Journal of the Royal Society of Western Australia, 94: 107–119, 2011

Notes on the origins and biogeomorphology of Montgomery Reef, Kimberley, Western Australia

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Manuscript received December 2010; accepted April 2011

Abstract

Montgomery Reef, lying at the boundary of Camden Sound and Collier Bay is a very large rock platform (c. 400 km^2) in an open sea setting of the Kimberley Bioregion, Western Australia. It is not a coral reef platform in the strict sense but an ancient terrestrial structure, probably a flat-topped mesa, with a Holocene veneer of marine biogenic sediments superimposed over inherited terrestrial geomorphic features. The eastern end of the reef, at least, has base rocks (beneath the coralgal veneer) of dolomite, underlying quartz sandstone mapped as Pentecost Sandstone, an upper member of the Paleoproterozoic Kimberley Group. The dolomite is an unrecognised formation and its well preserved stromatolites are undescribed. Although the coral fauna on the reef platform is moderately diverse, coral reef-building is located primarily in the impounded pools lagoons of the reef platform. There is very little coral growth on the reef-front. An unusual feature is the relative importance of rhodoliths that form massive containment banks around the perimeter of the reef and are responsible for creating the high lagoon habitats. Field observations suggest that rhodoliths may be the most important contemporary reef-builders on Montgomery Reef with very high primary production inferred.

Keywords: Montgomery Reef, Holocene reef growth, rhodoliths, corals, stromatolites, biogeomorphology

Introduction

Montgomery Reef is a very large, flat-topped geomorphic structure whose platform surface is exposed at low tide. It has an estimated area of c. 400 km^2, located in open sea at the Collier Bay-Camden Sound boundary about 15 nautical miles north of the Yampi Peninsula. Recent surveys of the modern reef fauna of the Montgomery Reef platform have been carried out by the Australian Institute of Marine Science and the Western Australian Museum, rendering this one of the better known reefs in the Kimberley in regard to its biota. However, its geology and reef-building processes remain undescribed. There have been various interpretations of the nature of the reef and its origins. Teichert and Fairbridge (1948) referred to it as one of several "large, rather irregular patches of reefs [that] rise in the deeply indented bays of the Kimberley coast". Burbidge *et al.* (1991) noted that "the Montgomery Islands at the centre of the platform are surrounded by "sand flats and coral reef". The Marine Parks and Reserves Selection Working Group referred to Montgomery Reef as "an extensive intertidal and shallow subtidal rock platform" (CALM 1994). Brooke (1997) described it as one of several large "carbonate bioherms" near the Kimberley coastline. This report considers the nature of the reef and its origins and reef-building processes on the basis of field observations made during a brief visit.

The geological and biogeomorphic history of Montgomery Reef and its biota have particular importance because its small islands have high cultural significance. O'Connor (1994) excavated material from an open habitation site on the largest of the High Cliffy Islands (Ngalanguru) and dated it at round 6,700 years B.P., indicating that the islands of this reef were populated by people with a specialised maritime economy soon after the end of the post-glacial transgression. Since that time, people lived there, at least periodically, until the "contact" period in the early part of the 20th century. It is said that these people, who were known as the Jaudibaia, spoke a distinctive dialect (Love, quoted by Tindale 1974) indicating a long independent heritage. The resources that supported this group were primarily those associated with the reef.

Methods

This report is largely descriptive, presenting field observations from a brief visit to Montgomery Reef by a party from the Western Australian Marine Science Institution [WAMSI] in August–September, 2009 aboard the W.A. Fisheries patrol vessel *P.V. Walcott.* Hyperspectral airborne imaging of Montgomery Reef, including tri-colour scanner and high resolution digital photographs of the study area commissioned by WAMSI were produced and processed by *Airborne Research Australia* and Curtin University Department of Applied Physics. These data provide the first high resolution

Figure 1. Montgomery Reef. Acknowledgements to Google Earth.

digital base map with 3 metre on ground resolution that can be further interrogated for detailed spectral information from the key "end members" including corals, algae, rhodoliths, sediments and mangroves.

Terminology

In this report *rock platform* is used as a geomorphic term meaning a reef structure that has a near-horizontal surface in the intertidal zone, the rock being of any kind. Such a platform surface may have been an outcome of erosional or constructional processes, or a combination thereof. Intertidal rock platforms are thought to be erosional and are often referred to as "wave-cut platforms" (Edwards 1958). A *coral reef* platform is one where the framework of the structure is constructed, *in situ*, by growth of coral and calcareous algae and the level of the platform surface is determined by limits to vertical coral growth. The term *coral platform reef* is a category of coral reef that lacks a lagoon and commonly has an oval outline, a central sand island and a flat intertidal surface. On the Kimberley coast there are many intertidal rock platforms of flat-bedded Proterozoic rocks that have a wedge of Holocene coral and algal growth and carbonate deposition at the reef-front, thereby warranting the term *fringing reef.* Rock and coral reef platforms generally have a sloping lower-littoral *reef-front ramp* with a distinct *reef edge*, a *reef crest* and a mid-littoral *reef flat.*

As a geomorphic structure, Montgomery Reef and its parts do not fit, exactly, any of these terms and it is necessary to describe what is observed and use standard reef terminology with caution and explanation.

Results

General morphology of Montgomery Reef

Montgomery Reef has a horizontal but terraced surface within the intertidal zone, referred to here as the reef platform, and steep, cliff-like peripheral walls in the subtidal fore-reef zone. Three primary biogeomorphic units may be distinguished, the main reef, a north-pointing arm called The Breakwater at its western end, and a small satellite reef separated by a deep channel at its eastern end called High Cliffy Reef (Fig. 1). There are several small islands on the platform. The Montgomery Islands comprise a cluster of low, mud islands at its centre, vegetated with mangroves and grassy flats and

Figure 2. High Cliffy Reef with its five small islands, separated from the main Montgomery Reef platform by a deep channel. (Data courtesy of WAMSI and Airborne Research Australia, and images processed by Curtin University.)

largely surrounded by sand sheets. There are also eight small rocky islands on the eastern margin of the complex. They include five islands, known collectively as the High Cliffy Islands, arranged around the eastern and southern fringe of High Cliffy Reef (Fig. 2). The other three are located on or near the eastern margin of the main Montgomery Reef and are known as the dual Egret Islands (Fig. 3) (referred to as Jungadi by Roy Wiggan) and Wulajarlu Island (Fig. 4).

The form of the main reef platform is atypical. There is very little coral reef growth at the reef-front and calcareous algal growth appears to dominate biogenic carbonate deposition on the reef flat. There are some parts of the reef flat where rock pavement (with a crustose algal veneer) is exposed at low tide but most of its vast area (c. 350 km^2) is occupied by a shallow lagoon and pools. The reef flat and its lagoon and pools are at two levels separated by an impoundment bank of rhodoliths, the upper level about 50 cm above the lower one behind the reef crest. There is no back-reef and in that respect Montgomery Reef resembles a very large coral platform reef. Some details are given in the following section on intertidal habitats.

Geology

The mainland coast and islands east and south of Montgomery Reef lie along the south-western margin of the Kimberley Basin, its rocks being upper members of the Paleoproterozoic Kimberley Group, namely, the Pentecost Sandstone, Elgee Siltstone and Yampi Formation and intrusive igneous rocks. By its location it might be expected that the base rocks of the Montgomery Reef complex would belong in this series.

The Islands

The low Montgomery Islands at the centre of the main reef (Fig.1) consist of Quaternary sediments comprising mud banks and sand sheets (Brooke 1995). They are a product of marine sedimentary processes since inundation.

The five rocky High Cliffy Islands comprise Paleoproterozoic rocks mapped (Map Sheet SD51-16 &15) as possibly Pentecost Sandstone, one of the uppermost members of the Kimberley Group. However, archaeologist Sue O'Connor (1987) noted the presence at Ngalanguru Island of both "quartz sandstone and limestone". Brooke (1995) noted that these islands have "cliffed and etched limestone shorelines formed in flat bedded massive stromatolitic limestone and siltstone". During a WAMSI visit to Montgomery Reef (September 2009) landings were made on three of the five High Cliffy Islands and the following observations were made.

On top of all the High Cliffy Islands there is a cap of blocky, bedded, strongly jointed, fine-grained quartz sandstone or siltstone, that is the basis for mapping the islands as Pentecost Sandstone (Fig. 5). The sandstones overlie beds of a massive, silicified, laminated, richly stromatolitic dolomite that outcrops along the island shores and is the rock referred to by O'Connor and Brooke as limestone. This rock is very hard and very heavy and breaks into sharp edges. It was used for tool-making by the pre-contact inhabitants. It appears to be an unnamed formation and is not mentioned in the geological notes accompanying the map sheet. Some layers of the stromatolite domes exposed at the surface have a hard covering of secondary accretion that is stark white and, from a distance, makes the rocks look as if they are covered with cormorant droppings (Figs 6, 7). On the shore, below high tide mark, the dolomite is grey and etched (*i.e.* eroded into multi-faceted, sharp-edged ridges and turrets). On the eastern shores of the islands the top of the dolomite is up to 14 m above low tide level. In places it is horizontally laminated and gently folded and there is a 3–4° dip to the northwest so that, while it forms supralittoral cliffs along the eastern shores, on most islands it disappears into the intertidal zone along the western or northwestern shores.

Wuljarli and Egret Islands

These islands are located on the upper level of the reef flat at the south eastern side of the main Montgomery Reef platform, a step up from the lower level close to the reef front (Figs 3, 4). Like the High Cliffy Islands, Wuljarli and Egret Islands are mapped as Pentecost Sandstone. Landings were made on all three islands and the rocks of them all were found to be blocky fine-grained quartzite like the upper rocks of the High Cliffy Islands. On the southwestern shore of Wuljarlu Island there is also a southwest-dipping conglomerate comprising rounded river stones in a ferrous matrix. There was no dolomite on any of these islands.

Figure 3. The Egret Islands on the edge of the high platform on the south-eastern margin of Montgomery Reef. Note the double containment banks of the high platform margin above the lower platform, with sand fans along their downside margin, and the crescent-shaped pools formed by coalescing ridges of rhodoliths and coral rubble in the lagoon. (Data courtesy of WAMSI and Airborne Research Australia, and images processed by Curtin University.)

Figure 4. Wulajarlu Isand on the rim of the upper lagoon of Montgomery Reef where it impinges on the reef-front without a lower reef flat. This island is built of Paleoproterozoic quartz sand stone and conglomerates and there is no dolomite. (Data courtesy of WAMSI and Airborne Research Australia, and image processed by Curtin University.)

Figure 5. On the top of Wulajarlu Island, looking north at high tide. Blocky quartz sandstone in the foreground, the Egret Islands on the skyline. (Photo Barry Wilson).

Montgomery Reef and the High Cliffy Reef

While the rocks of the eastern islands are Paleoproterozoic and probably of the Kimberley Group, there is no published account of the rock of the reef platforms, *i.e.* beneath the Holocene sediment and crustose algal veneer. In September 2009, a WAMSI party landed on the eastern margin of the main Montgomery Reef opposite High Cliffy Reef during a period of neap low tide. Standing on the mid-littoral platform behind the reef crest, about two hundred metres from the reef edge, there is a group of massive, silicified dolomite rocks, the tops of which are emergent at high tide (Fig. 9). Stromatolite structures were not observed in these rocks but the lithology of the rock is otherwise quite similar to the stromatolitic dolomite of the High Cliffy Islands. One flat-topped stack about 10 m in diameter, stands 4 m high above the lower reef flat surface, its upper part demarcated from the etched lower part by a conspicuous bedding plane with a slight dip west. These rocks were thought to be *in situ* erosional relics of the rock platform. If that is the case, the lower, mid-littoral rock platform on this part of the main Montgomery Reef has a base of massive dolomite that is older than the Pentecost Sandstone which, on the High Cliffy Islands, overlies it. However, the thickness of the Holocene sedimentary veneer on the reef surface around the emergent stacks is unknown.

Intertidal habitats of the Montgomery Reef complex

The following notes provide a provisional account of the habitats of Montgomery Reef. They are derived mainly from reports by Brooke (1995, 1997), interpretation of high definition imagery produced by Curtin University for WAMSI, field surveys by W.A. Museum and AIMS, and the recent field observations by the authors.

High Cliffy Reef

Brooke (1997) noted some shoreline features around Ngalanguru Island. Wells *et al*. (1995) referred to "gentle terracing" of the reef platform and noted the presence of a large lagoon. Aerial photographs (Fig. 2) show a wide reef flat and lagoon on the western side of the High Cliffy Islands. The western reef edge, bordering the High Cliffy channel, appears to be poorly defined and observations by the WAMSI party during a period of neap tides indicated that this reef platform is lower than that of Montgomery Reef on the opposite side of the channel. The eastern side of High Cliffy Reef has a steep fore-reef slope but the reef edge was not observed.

The Breakwater

The Breakwater is a long finger of reef jutting north from the western end of the main Montgomery Reef (Fig. 1). It appears to be a distinct structure attached to the main reef. Brooke (1997) provided a description of a site on the western side, noting that the lower-littoral ramp is characterized by extensive algal turf and pavement with two to three low terraces around 20 cm high. Reef-front coral growth did not feature in his description except for *Porites* sp. rimming shallow sandy pools. The mid-littoral reef flat is composed of a network of pools separated by

Figure 6. Top of the stromatilite dolomite forming a supra-littoral bench on a small islet south of Ngalanguru Island, High Cliffy Group. Note the circular tops of large stromatolites in the foreground and the stark white crust over much of the rock surface. This surface appears to be the top of the dolomite sequence exposed by removal of the sandstone above it. (Photo Barry Wilson.)

Figure 7. Two forms of stromatolite, about 3 m above high tide level on the northern side of a small islet south of Ngalanguru Island, High Cliffy Group. (Photo Barry Wilson).

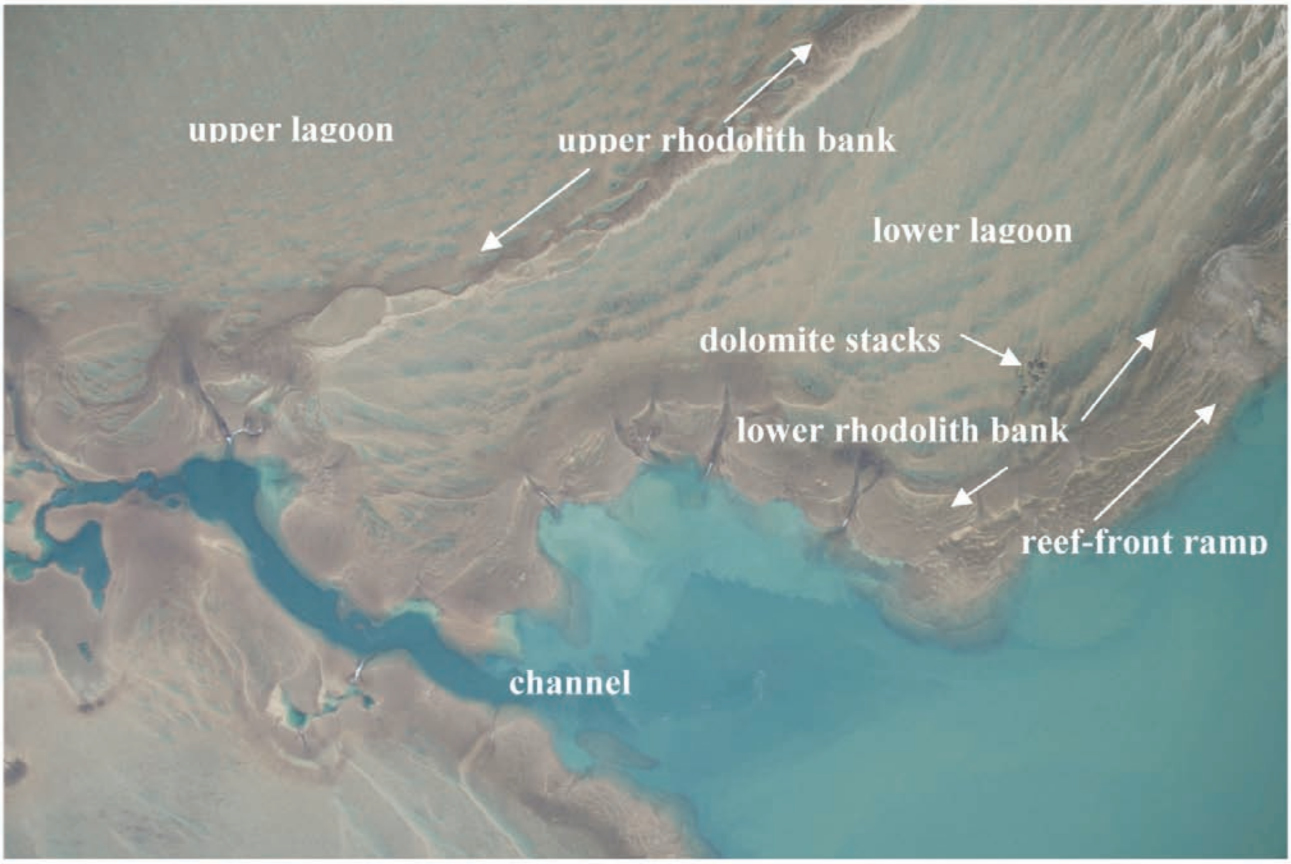

Figure 8. The south-eastern margin of Montgomery Reef, opposite High Cliffy Reef. Note the broad reef-front ramp dissected at intervals by drainage gutters, and the reef crest with rhodolith banks impounding shallow pools on the midlittoral reef flat with pools. Running diagonally across the top left corner is the higher complex of rhodolith banks that impound the high lagoon. A major drainage channel entering from the left originates in the high lagoon. (Data courtesy of WAMSI and Airborne Research Australia, and image processed by Curtin University.)

narrow strips of algal pavement. These clear water pools also contain abundant coarse sand and calcareous mud.

Main Montgomery Reef

a) The subtidal fore-reef

The subtidal fore-reef zone is difficult to observe. The following notes derive from drop-camera and ROV observations made by AIMS (Andrew Heyward *pers. com.).* Around most of the reef's periphery the fore-reef is a vertical, stepped or steeply sloping wall to a depth of about 10 m and thence a slope to the surrounding seabed at around 20 m. The wall appears to bear little epifaunal or epiphytic growth. There are sand sheets in the sublittoral zone at some localities, often with pronounced "dune" formation, probably a result of the intense tidal currents [up to 2 m/sec associated with an 11m tidal range during Spring Tides. S.Blake pers. obs] recorded around the margins of Montgomery Reef. A fore-reef spur and groove system is not present. Nor is there a rich community of large *Porites sp.* and foliaceous corals like those known to occur in this zone of those few Kimberley fringing reefs that have been studied. However, there are many shallow subtidal ledges and patch reefs that bear moderately diverse coral communities. The seabed beyond the fore-reef is a rocky pavement with little sediment and bears well developed though patchy filter-feeding communities of mainly sponges, sea-whips, sea-fans and soft corals.

b) Lower-littoral – reef-front ramp

The lower-littoral reef-front of Montgomery is a high-energy environment, not from wave action but from intense off-reef tidal flow. It is an extreme habitat where calcareous algae and low turf algae flourish but coral colonies are small and sparse. The huge volume of water impounded above the two impoundments banks and the many lesser terraces on the reef flat, results in spectacular, high velocity cascades over the terraces where the reef-front is high and steep and, in spring tide periods, over the reef front (Fig. 10). At such times, the larger drainage channels across the lower reef platform act like mountain rivers with extremely turbulent flow.

The reef-front ramp around Montgomery Reef is clearly evident in aerial photographs as a prominent zone varying in width from 50 to 100 m. It is generally high and steep, sloping at around 5–10° or more, sometimes convex, and has a distinct reef edge. At Spring Low Tide the reef edge may be several meters above water level (Figure 10). The ramp pavement is covered with a calcareous algal crust and a low turf. In most places the ramp is distinctly terraced by ridges of crustose algae a few cm high that impound networks of shallow pools, rather like a miniature Javanese hillside with rice

Figure 9. A massive dolomite stack on the mid-littoral reef flat near the south-eastern margin of Montgomery Reef (15°55.221'S; 124°18.795'E). Etched rocks on the lower part (*i.e.* below high tide level). Also visible as a cluster of small dots on Figure 8. (Photo Steve Blake, WAMSI.)

Figure 10. The reef edge at low tide; major channel, south west of Wulajarlu Island, Montgomery Reef. (Image courtesy Tim Willings, Pearl Sea Coastal Cruises)

terraces. The depth of the algal crust is unknown but is probably superficial.

Corals in the reef-front zone may be common, sparse or lacking. When present, corals are small colonies with flattened morphologies, mostly growing around the edges of the shallow pools. There is no zone of prolific coral growth along the reef-front like that of fringing reefs in the Bonaparte Archipelago and no evidence of a Holocene coralline limestone wedge and outward reef growth at the reef-front.

c) Mid-littoral – reef crest

A boulder zone is lacking but commonly there is a reef crest equivalent comprising an elevated bank of rhodoliths up to 100 m wide fronted by a narrow fan of coarse sand (Figs 11, 12, 13). Unlike the boulders of coral reef crests that are derived from the fore-reef and deposited by wave action, the rhodoliths appear to be derived from the sandy pools of the mid-littoral lagoon behind the reef crest and deposited there by ebbing tidal flow and wind-driven waves. The rhodolith banks are mobile, moved back and forth over the reef crest zone by tidal flow. They are generally very long and wind their way around the reef crest zone, often dividing into multiple bands that coalesce. The rhodolith banks are not terraces in the strict sense but they impound water behind and between them. The rhodoliths are irregular in form. Some have a core of coral fragments but many are more or less globular, ranging in diameter from 5 cm to 12 cm and are of entirely algal construction (Fig. 13).

d) Mid-littoral reef flat

The reef flat of Montgomery Reef, behind the reef crest, is unusually high in the intertidal zone and, at least on the eastern side, is formed at two distinct levels that are separated by an upper rhodolith impoundment bank (Figs 8, 11).

(i) Lower reef flat

The lower mid-littoral reef flat behind the reef crest varies in its nature, sometimes being a typical reef flat with an exposed pavement, crustose surface and low algal turf, and sometimes comprising a mosaic of shallow, knee-deep to waist-deep (at low tide) pools separated by secondary rhodolith ridges or crustose coralline algal ridges, the tops of which may be exposed. Aerial photographs show that the ridges are crescent-shaped and coalescent (Figs 3, 8) with steep outer margins and sloping inner margins, indicating that they are formed by the force of the ebb tide. In areas where pools dominate, this habitat might be called a lower mid-littoral lagoon rather than a reef flat, but neither term is strictly apt.

The pools are lenticular, with sand, rhodolith and rubble beds and contain moderately diverse coral communities, leafy brown algae and some seagrass (*Thalassia)*. Similar configurations of rhodolith ridges and pools were observed at Turtle Reef in the nearby Talbot Bay on Yampi Peninsula (Wilson *et al*, this volume, Fig. 9). The abundant rhodoliths apparently grow in the pools where they are rolled by the tide to form the networks of ridges and eventually up onto the reef crest where they build the banks that rim and impound the pools and lagoon.

(ii) Upper reef flat (lagoon)

The upper reef flat is actually a shallow lagoon occupying most of the area of Montgomery Reef although there are some areas of rock pavement exposed at low tide. Little information is available at this time on the extent of coral and rhodolith growth in this zone. Aerial photographs show that the high lagoon includes areas where shallow, lenticular pools dominate, separated by coalescing ridges of rhodoliths and rubble, like those of the lower reef flat/lagoon so that vigorous rhodolith growth may be inferred.

The upper and lower platforms are demarcated by the upper complex of rhodolith banks, with a sand fan in front of it (Fig. 3). This upper terrace is virtually continuous and almost encircles Montgomery Reef and is clearly evident in the satellite images and the aerial photographs (Figures 1, 3, 11). Its height is not known. This conspicuous feature may be related to the underlying geological structure or a historical constructional feature relating to a Holocene (eustatic)

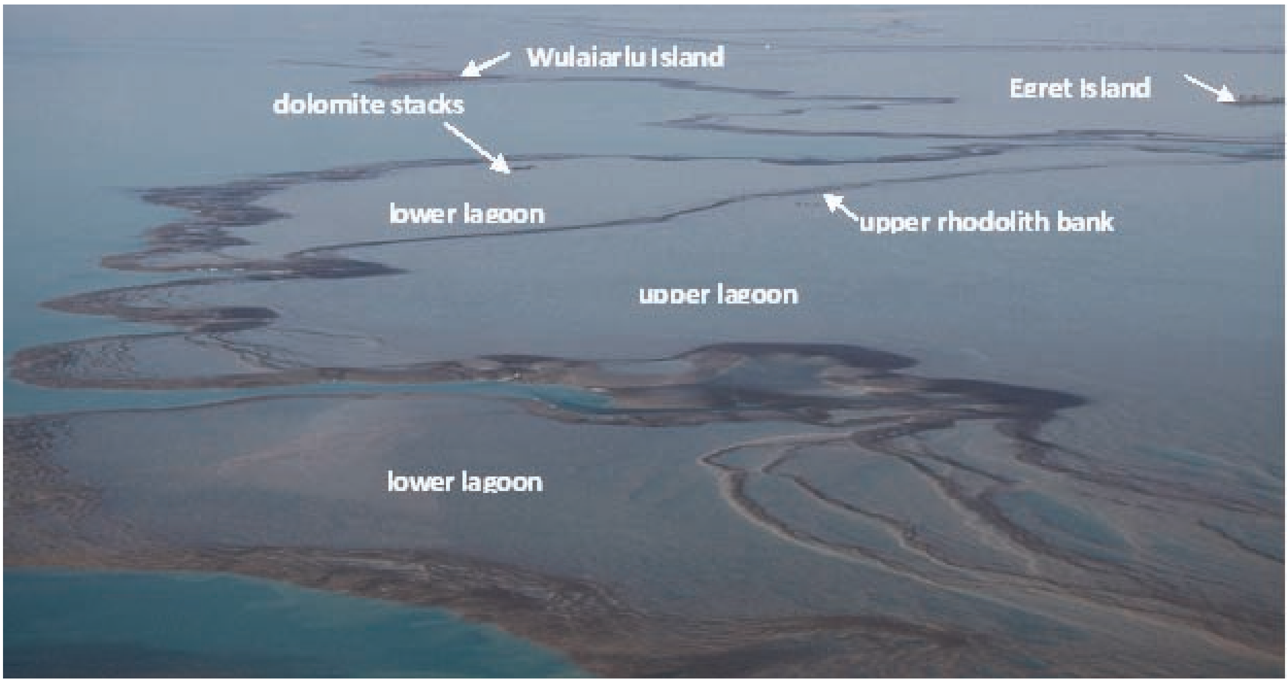

Figure 11: Rhodolith banks, lagoons and reef-front ramps along the S.E margin of Montgomery Reef. In the right fore-ground there are several rhodolith banks forming steps down from the upper lagoon to a mid-littoral reef flat. In the centre a tongue of the upper lagoon stretches to the reef edge and there is no mid-littoral reef flat. Wulajarlu Island top left; Egret Island top right margin. (Photo Steve Blake, WAMSI)

Figure 12. Rhodolith bank on the reef crest; S.E. Montgomery Reef (15°55.331'E; 124°18.851'E; elevation c. 4 m). Mid-littoral reef flat on the left; High Cliffy Reef and islands in the background. (Photo Barry Wilson.)

Figure 13. Rhodoliths on the reef crest (see Fig. 12). Some of these have a coral fragment core but the majority are entirely of algal construction. (Photo Barry Wilson.)

high sea level. However, it is more likely to be a contemporary constructional, biogenic feature relating to tidal level.

The area occupied by the upper reef flat lagoon is enormous (c. 350 km^2). It forms a vast light trap at low tide, with shallow conditions where autotrophic organisms flourish without exposure to the air or significant wave action (except during cyclonic storms). Primary productivity in these intertidal lagoons has not yet been measured but must be prodigious.

Summary and discussion

Reef growth

While there is a diverse coral fauna on Montgomery Reef, there is no prolific coral growth on the reef-front edge or the fore-reef wall and no evidence of the development of a reef-front biogenic limestone wedge. In other words, there is little reef-building activity in the reef-front zone and no significant lateral reef growth. However, there is vigorous biological growth of both rhodoliths and scleractinian corals in the pools and lagoons of the intertidal platform behind the rhodolith impoundment banks. Biogenic rubble and sand produced by these processes is filling in the pools and lagoons and raising the level of the platform.

The rhodolith banks cover large areas of the reef crest, pools and lagoons of the reef flat and clearly play a significant reef-building role. It would be interesting to obtain estimates of the rates of growth of the rhodoliths and corals but the impression gained from visual observations is that the rhodoliths are the primary reef-building organism on the Montgomery Reef platform.

The presence and configuration of these ridges and banks of rhodoliths and algal terraces, and the pools and lagoons they create, are functions of the macro-tidal regime and an unusual biogeomorphic feature. Kuenen (1933) discussed the importance of “lithothamnium” in reef-building on coral reefs and mentioned a report of the Siboga Expedition (Weber 1902) of “lithothamnium in loose nodules covering bare reefs … in several parts of the East Indies”. This latter study has not been seen but is the only reference known to these authors to large scale intertidal rhodolith banks and significant reef-building by these organisms.

It is suggested that calcareous algae may be the predominant reef-building organisms on Montgomery Reef, probably more significant that the corals, affecting the process in two ways:

- by their own carbonate production in the shallow pools and lagoons of the reef platform, and
- by their construction of the rhodolith banks and terraces around the perimeter of the reef that create the lagoonal habitat where the bulk of the carbonate production takes place (by rhodoliths and corals).

The vast area (c. 350 km^2) of shallow, sheltered, sunlit, lagoon and pools of the Montgomery Reef platform represents a very significant extent of Benthic Primary Production Habitat. High primary production in the impounded lagoons may be the explanation of the abundance of herbivorous macrofauna, notably green turtles and dugong, for which this area is renowned. If this is true, the rhodolith banks may be responsible for it.

Age of the islands

In the mainland area adjacent to Montgomery Reef, the second youngest unit in the Kimberley Group series is the Pentecost Sandstone and it is underlain by the Elgee Siltstone. Both these units are older than 1790±4 Ma, based on zircon dating of the intrusive Hart Dolerite (Schmidt and Williams 2008). Assuming that the quartz sandstone of Wuljarli and the Egret Islands and atop the High Cliffy Islands is correctly mapped as Pentecost Sandstone, the rocks of those islands are Paleoproterozoic and around 1.8 billion years old.

Identity and age of the High Cliffy stromatolites

Commonly, along the eastern shores of the High Cliffy Islands, the top of the dolomite bed is exposed as a supratidal bench around 12–14 m above low tide level. In those situations the stromatolites are exposed on the surface as well preserved dome-shaped bosses, up to 1 m in diameter (Fig. 6). On worn, flat surfaces, they appear as finely laminated concentric rings. Where the stromatolites are exposed in section on cliff faces, they appear as cone-shaped structures with irregular, drooping layers at the top (Fig. 7). At one location a cluster of massive stromatolites was observed comprising rounded turrets standing up to 30 cm high, and occupying an area of around 20 m^2 (Fig. 7).

The High Cliffy stromatolites were first reported by Mr Kevin Coates who took specimens to Dr Kathleen Grey of the Western Australian Geological Survey in the late 1980s. Dr Grey identified them as a previously unknown form of conical stromatolites belonging to the Group (morpho-genus) *Conophyton.* She has confirmed that specimens collected by the WAMSI party in September 2009 are of the same kind (Grey *pers. com.)*. These stromatolites are unlike any Form (morpho-species) known from the Kimberley area. *Conophyton* usually indicates quiet water conditions, below the wave base and the High Cliffy examples represent a biohermic construction in the Kimberley Basin very early in the history of life on this planet.

At the time of this report, the High Cliffy stromatolites remain undescribed and their stratigraphic interpretation is uncertain. The Group *Conophyton* is common throughout the Proterozoic. It ranges into the Cambrian and there are modern analogues, so the age of the succession cannot be determined until the taxon can be identified to Form level although stratigraphically a Paleoproterozoic age is indicated.

In regard to the age and stratigraphic relationships of the stromatolitic dolomite, and noting that on the High Cliffy Islands it underlies the quartz sandstone mapped as Pentecost Sandstone, Dr Grey (*pers. com.*) suggested three possible interpretations:

- It is a hitherto unknown carbonate unit within the Pentecost Sandstone.
- It is a previously unrecognized facies within the older Elgee Siltstone.

- The stromatolite unit and overlying sandstone of the High Cliffy Islands are not part of the Kimberley Group, but are either a younger or older sedimentary package that has not yet been recognized elsewhere in the Kimberley.

Age of the rocks of Montgomery Reef platform

If the dolomite stacks of the lower platform at the eastern end of the main Montgomery Reef are correctly correlated with the stromatolitic dolomite of the High Cliffy Islands, it may be assumed that the rock of the lower platform in that area is also of Paleoproterozoic age. The age of the rocks of the upper platform remains conjectural. Because they are higher than the dolomite of the lower platform it is possible that they are Pentecost Sandstone, like the Wuljarli and Egret Islands.

The age of the contemporary biogenic limestone that veneers the Proterozoic rocks of the reef platform surface is certainly Holocene. It is possible that there is Pleistocene coralline limestone beneath the Holocene veneer but no surface exposure of it was seen on Montgomery Reef (or anywhere else in the Kimberley north of Cape Leveque). There is evidence of ongoing subsidence of the continental margin in the Kimberley (Gregory 1913; Teichert and Fairbridge 1948; Fairbridge 1953; Carrigy and Fairbridge 1964; Jongsma 1970; Sandiford 2007) in which case Pleistocene reef limestone, if it exists, is likely to be at some depth below the Montgomery Reef platform surface.

Age and formation of the reef platform

While the base rocks of the Montgomery Reef structure are probably of early Proterozoic age, the means and the time at which the flat reef platform was created are conjectural. There are several possibilities.

1. A wave-cut rock platform

Edwards (1958) described wave-cut rock platforms around the shores of islands in the Buccaneer Archipelago and the mainland of the Yampi Peninsula. He noted that such rock platforms are best developed where the shore rocks are quartz-feldspar porphyry or schists that weather easily and poorly developed where the rocks are quartzites. The rock exposures of the islands of Montgomery Reef are all hard quartzites or silicified dolomite and there are no wave-cut rock platforms around their shores. It is improbable that the intertidal platform of Montgomery Reef could be an erosional surface created by wave action and chemical erosion during the Holocene.

2. A Quaternary coral reef platform built on and around a Proterozoic rock core.

Such a process would require extremely rapid reef growth to create a platform reef as large as Montgomery. It could be possible if there were a pre-existing Late Pleistocene reef (as at Ningaloo Reef) upon which Holocene reef growth occurred. However, the evidence of subsidence in the region suggests that this is unlikely. Also, if there were rapid contemporary reef growth, vigorous reef-front and fore-reef coral communities would be expected. This does not appear to be the case. Those habitats are poorly populated by corals and there is no evidence of lateral reef growth. Upward growth on the reef platform would level and raise the surface but would not create a reef platform on the scale of Montgomery Reef without there being lateral growth as well.

3. A pre-existing flat terrestrial erosional surface

Prior to the post-Last Glacial Maxima transgression, the Montgomery structure would have stood as a mountain on a plain many kilometres from the coast. The rocks of which it is built are probably upper units of the Kimberley Group. In this regard, Montgomery Reef is like the fringing reefs of the Kimberley Bioregion where Holocene biogenic growth appears to be built directly on Proterozoic rocks of the Kimberley Group, except that at Montgomery there is no evidence of a Holocene biogenic limestone wedge at the reef-front.

We suggest that, prior to the Last Glacial Maxima, the Montgomery structure was a flat-topped terrestrial mesa. There are analogues of such structures, of that age and of similar height and area, further inland in the Kimberley Basin in a similar position in relation to the boundary between the basin and the King Leopold Orogen (*e.g.* Mount House, Mount Clifton). The primary geomorphic features of Montgomery Reef today are the same as those of the inland mesas – flat top, vertical walls, peripheral canyon-like incisions. By this interpretation, the main geomorphic features of Montgomery Reef, including its flat top, have been inherited from its long history of terrestrial erosion.

Conversion of the terrestrial Montgomery mesa to a marine platform reef would have occurred in the Holocene with the advent of the post-Last Glacial Maxima transgression. Mean Sea Level rose to just above the flat top of what was previously the mesa, placing it within the intertidal zone of a macro-tidal shore, open to colonization by intertidal marine organisms. Geomorphic features of the reef surface today (central mud islands, sand sheets, lagoons and rhodolith banks) are results of contemporary marine coral and algal reef-building processes superimposed on pre-existing terrestrial features, perhaps further leveling the intertidal platform surface by means of biogenic growth and sedimentation.

Conclusions

Montgomery Reef is not a coral platform reef in the strict sense. It is a coral reef in the ecological sense of having diverse coral growth in the lagoons and pools of the intertidal platform but its geomorphic form is atypical. There is no evidence of lateral reef growth and it does not have a biogenic limestone framework. Rather, the evidence suggests that it is an inundated terrestrial structure, built of Paleoproterozoic metasedimentary rocks, with a Holocene veneer of biogenic limestone and sediment on its intertidal platform surface. The thickness of the Holocene veneer is unknown but is probably not great. A drilling program on the reef flat would be required to confirm this interpretation.

The reef has inherited its primary geomorphic features, including its level platform, from its terrestrial erosional history. Contemporary geomorphic processes on the reef platform are constructional and involve production and distribution of modern biogenic sediments. Extreme macro-tidal conditions and wind-driven waves are the dominant forces involved and the formation of vast mobile banks of rhodoliths that impound shallow lagoons is the key factor that creates the highly unusual intertidal habitats of the reef platform.

Acknowledgements*:* Information and comments provided by Andrew Heyward (AIMS) and Clay Bryce (W.A. Museum) are gratefully acknowledged. TO Isobel Peters and guide, Roy Wiggan, contributed vital local knowledge and guidance. From data produced by the *School of the Environment, Airborne Research Australia, Flinders University, Adelaide,* Curtin University produced extremely detailed aerial photographs and hyperspectral images of the reef, some of which are reproduced here. The skills and good company of skipper Andy Passmore and crew of the Fisheries vessel P.V. *Walcott* are also greatly appreciated. Field work was supported by the Western Australian Marine Science Institution.

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