraphic investigations of a silic-dominated large igneous province. *Journal of Volcanology and Geothermal Research*, 99 (1-4), p. 55-78.

Burridge CY, Pitcher CR, Wassenberg TJ, Poiner IR and Hill BJ (2003) Measurement of the rate of depletion of benthic fauna by prawn (shrimp) otter trawls: an experiment in the Great Barrier Reef, Australia; *Fisheries Research*; v. 60, no. 2-3, p 237-253.

Bunt JS, Williams WT and Bunt ED (1985) Mangrove species distribution in relation to tide at the seafront and up rivers: *Australian Journal of Marine & Freshwater Research*, v. 36, no. 4, p. 481-492.

Byrne M (2011) Impact of ocean warming and ocean acidification on marine invertebrate life history stages: vulnerabilities and potential for persistence in a changing ocean. *Oceanography Marine Biology: an Annul Review*; 49:1-42.

Byron T (1985) *Blue Holes: Land of coral rivers, raging currents and whirlpools.,*In Scuba divers guide to the Whitsundays: Sydney, Aqua Sports Publications, p. 82-87.

Carson CJ, von Gnielinski FE and Bultitude RJ (2006) *Results of the joint GSQ-GA geochronology project, New England Orogen, Rosedale, Mount Perry and Gladstone 1:100 000 sheet areas – March 2006-December 2006*. Queensland Geological Record 2006/01.

Carter RM and Johnson DP (1986) Sea-Level Controls On The Postglacial Development Of The Great-Barrier-Reef, Queensland: *Marine Geology*, v. 71, no. 1-2, p. 137-164.

Castelle B, Turner IL, Bertin X, Tomlinson R (2009) Beach Nourishment at Coolangatta Bay over the Period 1987-2005: Impacts and Lessons. *Coastal Engineering*; Volume 56, Issue 9.

Cavanagh JE, Burns KA, Brunskill GJ and Coventry RJ (1999) Organochlorine pesticide residues in soils and sediments of the Herbert and Burdekin River regions, north Queensland - implications for contamination of the Great Barrier Reef. *Marine Pollution Bulletin* 39, 367-375.

Chappell J and Grindrod J (1984) *Chenier plain formation in Northern Australia*, in Thom, B.G., ed., Coastal geomorphology in Australia: Canberra, Academic Press, p. 197-231.

Chappell J, Chivas A, Wallensky E, Polach H and Aharon P (1983) Holocene palaeo-environmental changes central to north Great Barrier Reef inner zone: BMR *Journal of Australian Geology and Geophysics*, v. 8, p. 223-235.

Chappell J, Rhodes EG, Thom BG and Wallensky E (1982) Hydro-isostacy and the sea-level isobase of 5500B.P. in North Queensland, Australia.: *Marine Geology*, v. 49, no. 1-2, p. 81-90.

Chernicoff S (1995) *Geology, An Introduction to Physical Geology*. New York, NY: Worth Publishers.

Chivas A, Chappell J, Polach H, Pillans B, and Flood P (1986) Radiocarbon evidence for the timing and rate of island development, beach-rock formation and phosphatization at Lady Elliot Island, Queensland. *Marine Geology,* 69, 273.287.

Choukroun S (2010) *The surface circulation of the Coral Sea and Great Barrier Reef*. PhD thesis, James Cook University.

Church JA and White NJ (2006) a 20th century acceleration in global sea level rise. *Geophysical Research letters* 33.

Clarke DE, Paine AGL and Jensen AR (1971) *Geology of the Prosperpine 1:250 000 sheet area*, Queensland Bureau of Mineral Resources, Geology and Geophysics Report 144.

Coles RG, McKenzie L and Campbell S (2003) *The seagrasses of eastern Australia*. In: Green, E.P., Short, F.T. (Eds.), World Atlas of Seagrasses. UNEP, WCMC, pp. 131–147.

Connolly RM (2009) *Seagrass.* In A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009 (Eds. E.S. Poloczanska, A.J. Hobday and A.J. Richardson), NCCARF Publication 05/09, ISBN 978-1-921609-03-9.

CSIRO (2007) *Climate change in Australia – technical report.* Commonwealth of Australia.

Daley B (2005) '*Changes in the Great Barrier Reef since European Settlement: Implications for Contemporary Management'*, PhD Thesis, School of Tropical Environment Studies and Geography: James Cook University.

Davies PJ and Hopley D (1983) Growth fabrics and growth rates of Holocene reefs in the Great Barrier Reef.: *BMR Journal of Australian Geology and Geophysics*, v. 8, p. 237-251.

Davies PJ and Marshall JF (1979) Aspects of Holocene reef growth - Substrate age and accretion rate.: *Search*, v. 10, p. 276-279.

Davies PJ, Marshall JF and Hopley D (1985) Relationships between reef growth and sea level in the Great Barrier Reef*: 5th International Coral Reef Congress*, v. 3, p. 95-103.

Dawson JL, Hua Q and Smithers SG (2012) Benthic foraminifera: Their importance to future reef island resilience, *12th International Coral Reef Symposium*, Cairns, Australia, p. online.

Dawson JL and Smithers SG (2010) Shoreline and beach volume change between 1967 and 2007 at Raine Island, Great Barrier Reef, *Australia: Global and Planetary Change*, v.72, no. 3, p. 141-154.

Day J, Fernandes L, Barnett B, Slegers S, Kerrigan B, Breen D, De'ath G, Lewis A, Innes J and Oliver J (2002) The Representative Areas Program for protecting the biodiversity of the Great Barrier Reef World Heritage Area, *Proceedings of the Ninth International Coral Reef Symposium*, Bali, Indonesia, 2000.

De'ath AG and Fabricius KE (2010) Water quality as regional driver of coral biodiversity and macroalgal cover on the Great Barrier Reef. *Ecological Applications* 20: 840-850.

De Jersey NJ (1960) Geology of Queensland, Cretaceous. The Plutoville Beds. The Styx Coal Measures, *Geological Society of Australia. Journal*, 7, p329-330

Dennison WC, Orth RJ, Moore, KA, Stevenson JC, Carter V, Koller S, Bergstrom PW and Batuik RA (1993) Assessing water quality with submersed aquatic vegetation: Habitat requirements as barometers of Chesapeake Bay Health. *Bioscience* 43 (2), 86–94.

Devlin MJ and Brodie J (2005) Water Quality Issues in the Great Barrier Reef Region Terrestrial discharge into the Great Barrier Reef Lagoon: nutrient behaviour in coastal waters. *Marine Pollution Bulletin* 51, Pages 9–22.

Dobbs K (comp.) (2011) *Identifying special or unique sites in the Great Barrier Reef World Heritage Area for inclusion in the Great Barrier Marine Park Zoning Plan 2003*, Great Barrier Reef Marine Park Authority, Townsville.

Drew EA (1983) Halimeda biomass, growth rates and sediment generation on reefs in the central GBR province. *Coral Reefs* 2:101–110

Duke NC (2006) *Australia's Mangroves*, Brisbane, The University of Queensland and Norman C Duke.

Duke NC (1997) Mangroves in the Great Barrier Reef World Heritage Area: Current status, long-term trends, management implications and research. In: David Wachenfeld, Jamie Oliver and Kim Davis, State of the Great Barrier Reef World Heritage Area Workshop: Proceedings of a technical workshop held in Townsville, Queensland, Australia, 27-29 November 1995. *State of the Great Barrier Reef World Heritage Area Workshop*, Townsville, Australia, (288-299). 27-29 November 1995.

Dunbar GB and Dickens GR (2003a) Massive siliciclastic discharge to slopes of the Great Barrier Reef Platform during sea-level transgression: constraints from sediment cores between 15° S and 16° S latitude and possible explanations. *Sediment. Geol*. 162, 141–158.

Dunbar GB and Dickens GR (2003b) Late Quaternary shedding of shallow-marine carbonate along a tropical mixed siliciclastic-carbonate shelf: Great Barrier Reef, *Australia: Sedimentology*, v. 50, no. 6, p. 1061-1077.

Dunbar GB, Dickens GR, Carter RM (2000) Sediment flux across the Great Barrier Reef shelf to the Queensland trough over the last 300 ky. *Sediment. Geol*. 133, 49–92.

Ebert SP (1995) *The geomorphological response to sediment discharge from the Herbert River, north Queensland, 1*943- 1991. Honours Thesis. Department of Geology, JamesCook University of North Queensland.

Ewart A, Schon RW and Chappell BW (1992) The Cretaceous volcanic-plutonic province of the central Queensland (Australia) coast - a rift related 'calc-alkaline' province. *Transactions - Royal Society of Edinburgh: Earth Sciences*, v 83, n 1-2, p 327-345.

Fabricius KE (2005) Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis: *Marine Pollution Bulletin*, v. 50, no. 2, p. 125-146.

Fabricius K, Hoegh-Guldberg O, Johnson JE, McCook L and Lough JM (2007) *Vulnerability of coral reefs of the Great Barrier Reef to climate change*, in Johnson, J. E., and Marshall, P. A., eds., Climate change and the Great Barrier Reef: A Vulnerability Assessment: Townsville, Great Barrier Reef Marine Park Authority and the Australian Greenhouse Office, p. 515-554.

Fairbanks RG (1989) A 17,000-yr glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation: *Nature*, v. 342, p. 637-642.

Fairbridge RW and Teichert C (1947) The rampart system at Low Isles, 1928-1945.: *Reports of the Great Barrier Reef Committee*, v. 6, p. 1-16.

Fairbridge RW and Teichert C (1948) The Low Isles of the Great Barrier Reef: A new analysis: *Geography Journal*, v. 111, p. 67-88.

Falvey DA and Mutter JC (1981) Regional plate tectonics and the evolution of Australias passive continental margins, BMR *Journal of Australian Geology and Geophysics*, 6, 1-9.

Fergusson CL, Henderson RA and Wright JV (1994): Facies in a Devonian-Carboniferous volcanic fore-arc succession, Campwyn Volcanics, Mackay district, central Queensland , *Australian Journal of Earth Sciences*, 41:4, 287-300.

Fernandes L, Day J, Lewis A, Slegers S, Kerrigan B, Breen D, Cameron D, Jago B, Hall J, Lowe D, Innes J, Tanzer J, Chadwick V, Thompson L, Gorman K, Simmons M, Barnett B, Sampson K, De'ath G, Mapstone B, Marsh H, Possingham H, Ball I, Ward T, Dobbs K, Aumend J, Slater D and Stapleton K (2005) Implementing representative no-take areas over 1/3 of the Great Barrier Reef: large-scale implementation of Marine Protected Area theory with lessons for global application, *Conservation Biology*, 1733-1744.

Fielding CR, Trueman JD, Dickens GR and Page M (2003) Anatomy of the buried Burdekin River channel across the Great Barrier Reef shelf: how does a major river operate on a tropical mixed siliciclastic/carbonate margin during sea level lowstand? *Sediment. Geol*. 157, 291–301.

Fielding CR, Trueman JD, Dickens GR and Page M (2005) Geomorphology and internal architecture of the ancestral Burdekin River across the Great Barrier Reef shelf, north-east Australia. Int. Assoc. *Sedimentol. Spec. Publ*. 35, 321–347 (Oxford, UK).

Flood PG (1977) Coral cays of the Capricorn and Bunker Groups, Great Barrier Reef province, Australia: *Atoll Research Bulletin*, v. 195, p. 7 pp.

Flood PG (1984) Variability of *shoreline position on five uninhabited islands of the Capricornia Section, Great Barrier Reef Marine Park., in Proceedings Royal Society of Queensland Symposium, Capricornia Section, Great Barrier Reef,* p. 17-23.

Foden J, Rogers SI and Jones AP (2010) Recovery of UK seabed habitats from benthic fishing and aggregate extraction—towards a cumulative impact assessment. *Mar Ecol Prog Ser* 411:259-270

Frank TD (2008) Late Holocene island reef development on the inner zone of the northern Great Barrier Reef: Insights from Low Isles Reef: *Australian Journal of Earth Sciences*, v. 55, no. 5, p. 669-683.

Frank TD and Jell JS (2006) Recent developments on a nearshore, terrigenous-influenced reef: Low isles reef, Australia: *Journal of Coastal Research*, v. 22, no. 3, p. 474-486.

Furnas M (2003) *Catchments and corals: terrestrial run-off to the Great Barrier Reef*, Townsville, Australian Institute of Marine Science, 334 p.

Gagan M, Anker S, Ayliffe L, Barnes D, Chappell J, Hopley D, Isdale P, Lough L and McCulloch M (1996) Massive corals: grand archives of Australian paleoclimate, *in Proceedings The Great Barrier Reef: Science, use and management*, James Cook University, Townsville, 25-29 November 1996, Volume 1, Great Barrier Reef Marine Park Authority, p. 195-209.

Galloway WE (1975) *Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems* in Walker RG and James NP (eds) (1992) Facies Models. Response to Sea Level Change, Geological Association of Canada.

Geological Survey of Queensland (1975) Queensland Geology. Map 2, Scale 1:2 500 000. Department of Mines, Brisbane.

Geoscience Australia (2012) *Australian Stratigraphic Names Database*: http://dbforms.ga.gov.au/pls/www/geodx.strat_units.int.

Geoscience Australia (2009) *Australian Bathymetry and Topography Grid*, https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=67703

Geoscience Australia (2006) *Geomorphic Features of Australia's Marine jurisdiction*, https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=69797

Gischler E (2011) *Blue hole*, in Hopley, D., ed., Encyclopedia of Modern Coral Reefs: Structure, Form and Process., Volume 1: Dordrecht, Netherlands, Springer-Verlag, p. 164-165.

Goh S (1992) *A morphological prediction of Cape Bowling Green*, North Queensland, Australia Honours: James Cook University.

Goudkamp K and Chin A (2006) *'Mangroves and Saltmarshes' in* Chin. A, (ed) The State of the Great Barrier Reef On-line, Great Barrier Reef Marine Park Authority, Townsville. Viewed on (viewed on the 20/12/2012), http://www.gbrmpa.gov.au/publications/sort/mangroves_saltmarshes

Graham TL (1993) *Geomorphological response of continental shelf and coastal environments to the Holocene transgression - Central Great Barrier Reef* [PhD: James Cook University, 206 p.

Great Barrier Reef Marine Park Authority (GBRMPA) (2012a) *Managing the Great Barrier Reef World Heritage Area – The Australian Government's response to the World Heritage Committee's decision of June 2011*. Commonwealth of Australia.

Great Barrier Reef Marine Park Authority (GBRMPA) (2012b) *The State of the Great Barrier Reef Report,* viewed in November 2012 at: http://kurrawa.gbrmpa.gov.au/corp_site/info_services/publications/sotr/intro/index.html

Great Barrier Reef Marine Park Authority (GBRMPA) (2012c) *Dredging and Spoil Disposal in the Marine Park*, viewed in December 2012 at: http://www.gbrmpa.gov.au/about-us/consultation/legislative-requirements-for-permits/dredging-and-spoil-disposal-in-the-marine-park

Great Barrier Reef Marine Park Authority (2012d) *Environmental Status: Seagrasses of the GBR,* Viewed at 24 January 2012 at: http://kurrawa.gbrmpa.gov.au/corp_site/info_services/publications/sotr/seagrasses/page_02.html

Great Barrier Reef Marine Park Authority (GBRMPA) (2009) *Great Barrier Reef Outlook*. Great Barrier Reef Marine Park Authority, Townsville.

Great Barrier Reef Marine Park Authority (GBRMPA) (2007), *GBR Features spatial dataset of spatial features in the GBR*. Great Barrier Reef Marine Park Authority, Townsville.

Great Barrier Reef Marine Park Authority (GBRMPA) (2006) *Environmental Status: Mangroves and Saltmarshes*. Great Barrier Reef Marine Park Authority, Townsville.

Gretch A (2011) A broad-scale assessment of the risk to coastal seagrasses from cumulative threats; *Journal of Marine Policy*; Vol. 35, p 560-567.

Gribble NA, Wassenberg T and Burridge C (2007) Factors affecting the distribution of commercially exploited penaeid prawns (shrimp) (Decapod:Penaeidae) across the northern Great Barrier Reef, Australia; *Journal of Fisheries Research*; vol. 85, issues 1-2, p 174-185.

Grimes KG (1982) *Drill site report - AIMS Davies No. 1*.: Geological Survey of Queensland Record, v. 18.

Grindrod J, Moss P and Van der Kaars S (1999) Late Quaternary cycles of mangrove development and decline on the north Australian continental shelf: *Journal of Quaternary Science*, v. 14, no. 5, p. 465-470.

Grindrod J and Rhodes E (1984) *Holocene sea-level history of a tropical estuary: Missionary Bay*, North Queensland, in Thom, B., ed., Coastal Geomorphology in Australia: Sydney, Academic Press, p. 151-178.

Hamanaka N, Kan H, Yokoyama Y, Okamoto T, Nakashima Y and Kawana T (2012) Disturbances with hiatuses in high-latitude coral reef growth during the Holocene: Correlation with millennial-scale global climate change: *Global and Planetary Change*, v. 80-81, p. 21-35.

Harris PT, Bridge TCL, Beaman RJ, Webster JM, Nichol S and Brooke BP (2012) Submerged banks in the Great Barrier Reef, Australia, greatly increase available coral reef habitat. *ICES Journal of Marine Science* doi:10.1093/icesjms/fss165

Harris PT, Heap AD, Marshall JF and McCulloch MT (2008) A new coral reef province in the Gulf of Carpentaria, Australia: colonisation, growth and submergence during the early Holocene. *Marine Geology*, 251: 85–97.

Harris PT and Heap AD (2009) Cyclone-induced net sediment transport pathway on the continental shelf of tropical Australia inferred from reef talus deposits, *Journal of Continental Shelf Research;* Volume 29, Issue 16

Harris PT and Davies PJ (1989) Submerged reefs and terraces on the shelf edge of the Great Barrier Reef, Australia: morphology, occurrence and implications for reef evolution. *Coral Reefs* 8: 87-98

Harris PT, Davies PJ and Marshall JF (1990) Late Quaternary sedimentation on the Great Barrier Reef continental shelf and slope east of Townsville, Australia. *Marine Geology* 94 (1), 55-77

Harris PT and Whiteway T (2011) Global distribution of large submarine canyons: Geomorphic differences between active and passive continental margins: *Marine Geology*, v. 285, no. 1-4, p. 69-86.

Harvey N (1977) The identification of subsurface solution disconformities on the Great Barrier Reef between 14S and 17S using shallow seismic refraction techniques, *Proceedings of the 3rd International Coral Reef Symposium*, Volume 2: Miami, p. 45-51.

Harvey N (1980) *Seismic investigations of pre-Holocene substrate beneath modern reefs in the Great Barrier Reef province*. [PhD: James Cook University].

Hendy EJ, Gagan MK, Alibert CA, McCulloch MT, Lough JM and Isdale PJ (2002) Abrupt decrease in tropical Pacific Sea surface salinity at end of Little Ice Age: *Science*, v. 295, no. 5559, p. 1511-1514.

Henrich R, Cherubini Y and Meggers H (2010) Climate and sea level induced turbidite activity in a canyon system offshore the hyperarid Western Sahara (Mauritania): The Timiris Canyon: *Marine Geology*, v. 275, no. 1-4, p. 178-198.

Hayne M and Chappell J (2001) Cyclone frequency during the last 5000 years at Curacoa Island, north Queensland, Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 168, pp. 207–219

Haynes D, Ralph P, Prange J and Dennison B (2000a) The impact of the herbicide diuron on photosynthesis in three species of tropical seagrass. *Marine Pollution Bulletin* 41, 288–293.

Haynes D, Mu¨ ller J and Carter S (2000b) Pesticide and herbicide residues in sediments and seagrass from the Great Barrier Reef World Heritage Area and Queensland coast. *Marine Pollution Bulletin* 41, 279–287.

Henderson R (1997) in Geological Aspects of Continental Islands, Lucas PH, Webb T, Valentine PS and Marsh H (1997) *The Outstanding Universal Value of the Great Barrier Reef World Heritage Area,* Great Barrier Reef Marine Park Authority, Townsville, Qld. pp.147-148.

Henderson RA, Fergussion CL, Bryan SE, Holcombe RJ, Fielding CR and Cook A (2010) Discussion and Reply Stratigraphy, facies architechture and tectonic implications of the Upper Devonian to lower Carboniferous Campwyn Volcanics of the northern New England Fold Belt. *Australian Journal of Earth Sciences*, 51: 3, 451-458.

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias- Prieto R, Muthiga N, Bradbury RH, Dubi A and Hatziolos ME (2007) Coral reefs under rapid climate change and ocean acidification: *Science* (New York, N.Y.), v. 318, no. 5857, p. 1737-1742.

Hopley D (1997) The age of the outer ribbon reef surface, Great Barrier Reef, Australia: implications for hydroisostatic models, in *Proceedings Third International Coral Reef Symposium*, Miami, Volume 2, p. 23-28.

Hopley D (2006) Coral Reef Growth on the Shelf Margin of the Great Barrier Reef with Special Reference to the Pompey Complex. *Journal of Coastal Research*: Volume 22, Issue 1: pp. 150 – 158.

Hopley D (2008) *Raine Island climate change risk assessment: evaluation of current knowledge, research and monitoring needs and potential adaptive management strategies*. Workshop discussion paper.: GBRMPA.

Hopley D (1996) Coral reefs and small islands - Implications of more modest climate and sea-level change predictions., in *Proceedings Recent advances in marine science and technology: Proceedings of PACON* 96, p. 249-258.

Hopley D (1982) *Geomorphology of the Great Barrier Reef: Quaternary development of coral reefs*, New York, John Wiley-Interscience, 453 p.

Hopley D (1984) *The Holocene 'high energy window' on the central Great Barrier Reef*, *in* Thom, B. G., ed., Coastal geomorphology in Australia.: Canberra, Academic Press, p. 135-150.

Hopley D (1993) *Coral reefs in a period of global sea level rise*, in Proceedings PACON international: Recent advances in marine science and technology, 92, Honolulu, 1993, Volume 1, PACON, p. 453-462.

Hopley D (1983) *Morphological classification of shelf reefs: A critique with special reference to the Great Barrier Reef*, in Barnes DJ (ed.) Perpectives on Coral Reefs: Canberra, Brian Clouston, p. 180-199.

Hopley D (ed) (2011) *Encyclopaedia of Modern Reefs Structure,* Form and Process, Springer Publishing, The Netherlands.

Hopley D and Barnes R (1985) Structure and development of a windward fringing reef, Orpheus Island, Palm Group, Great Barrier Reef., in *Proceedings 5th International Coral Reef Congress*, Tahiti, Volume 3, p. 141-146.

Hopley D and Harvey N (1982) Radiocarbon ages and morphology of reef tops in the Great Barrier Reef between 14*39'S and 20*45'S: Indicators of shelf neotectonics?, in *Proceedings Proceedings of the Fourth International Coral Reef Symposium, Manila*, Volume 1, International Society for Reef Studies, p. 523-530.

Hopley D, McLean RF, Marshall J and Smith AS (1978) Holocene-Pleistocene boundary in a fringing reef: Hayman Island, North Queensland: *Search*, v. 9, p. 323-324.

Hopley D, Parnell KE and Isdale PJ (1989) The Great Barrier Reef Marine Park: dimensions and regional patterns: *Australian Geographical Studies*, v. 27, p. 47-66.

Hopley D and Partain BR (1987) The structure and development of fringing reefs of the Great Barrier Reef Province, *in Proceedings Fringing Reef Workshop: Science, Industry and Management, Magnetic Island*, 23-25 October, Volume 1, Great Barrier Reef Marine Park Authority, p. 13-33.

Hopley D, Smithers SG and Parnell KE (2007) *The Geomorphology of the Great Barrier Reef; Development Diversity and Change*, Cambridge University Press, USA.

Horton BP, Larcombe P, Woodrofe SA, Whittaker JE, Wright MR, Wynn C (2003) Contemporary foraminiferal distributions of a mangrove environment, Great Barrier Reef coastline, Australia: implications for sea-level reconstructions, *Marine Geology*, 198, 225-243.

Hughes TP (1999) Off-reef transport of coral fragments at Lizard Island, Australia: *Marine Geology*, v. 157, no. 1-2, p. 1-6.

IPCC (Intergovernmental Panel on Climate Change) (2007): *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jensen AR, Gregory CM, Forbes VR (1966) *Geology of the Mackay 1:250 000 sheet area*. Bureau of Mineral Resources, Geology and Geophysics, Report 104.

Johnson D and Carter R (1987) *Sedimentary framework of mainland fringing reef development, Cape Tribulation area*: Great Barrier Reef Marine Park Authority, GBRMPA-TM-14.

Johnson D, Cuff C and Rhodes E (1984) Holocene Reef Sequences and Geochemistry, Britomart Reef, Central Great Barrier-Reef, Australia: *Sedimentology*, v. 31, no. 4, p. 515-529.

Johnson DP and Risk MJ (1987) Fringing reef growth on a terrigenous mud foundation, Fantome Island, central Great Barrier Reef, Australia.: *Sedimentology*, v. 34, p. 275-287.

Johnson DP, Searle DE, Hopley D (1982) Positive relief over buried post-glacial channels, Great Barrier Reef province, Australia. *Mar. Geol*. 46, 149–159.

Johnston K (1995) *Comparison of sedimentation trends at Low Isles, Northern Great Barrier Reef, 1928-29 and 1991-93.* [MSc: James Cook University], 159 p.

Kan H, Nakashima Y and Hopley D (1997) Coral communities during structural development of a fringing reef flat, Hayman Island, the Great Barrier Reef., *in Proceedings Proceedings of the 8th International Coral Reef Symposium*, Panama, Volume 1, Smithsonian Institute, p. 465-470.

Kench PS (2011) *Low wooded islands*, in Hopley, D., ed., Encyclopedia of Modern Coral Reefs: Dortrecht, Springer, p. 639-645.

Kench PS, Smithers SG and McLean RF (2012), Rapid reef island formation and stability over an emerging reef flat: Bewick Cay, northern Great Barrier Reef, Australia, *Geology*, vol. 40, no. 4, pp. 347 – 350.

Kleypas JA (1991) *Geological development of fringing reefs in the Southern Great Barrier Reef, Australia*. [PhD: James Cook University, 199 p.

Kleypas JA (1996) Coral reef development under naturally turbid conditions: fringing reefs near Broad Sound, Australia: *Coral Reefs*, v. 15, no. 3, p. 153-167.

Kleypas J and Hopley D (1992) *Reef development across a broad continental shelf, Southern Great Barrier Reef, Australia*, in Proceedings Seventh International Coral Reef Symposium, Guam, Volume 2, University of Guam Marine Laboratory, p. 1129-1141.

Koch M, Bowes G, Ross C and Zhang, X (2012) Climate Change and Ocean Acidification Effects on Seagrasses and Marine Macroalgae. *Global Change Biology*, v.19, no 1, p. 13-132.

Lambeck K and Nakada M (1990) Late Pleistocene and Holocene sea-level change along the Australian coast: *Palaeogeography Palaeoclimatology Palaeoecology*, v. 89, no. 1-2, p. 143-176.

Larcombe P, Carter RM, Dye J, Gagan MK and Johnson DP (1995) New evidence for episodic post-glacial sea-level rise, central Great Barrier Reef, Australia: *Marine Geology*, v. 127, no. 1-4, p. 1-44.

Larcombe P, Costen A and Woolfe KJ (2001) The hydrodynamic and sedimentary setting of nearshore coral reefs, central Great Barrier Reef shelf, Australia: Paluma Shoals, a case study: *Sedimentology*, v. 48, no. 4, p. 811-835.

Lee Long WJ, Mellors JE and Coles RG (1993) Seagrasses between Cape York and Hervey Bay, Queensland, Australia. *Australian Journal of Marine and Freshwater Research* 44: 19-32.

Lees B (2006) Timing and Formation of Coastal Dunes in Northern and Eastern Australia. *Journal of Coastal Research* 22, 78–89.

Leitch EC, Fergusson CL, Henderson RA and Morand VJ (1994): Ophiolitic and metamorphic rocks in the Percy Isles and Shoalwater Bay region, New England Fold Belt, central Queensland, *Australian Journal of Earth Sciences*, 41:6, 571-579

Levitus S, Antonov J and Boyer T (2005) Warming of the world ocean, 1995-2003. *Geophysical Research Letters*, 32.

Lewis S, Brodie J, Bainbridge Z, Rohde K, Davis A, Masters B, Maughan M, Devlin M, Mueller J and Schaffelke B (2009) Herbicides: a new threat to the Great Barrier Reef, *Environ. Pollution*, 157.

Lough JM (2007) Tropical river flow and rainfall reconstructions from coral luminescence: Great Barrier Reef, Australia*: Paleoceanography*, v. 22, no. 2.

Lovelock CE and Ellison JC (2007) *Vulnerability of mangroves and tidal wetlands of the Great Barrier Reef to climate change. In: Climate Change and the Great Barrier Reef: A Vulnerability Assessment*. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia, Australia, pp. 237-269.

Lucas PH, Webb T, Valentine PS, and Marsh H (1997) *The Outstanding Universal Value of the Great Barrier Reef World Heritage Area,* Great Barrier Reef Marine Park Authority, Townsville, Qld.

Manders J (2010) *Acid sulfate soil depositional environments of the Barron River delta, North Queensland*, 19th World Congress of Soil Science, Soil Solutions for a Changing World 1 – 6 August 2010, Brisbane, Australia. Published on DVD.

Marshall JF (1985) Cross-shelf and facies related variations in submarine cementation in the central Great Barrier Reef.: *Proceedings of the 5th International Coral Reef Congress*, v. 3, p. 221-226.

Marshall J and Davies P (1982) Internal structure and Holocene evolution of One Tree Reef, Southern Great Barrier Reef: *Coral Reefs*, v. 1, p. 21-28.

Marshall JF and Davies PJ (1988) Halimeda bioherms of the Northern Great Barrier Reef. *Coral Reefs* 6:139–148

Marshall SM and Orr AP (1931) *Sedimentation on Low Isles Reef and its relation to coral growth.: Scientific Reports Great Barrier Reef Expedition*, v. 1, no. 94-133.

Mateo MA, Romero J, Pérez M, Littler MM and Littler DS (1997) Dynamics of millenary organic deposits resulting from the growth of the Mediterranean seagrass *Posidonia oceanica. Estuarine Coastal and Shelf Science*, 44, 103-110.

Maxwell WGH (1968) *Atlas of the Great Barrier Reef*, Elsevier, 258 p.:

Maxwell WGH (1970) Deltaic patterns in reefs. *Deep Sea Research*, 17, 1005–1018.

Maxwell WGH (1972) The Great Barrier Reef – past present and future, *Queensland Naturalist*, vol. 20, 65-78.

McConachie BA, Wellman P, Dunster JN, Wilford JR, Denaro TJ and Draper JJ (1997) *Quinkan Region*. IN 'North Queensland Geology' Bain J.H.C. and Draper J.J. Australian Geological Survey Organisation Bulletin/Queensland Department of Mines and Energy Qld Geo 204/9 p399-407

McLean RF, Stoddart DR, Hopley D and Polach H (1978) Sea-level change in Holocene on Northern Great-Barrier Reef. *Philosophical Transactions of the Royal Society of London Series A-Mathematical Physical and Engineering Sciences* 291, 167-86.

Mesophotic.org (2012) Website information on the mesophotic zone of coral reefs, viewed on the 12/12/2012 at http://www.mesophotic.org/

Moorehouse FW (1933) The recently-formed natural breastwork on Low Isles.: *Reports to the Great Barrier Reef Committee*, v. 4, p. 35-36.

Moorehouse FW (1936) The cyclone of 1934 and its effect on Low Isles with special observations on Porites.: *Report to the Great Barrier Reef Committee*, v. 4, p. 37-44.

Mutter JC and Karner G (1980) *The continental margin off northeast Australia. Henderson* In RA and Stephenson PJ (Eds) (1980) The geology and geophysics of northeastern Australia, Brisbane, Geological Society of Australia (Queensland Division), pp.47-69.

Neil DT, Orpin AR, Ridd PV and Yu B (2002) Sediment yield and impacts from river catchments to the Great Barrier Reef lagoon: a review. *Marine and Freshwater Research* 53(4), 733–752.

Nott J (2006) Tropical Cyclones and the Evolution of the Sedimentary Coast of Northern Australia. *Journal of Coastal Research*: Volume 22, Issue 1: pp. 49 – 62.

Nott J, and Hayne M (2001) High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5,000 years . *Nature,* 413, 508-512.

O'Neill P, Stock E, Ferenczi P, Murray C and JR (2009) *Chapter 4 - Climate, geology and soils*, State of the environment Report for Shoalwater Bay Training Area 2008: Canberra, Department of Defence, Commonwealth of Australia, p. 71-100.

Ooi Lean-Sim J, Kendrick GA and Van Niel KP (2011) Effects of sediment burial on tropical ruderal seagrasses are moderated by clonal integration. *Continental Shelf Research,* 31: 1945-1954.

Orme GR (1985) The sedimentological importance of Halimeda in the development of back reef lithofacies, Northern Great Barrier Reef (Australia). *Proc 5th Int Coral Reef Symp* 5:31–37

Orme GR and Salama MS (1988) Form and seismic stratigraphy of Halimeda banks in part of the Northern Great Barrier Reef Province. *Coral Reefs* 6:131–137

Palmer SE, Perry CT, Smithers SG and Gulliver P (2010) Internal structure and accretionary history of a nearshore, turbid-zone coral reef: Paluma Shoals, central Great Barrier Reef, Australia: *Marine Geology*, v. 276, no. 1-4, p. 14-29.

Pandolfi JM, Jackson JBC, Baron N, Bradbury RH, Guzman HM, Hughes TP, Kappel CV, Micheli F, Ogden JC, Possingham HP and Sala E (2005) Are US coral reefs on the slippery slope to slime? *Science* 307:1725–1726.

Partain B and Hopley D (1989) *Morphology and development of the Cape Tribulation fringing reefs, Great Barrier Reef, Australia*: Great Barrier Reef Marine Park Authority, 21.

Pastorok R and Bilyard G (1985) Effects of sewage pollution on reef communities: *Marine Ecology Progress Series*, v. 21, p. 179-189.

Perry,CT, and Larcombe P (2003) Marginal and non-reef-building coral environments: *Coral Reefs*, v. 22, no. 4, p. 427-432.

Perry CT and Smithers SG (2006) Taphonomic signatures of turbid-zone reef development: Examples from Paluma Shoals and Lugger Shoal, inshore central Great Barrier Reef, Australia: *Palaeogeography Palaeoclimatology Palaeoecology*, v. 242, no. 1-2, p. 1-20.

Perry CT and Smithers SG (2010) Evidence for the episodic "turn on" and "turn off" of turbid-zone coral reefs during the late Holocene sea-level highstand: *Geology*, v. 38, no. 2, p. 119-122.

Perry CT and Smithers SG (2011) Cycles of coral reef 'turn-on', rapid growth and 'turn-off' over the past 8500 years: A context for understanding modern ecological states and trajectories: *Global Change Biology*, v. 17, no. 1, p. 76-86.

Perry CT, Smithers SG, Gulliver P and Browne NK (2012) Evidence of very rapid reef accretion and reef growth under high turbidity and terrigenous sedimentation: *Geology*, v. 40, no. 8, p. 719-722.

Pierau R, Hanebuth TJJ, Krastel S and Henrich R (2010) Late Quaternary climatic events and sea-level changes recorded by turbidite activity, Dakar Canyon, NW Africa: *Quaternary Research*, v. 73, no. 2, p. 385-392.

Pierau R, Henrich R, Preiü-Daimler I, Krastel S and Geersen J (2011) Sediment transport and turbidite architecture in the submarine Dakar Canyon off Senegal, NW-Africa: *Journal of African Earth Sciences*, v. 60, no. 3, p. 196-208.

Pigram CJ, Davies PJ, Feary DA and Symonds PA (1989) Tectonic controls on carbonate platform evolution in southern Papua New Guinea: passive margin to foreland basin. *Geology* 17, 199–202.

Pitcher CR (1995) Status of inter-reefal benthos in the Great Barrier Reef World Herritage Area; *State of the Great Barrier Reef Herritage Area Workshop no. 23*; *Proceedings of a technical workshop* held in Townsville, Queensland, Australia, 27-29 November 1995.

Pitcher CR, Austin M, Burridge CY, Bustamante RH, Cheers SJ, Ellis N, Jones PN, Koutsoukos AG, Moeseneder CH, Smith GP, Venables W and Wassenberg TJ (2008) *Recovery of seabed habitat from the impact of trawling in the far northern section of the Great Barrier Reef Marine Park: CSIRO final report to GBRMPA*, CSIRO Marine and Atmospheric Research, Cleveland, Australia.

Pitcher CR, Burridge CY, Wassenberg TJ, Hill BJ and Poiner IR (2009) A large scale BACI experiment to test the effects of prawn trawling on seabed biota in a closed area of the Great Barrier Reef, Australia; *Fisheries Research*; v. 99, no. 3, p 168-183.

Pitcher R, Doherty P, Arnold P, Hooper J and Neil Gribble (2007) *Seabed Biodiversity on the Continental Shelf of the Great Barrier Reef World Heritage Area*, Final report by the CRC Reef Research Centre for the Great Barrier Reef World Heritage Area; CSIRO Marine and Atmospheric Research.

Pollock AB (2007) *A preliminary investigation of the vegetation and landforms of Wild Duck Island, Queensland Environmental Protection Agency* In: Referral of proposed action: Wild Duck Island Eco-Resort, Appendix L.

Preen A, Lee Long WJ and Coles RG (1995) Flood and cyclone related loss, and partial recovery, of more than 1000 sq km of seagrass in Hervey Bay, Queensland, Australia, *Aquatic Botany*, vol. 52, pp. 3–17.

Pringle AW (1984) Evolution of the east Burdekin delta coast, Queensland, Australia 1940-1980: *Zeitschrift fur Geomorphologie*, v. 28, no. 2, p. 129-154.

Pringle AW (1991) Fluvial sediment supply to the north-east Queensland coast, Australia: *Australian Geographical Studies*, v. 29, no. 1, p. 114-138.

Pringle AW (1996) History, geomorphological problems and effects of dredging in Cleveland Bay, Queensland: *Australian Geographical Studies*, v. 34, no. 1, p. 58-80.

Pringle AW (2000) Evolution of the east Burdekin Delta coast, Queensland, Australia 1980-1995: *Zeitschrift fur Geomorphologie*, v. 44, no. 3, p. 273-304.

Przeslawski R, Ahyong S, Byrne M, Worheide G, Hutchings P (2008) Beyond coral and fish: the effects of climate change on non-coral benthic invertebrates of tropical reefs. *Global Change Biology* 14: 2773-2795.

Puga-Bernabeu A, Webster JM and Beaman RJ (2012) Potential collapse of the upper slope and tsunami generation on the Great Barrier Reef margin, north-eastern Australia.: *Natural Hazards*, v. Published online November 25, p. 1-19.

Puga-Bernabeu A, Webster JM, Beaman RJ and Guilbaud V (2011) Morphology and controls on the evolution of a mixed carbonate-siliciclastic submarine canyon system, Great Barrier Reef margin, north-eastern Australia: *Marine Geology*, v. 289, no. 1-4, p. 100-116.

Puga-Bernabeu A, Webster JM, Beaman RJ and Guilbaud V (in review) Variation in canyon morphology on the Great Barrier Reef margin, north-eastern Australia: influence of slope and barrier reefs.: *Geomorphology*, v. in review.

Pye K (1982) Morphological development of coastal dunes in a humid tropical environment, Cape Bedford and Cape Flattery, north Queensland (Australia): *Geografiska Annaler, Series A*, v. 64 A, no. 3-4, p. 213-227.

Pye K and Bowman GM (1984) *The Holocene marine transgression as a forcing function in episodic dune activity on the eastern Australian coast*, in Thom, B. G., ed., Coastal geomorphology in Australia: Canberra, Academic Press, p. 179-196.

Pye K and Rhodes EG (1985) Holocene development of an episodic transgressive dune barrier, Ramsay Bay, North Queensland, Australia: *Marine Geology*, v. 64, no. 3-4, p. 189-202.

QLD DAFF (Queensland Department of Agriculture, Fisheries and Forestry). http://www.daff.qld.gov.au/28_15511.htm Website viewed on the 12 February 2013.

QLD DE (Queensland Department of Environment). *Coastal sand dunes – their vegetation and management. Leaflet No. 11-03*. http://www.ehp.qld.gov.au/coastal/pdf/coastal-sand-dunes-2-03.pdf

QLD DEH (Queensland Department of Environment and Heritage). *Regional Ecosystem Descriptions Database*: www.ehp.qld.gov.au/ecosystems/biodiversity/regional-ecosystems viewed in January 2013.

QLD EPA (Queensland Environmental Protection Agency) (1999), *Queensland's coast: managing its future: a position paper on coastal management in Queensland*. Queensland Environmental Protection Agency, Brisbane.

Rees S, Opdyke B, Wilson P et al (2007) Significance of Halimeda bioherms to the global carbonate budget based on a geological sediment budget for the Northern Great Barrier Reef, Australia, *Coral Reefs*, vol. 26, no. 1, pp. 177-188.

Roche D, Paillard D and Cortijo E (2004) Constraints on the duration and freshwater release of Heinrich event 4 through isotope modelling: *Nature*, v. 432, no. 7015, p. 379-382.

Ryan DA, Bostock HC, Brooke BP, and Marshall JF (2007) Bathymetric expression of the Fitzroy River palaeochannel, northeast Australia: Response of a major river to sea-level change on a semi-rimmed, mixed siliciclastic-carbonate shelf. *Sedimentary Geology,* 201*,* 196-211.

Ryan, DA, Brooke, BP, Bostock, HC, Radke, LC, Siwabessy, PJW, Margvelashvili, N, Skene, D, (2007) Bedload sediment transport dynamics in a macrotidal embayment, and implications for export to the southern Great Barrier Reef shelf. *Marine Geology*, 240, 197-215.

Ryan DA, Brooke BP, Collins LB, Spooner MI and Siwabessy PJW (2008) Formation, morphology and preservation of high-energy carbonate lithofacies: Evolution of the cool-water Recherche Archipelago inner shelf, south-western Australia. *Sedimentary Geology* 207, 41–55.

Schaffelke B, Mellors J and Duke NC (2005) Water quality in the Great Barrier Reef region: responses of marine plants and consequences of their disturbance. In: Hutchings, P.A., Haynes, D. (Eds.), Proceedings of the Catchment to Reef: Water Quality Issues in the Great Barrier Reef Region Conference. *Marine Pollution Bulletin*, doi:10.1016/j.marpolbul.2004.10.025

Searle DE and Flood PG (1988) Halimeda bioherms of the Swain Reefs—Southern Great Barrier Reef. *Proc 6th Int. Coral Reef Symp*. 3:139–144

SEWPAC (Department of Sustainability, Environment, Water, Population and Communities) (2010) *Magnetic Island, Queensland, EPBC Act Policy Statement 5.1*. Commonwealth of Australia.

Skene D, Brooke B and Ryan D (2004) Subbottom Profiling, Surface Sediment Sampling, Vibracoring and Mapping with Sidescan and Multibeam Sonar Systems in the Fitzroy River Estuary and Keppel Bay; Milestone report (CG04.01) to the Coastal CRC Coastal Habitat Mapping Project Coastal Geomorphology Subproject.

Skene D, Ryan D, Brooke B, Smith J and Radke L (2005) *The geomorphology and sediments of Cockburn Sound*. Geoscience Australia Record 2005/10, Geoscience Australia, Canberra, pp. 88.

Slocombe AM (1981) The structure and development of the fringing reef in Pioneer Bay, Orpheus Island.B.Sc. Hons.]: James Cook University.

Smith J, Douglas GB, Radke LC, Palmer M and Brooke BP (2008) Fitzroy River Basin, Queensland, Australia. III. Identification of sediment sources in the coastal zone. *Environmental Chemistry* 5, 231–242. doi:10.1071/EN07094.

Smithers SG (2011) *Fringing Reefs*, in Hopley, D., ed., Encyclopedia of Modern Coral Reefs: Dortrecht, Springer, p. 430-446.

Smithers S and Larcombe P (2003) Late Holocene initiation and growth of a nearshore turbidzone coral reef: Paluma Shoals, Central Great Barrier Reef, Australia: *Coral Reefs*, v. 22, no. 4, p. 499-505.

Smithers SG and Woodroffe CD (2000) Microatolls as sea-level indicators on a mid-ocean atoll: *Marine Geology*, v. 168, p. 61-78.

Smithers SG, Hopley D, and Parnell KE (2006) Fringing and Nearshore Coral Reefs of the Great Barrier Reef: Episodic Holocene Development and Future Prospects. *Journal of Coastal Research*: Volume 22, Issue 1: pp. 175 – 187.

Spenceley AP (1982) The geomorphological and zonational development of mangrove swamps in the Townsville area, North Queensland, 11.

State of the Environment (2011) *Independent report to the Australian Government Minister for Sustainability, Environment, Water, Population and Communities, Australian State of the*

Environment Committee; Hatton T, Cork S, Harper P, Joy R, Kanowski P, Mackay R, McKenzie N, Ward T, Wienecke, B, Commonwealth of Australia.

Steers JA (1938) Detailed notes on the islands surveyed and examined by the Geographical Expedition to the Great Barrier Reef in 1936. *Reports of the Great Barrier Reef Committee*, 4, 51-96.

Stephenson TA, Stephenson A, Tandy G and Spender MA (1931) The structure and ecology of Low Isles and other reefs: Scientific Reports, *Great Barrier Reef Expedition*, v. 3, p. 17-112.

Stieglitz T (2005) Submarine groundwater discharge into the near-shore zone of the Great Barrier Reef, Australia. *Marine Pollution Bulletin* 51, 51–59.

Stoddart DR (1978) The Great Barrier Reef and the Great Barrier Reef Expedition 1973: *Philosophical Transactions of the Royal Society of London Series* A, v. 291, p. 5-22.

Stoddart, D. R., McLean, R. F., and Hopley, D., 1978, Geomorphology of reef islands, northern Great Barrier Reef: *Philosophical Transactions of the Royal Society of London Series B*, v. 284, p. 39-61.

Stoddart DR, McLean RF and Hopley D (1978) Geomorphology of reef islands, northern Great Barrier Reef: *Royal Society of London Philosophical Transactions, ser. B,* v. 284, p. 39–61, doi:10.1098/rstb.1978.0052.

Stoddart DR and Fosberg FR (1991) Phytogeography And Vegetation of the Reef Islands of the Northern Great Barrier Reef, *Atoll Research Bulletin*, The Smithsonian Institution, Washington D.C. (349): 20.

Stoddart DR, McLean RF, Scoffin TP and Gibbs PE (1978) Forty-five Years of Change on Low Wooded Islands, Great Barrier Reef, *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences,* Vol. 284, No. 999, The Northern Great Barrier Reef (Nov. 14, 1978).

Sweatman H, Thompson A, Delean S, Davidson J. and Neale S (2007) *Status of Near-Shore Reefs of the Great Barrier Reef 2004*. Marine and Tropical Sciences Research Facility Research Report Series. Reef and Rainforest Research Centre Limited, Cairns (169 pp.)

Thom BG and Chappell J (1975) Holocene sea level relative to Australia. *Search* 6: 90-93.

Thom BG and Roy PS (1983) *Sea level changes in New South Wales over the past 15,000 years*. In Hopley D. (ed), Australian sea levels of the past 15,000 years, Department of Geography, James Cook university, monograph series occasional paper 3: 64-84.

Thom BG, Orme GR and Polach HA (1978) Drilling investigation of Bewick and Stapleton islands: *Philosophical Transactions of the Royal Society of London Series A,* v. 291, p. 37-54.

Toth LT, Aronson RB, Vollmer SV, Hobbs JW, Urrego DH, Cheng H, Enochs IC, Combosch DJ, Van Woesik R and Macintyre IG (2012) ENSO drove 2500-year collapse of Eastern Pacific coral reefs: *Science*, v. 336, no. 6090, p. 81-84.

UNESCO (United Nations Educational, Scientific and Cultural Organisation), (2012) *World Heritage Listing and description for the Great Barrier Reef*, viewed on the 6/12/2012 from: http://whc.unesco.org/en/list/154

van Oppen MJH, Bongaerts P, Underwood JN, Peplow LM and Cooper TF (2011) The role of deep reefs in shallow recovery: an assessment of vertical connectivity in a brooding coral from west and east Australia. *Molecular Ecology*, 20: 1647–1660.

Veron JEN and Hudson RCL (1978a) Ribbon Reefs of the Northern Region, *Philosophical Transactions of the Royal Society of London. Series B*, Biological Sciences, Vol. 284, No. 999, The Northern Great Barrier Reef (Nov. 14, 1978), pp. 3-21

Veron JEN (1978a) Evolution of the Far Northern Barrier Reefs, *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, Vol. 284, No. 999, The Northern Great Barrier Reef (Nov. 14, 1978), pp. 23-37

Veron JEN (1978b) Deltaic and Dissected Reefs of the far North Region, *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, Vol. 284, No. 999, The Northern Great Barrier Reef (Nov. 14, 1978), pp. 23-37

Walker RG and James NP (eds) (1992) *Facies Models. Response to Sea Level Change,* Geological Association of Canada.

Ward S, Harrison P and Hoegh-Guldberg O (2000) Coral bleaching reduces reproduction of scleractinian corals and increases susceptibility to future stress: *Proceedings 9th International Coral Reef Symposium*, Bali, Indonesia, 23-27 October.

Webster JM and Davies PJ (2003) Coral variation in two deep drill cores: significance for the Pleistocene development of the Great Barrier Reef: *Sedimentary Geology*, v. 159, no. 1-2, p. 61-80.

Webster JM, Beaman RJ, Puga-Bernabeu A, Ludman D, Renema W, Wust RAJ, George NPJ, Reimer PJ, Jacobsen GE and Moss P (2012) Late Pleistocene history of turbidite sedimentation in a submarine canyon off the northern Great Barrier Reef, Australia: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 331-332, p. 75 89.

Weeks SJ, Bakun A, Steinberg CR, Brinkman R and Hoegh-Guldberg O (2010) The Capricorn Eddy: A prominent driver of the ecology and future of the southern Great Barrier Reef. *Coral Reefs*, *29* 4: 975-985.

Wolanski EJ, Drew EA, Abel KM and O'Brien J (1988) Tidal jets, nutrient upwelling and their influence on the productivity of the alga Halimeda in the Ribbon Reefs, Great Barrier Reef. *Estuary Coast Shelf Sci* 26:169–201

Woolfe KJ, and Larcombe P (1999) Terrigenous sedimentation and coral reef growth: a conceptual framework*: Marine Geology*, v. 155, no. 3-4, p. 331-345.

Yamano H, Miyajima T and Koike I (2000) Importance of foraminifera for the formation and maintenance of a coral sand cay: Green Island, Australia: *Coral Reefs*, v. 19, no. 1, p. 51-58.

Zhao JX, Neil DT, Feng YX, Yu KF and Pandolfi JM (2009) High-precision U-series dating of very young cyclone-transported coral reef blocks from Heron and Wistari reefs, southern Great Barrier Reef, Australia. *Quaternary International* 195, 122-127.

Appendix A Mesophotic Spatial Datasets

Maps of geological features of OUV are provided with this report (in Section 6). Spatial datasets have been provided to the Department of Sustainability, Environment, Water, Population and Communities and are available on request.

Boundaries of features available in the GBRMPA dataset 'GBR_features' (2007) were used to defined the feature location. All attribute information from the GBRMPA dataset was retained in the final attribute table and additional geological information and a proposed classification of OUV was added.

Where boundaries for features were not available in the GBRMPA dataset, the location of the feature/group of features was defined by a generalised bounding polygon or box. The location of features not included in the GBRMPA dataset were sourced from the scientific literature and existing marine datasets, maps and charts.

Separate files are provided for each feature type listed in Section 6 with the exception of Seagrass Beds, *Halimeda* Banks and River Deltas, which could not be defined from datasets available within the timeframes of this project. All datasets are provided as ArcGIS vector shapefiles within a geodatabase with ANZLIC compliant metadata.

Dataset attribute tables contain a proposed classification of OUV as outlined below.

Identification of geological features of OUV and the accuracy of their mapped boundaries are limited to those addressed in existing research and datasets. Additional features of OUV may be identified through ongoing research and data collection/collation.

Table A.1 Datasets providing spatial location of Geological Features of OUV in the GBR (spatial data for Seagrass Beds, Halimeda Banks and River Deltas are not provided)

Feature type	Source location information
Fringing Reefs	GBRMPA 'GBR_Features' (2007)
Inshore Turbid Reefs	GBRMPA 'GBR_Features' (2007)
Shelf Reefs	GBRMPA 'GBR_Features' (2007)
Ribbon Reefs	GBRMPA 'GBR_Features' (2007)
Deltaic Reefs	GBRMPA 'GBR_Features' (2007)
Northern Detached Reefs	GBRMPA 'GBR_Features' (2007)
Submerged Coral Reefs and Banks	GBRMPA 'GBR_Features' (2007); scientific publications; Australian Bathymetry and Topography Grid (2009); Geomorphic Features of the Australian Margin (2006).
Carbonate Reef Islands	GBRMPA 'GBR_Features' (2007)
Gravel and Shingle Ridges	GBRMPA 'GBR_Features' (2007)
Mangrove Shorelines, Mangrove islands and Low Wooded Islands	GBRMPA 'GBR_Features' (2007)

Feature type	Source location information
Karstic Channels and Blue Holes	GBRMPA 'GBR_Features' (2007); scientific publications, Australian Bathymetry and Topography Grid (2009); Geomorphic Features of the Australian Margin (2006).
Palaeochannels	scientific publications; Australian Bathymetry and Topography Grid (2009).
Continental Islands	GBRMPA 'GBR_Features' (2007)
Dune Systems	GBRMPA 'GBR_Features' (2007); scientific publications
Submarine Canyons and Turbidite Deposits	scientific publications; Australian Bathymetry and Topography Grid (2009); Geomorphic Features of the Australian Margin (2006). Great Barrier Reef and Coral Sea Geomorphic Features (Beaman, 2012)

Appendix B Glossary of Terms

Bedload: Component of sediment in a stream that is transported with intermittent or continuous contact with the stream bed.

Benthic: ecological region at the bottom of the sea; of the sea floor.

Berm: a wave-deposited terrace extending landward of the beach face (above the high tide level).

Bioerosion: erosion of hard ocean substrates by living organisms.

Biogenic: produced by living organisms or through biological processes.

Bioherm: a mound-like form of built-up organic deposits of marine invertebrates such as corals, calcareous algae etc.

Ca: 'approximately'.

Carboniferous: a Period on the geologic timescale spanning from approximately 359.2 million years ago to 299 million years ago.

Calcareous: comprised mostly of calcium carbonate.

Caldera: volcanic feature formed by the collapse of the land following a volcano forming a cauldron-like shape.

Cenozoic: Also known as the Cainozoic, this is the most recent Period in the geological timescale commencing approximately 65 million years ago to the present.

Clastic: rocks composted of pre-exiting fragment or 'clasts'.

Cretaceous: A Period in the geological timescale commencing approximately 145 million years ago and ending approximately 0.3 million ago.

Detritus: particles of rock created through weathering and erosion.

Devonian: a Period on the geologic timescale spanning from approximately 419.2 million years ago to 358.9 million years ago.

Doline: a depression in the grounds surface (also known as a sink-hole), usually shallow and shaped like a funnel, caused by collapse, suffusion or solution of limestone.

Dry Tropics: An area with a tropical climate that has a pronounced (usually long – up to nine months) dry season. Where rainfall is less than 60mm in the driest months and intense, heavy rainfall periods occur during the summer months. In Australia the "Dry Tropics" often refers to a specific area defined in 2002 as part of a national natural resource management (NRM) program to facilitate delivery of on-ground resources for natural resource management activities. This area includes the Burdekin River Catchment and associated coastal and marine areas.

Epibiota: organisms that live on the surface of other organisms.

Eutrophication: increased aquatic nutrient levels and the resultant impact on aquatic flora and fauna.

Facies: a distinctive rock layer that has characteristics of a specific sedimentary environment.

Felsic: division of rocks based on silica content. Felsic rocks have the highest content of silica (followed by intermediate, mafic and ultramafic).

Foraminifera: a phylum of primarily marine organisms with an (a usually calcium carbonate) shell. They are usually less than 1 mm but can reach 20 cm.

Goniastrea: genus of coral that have been noted to form microatolls in the GBR.

High stand: periods of sea level transgression.

Guano: deposits formed by faeces of birds, bats and seals. Often used as fertilised because of its high phosphorus and nitrogen content.

Holocene: an Epoch on the geological timescale that begins at the end of the Pleistocene (from between 12,000 – 11,500 years before present) and continue to the present.

Hydo-isostatic flexure: where rising or falling sea level casus the lithosphere to rise and fall as it attempts to reach equilibrium with the changing mass (see isostacy).

Isostacy: a process where equilibrium is restored to the earths lithosphere if the mass changes. For example if the lithosphere is covered in ice, it will sink to a new equilibrium, and vice versa if the ice melts the land will rise.

ka: thousand years before present.

Karst: geological formations caused by erosion of rocks through dissolution of soluble rock such as carbonate rocks and limestone.

Lowstand: periods of sea level regression.

Lithofacies: a stratigraphic unit within a facies of a sedimentary rock that has unique characteristics of a particular sedimentary environment.

Ma: million years before present.

Macroalgae: a collective term used for seaweeds and other benthic marine algae that are visible to the naked eye.

Mafic: division of rocks based on silica content. Mafic rocks have the second lowest content of silica (where felsic and intermediate have higher silica content, and ultramafic has the least silica content).

Mesophotic: Deepest part of the photic zone (30-40 m to over 150 m).

Mesozoic: An Era in the geological timescale commencing approximately 250 million years ago and ending approximately 65 million ago (also referred to as the age of the reptiles).

Microatoll: intertidal corals dead on top, but living on their perimeter. They form if upward growth is constrained by exposure, but the marginal corals, still submerged continue to grow.

Packstone: a grain-supported carbonate rock comprising predominantly a lime mud matrix.

Palaeogene: A geological period that began about 65.5 million years ago and ended approximately 23.03 million years ago. This is the period during which mammals evolved.

Palaeozoic: is the earliest geological Era commencing approximately 541 million years ago and ending approximately 252.5 million years ago. This was a time of dramatic geological, climatic and evolutionary change.

Palaeosol: fossil soil layer.

Photic zone: Depth of water at which enough light penetrates for photosynthesis to occur.

Pillow Basalt: basalts formed underwater where the water cools and crystallises the basalt rapidly forming a pillow shape.

Pisonia: a genus of flowering plants.

Pleistocene: an Epoch on the geological timescale from approximately 2.588 million years before present to the start of the Holocene (approximately 11,500 years before present).

Quaternary: Is a Period in the geologic timescale. It is the most recent Period and includes the Pleistocene and the Holocene Epochs, spanning from 2.588 million years ago to the present.

Regolith: unconsolidated material on bedrock - often caused by weathering processes.

Ria: coastal valley, partially submerged.

Sea Level Regression: sea level falls relative to the land. This can occur if the sea falls or if land rises.

Sea Level Transgression: sea level rise relative to the land. This can occur if the sea rises or if land subsides.

Serpentinite: Rocks created through a metamorphic process where heat and water causes mafic and ultramafic rocks to oxidise forming unique serpentine group minerals.

Siliciclastic: clastic and non-carbonate sedimentary rocks bearing mostly silica.

Subtidal: an area along the shoreline that is predominantly submerged, but which is exposed during extreme low tides.

Supratidal: shoreline immediately above the high water level.

Symbiodinium: a genus of unicellular organisms usually in tropical waters. They live in tropical organisms where they provide photosynthesis products to their host, and the host provides them with inorganic nutrients. They are often called zooxanthellae.

Terrigenous: sediments that are sourced from erosion of rocks on land (i.e. not from marine accretions such as carbonate deposits).

Tombolo: a spit of land joining an island to the mainland.

Turbidites: underwater deposits of sediment resulting from an underwater avalanche.

Ultramafic: division of rocks based on silica content. Ultramafic rocks have the lowest silica content (where felsic, intermediate and mafic have higher silica content).

Wackstone: a grain-supported carbonate rock comprising predominantly a lime mud matrix, but where there is a larger portion of mud matrix than a packstone.

Wet tropics: an area with a tropical climate with large volumes of seasonal rainfall. In Australia the 'Wet Tropics of Queensland' runs from the coast to the peaks of the Great Dividing Range in Northeast Queensland, between Townsville and Cooktown. Rainfall in this landscape is controlled by the Great Dividing Range which causes topographic variation in distribution from 1,200 mm along the coast to up to 8,000 mm in the highlands. Rainfall is seasonal predominantly between December to March.

Zooxanthellae: see symbiodinium.