Reconnaissance of species-rich coral reefs in a muddy, macro-tidal, enclosed embayment, – Talbot Bay, Kimberley, Western Australia

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Abstract

Preliminary observations are presented on species-rich coral reefs in a mud-dominated, macro-tidal, virtually landlocked embayment on the Yampi Peninsula. The reef platforms stand 6–7 m above water level at extreme low spring tide. High lagoons on the top of the platforms, impounded by crustose algal terraces and banks of rhodoliths, provide habitat for a moderately diverse assemblage of scleractinian corals with up to 30% live cover. Reef flats in the lower-littoral zone around the periphery of the fringing reef platforms, and on small patch reefs scattered throughout the bay, support species-rich coral assemblages with live coral cover up to 90% even though heavily affected by mud. There is dynamic interaction between coral reef growth and the development of massive mud banks in the bay. Drilling will be required to determine the geological origins, age and composition of these massive reef structures. If they are entirely of Holocene construction they would represent a remarkably high rate of coral reef growth in such a mud-dominated environment.

Keywords: Kimberley, Talbot Bay, coral reef, reef origin, reef profiles, macrotidal, mud-dominated

Introduction

Although their presence has been known to science for almost two hundred years, the extent and species-richness of coral reefs in the Kimberley Bioregion (Cape Londonderry to Cape Leveque) of Western Australia has been revealed only during the last few decades. Little of the information now available has been published in the scientific literature.

This report presents preliminary observations on some remarkable reefs within Talbot Bay, an almost enclosed, macro-tidal, mud-dominated gulf on the northern side of the Yampi Peninsula. This part of the Kimberley is a ria coast with maximum tidal range round eleven metres and is characterised by extreme tidal fluxes and turbid water. Well developed coral reef structures occur in association with extensive intertidal and subtidal mud deposits and mangrove forests, in an environment typical of northern Australian macrotidal estuaries. Observations on these reefs are reported from a brief visit to Talbot Bay by staff and associates of the Western Australian Marine Science Institution (WAMSI) in September 2010, aboard the charter vessel *Olivia J.*

The purpose of the report is to draw attention to these remarkable reef structures and the equally remarkable biogenic activities that prevail there. These preliminary observations suggest that future detailed studies of these reef systems are likely to reveal highly unusual reef-building processes and dynamic interactions between mud deposition and coral reef development that are perhaps without parallels elsewhere on the Australian coast.

Methods

Intertidal studies

At low tide, landings were made at reef sites selected using available Landsat 7 satellite imagery. Field activity was focussed primarily on a prominent reef structure known as Turtle Reef, which borders the rocky Molema Island, near the centre of Talbot Bay (Figs 1 and 2). The tidal range during the period of study is shown in Figure 3.

Reef elevation profiles, structure and biotic assemblages were recorded along line transects photographically (using a digital camera) at 1 m intervals. Six transects were completed, three on Turtle Reef South, one on Turtle Reef North, one on the south-western side of Mangrove Island, and one on a small patch reef in the channel off the NW corner of Molema Island (Fig. 4). Coordinates of these sites and basic transect data with summary descriptions are given in Appendix 1.

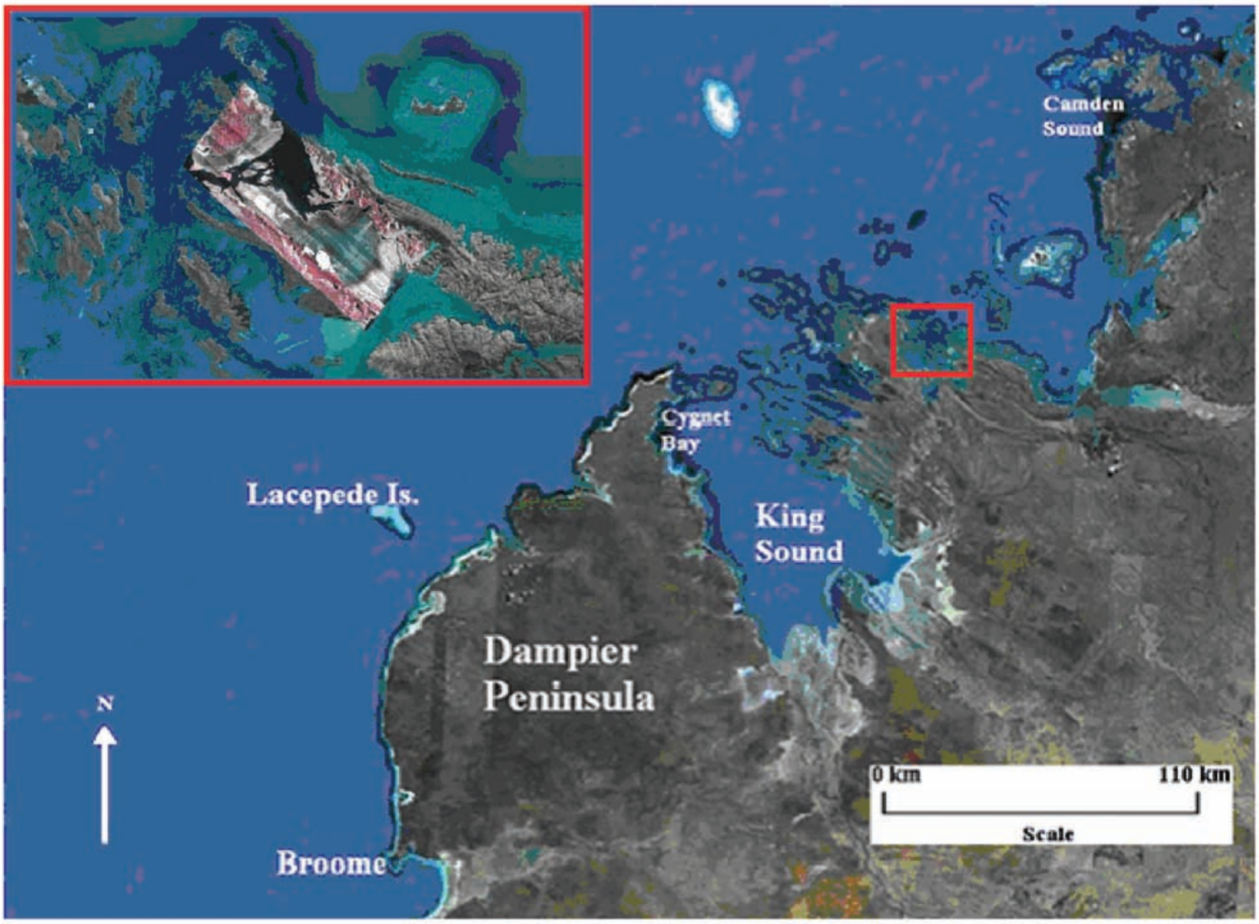


Figure 1. Location of Turtle Reef, Talbot Bay, Kimberley coast, WA. Inset: Airborne tri-colour mosaiced image of Turtle Reef. Most of the islands within the bay are un-named (but may have un-recorded indigenous names). The inset image gives an overview of the entire area surrounding Turtle Reef [Images: courtesy Google Earth and inset: Airborne Research Australia].

Figure 2. Low-tide aerial oblique view of South Turtle Reef, looking west. Molema Island is almost out of view on the right side. Note the massive mud bank in the foreground that overlaps the eastern margin of the reef platform [Photo: courtesy Kimberley Media and WAMSI].

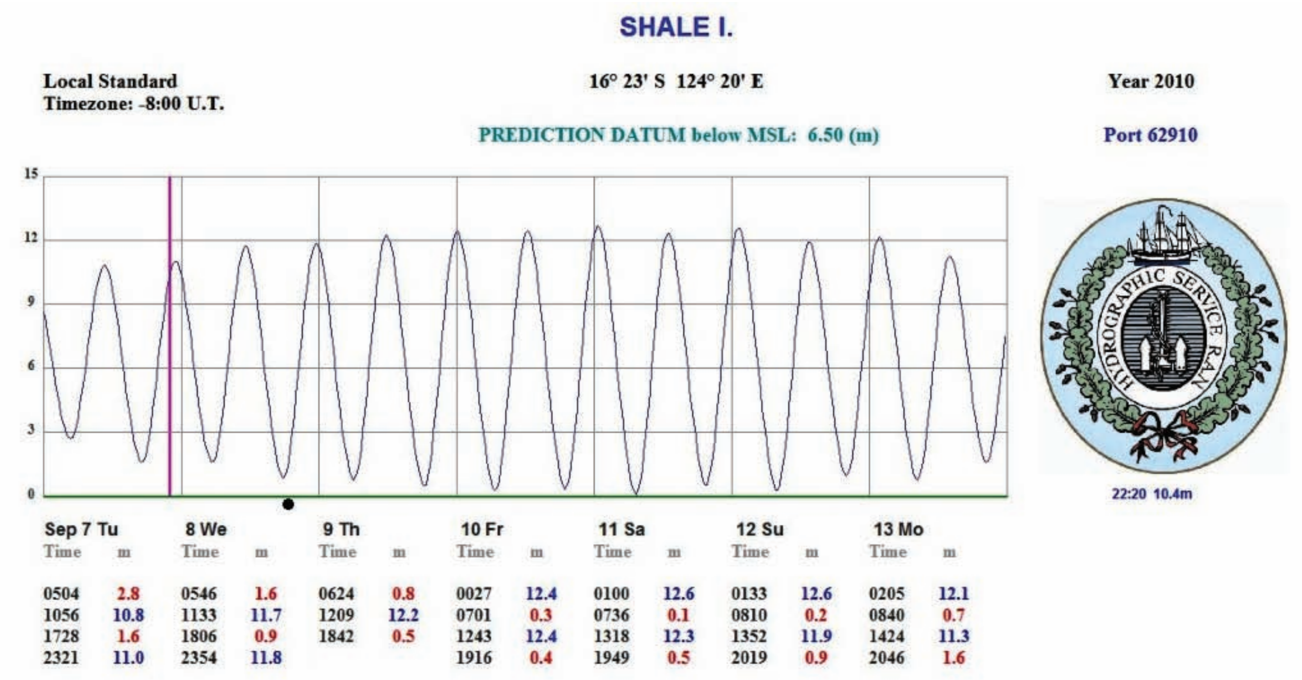


Figure 3. Hydrographic Service tide chart (Shale Island) for the period 7–13 September, 2010, the period of the Talbot Bay survey [Image: courtesy Australian Hydrographic Services, Royal Australian Navy].

Figure 4. Western end of Molema Island, looking south, at extreme low tide showing a large mud bank adjacent to the edge of a fringing coral reef. South Turtle Reef top left. Note the three small patch reefs in the channel, centre right (site of Transect 6). Site of Stuart photographs in the top right corner [Photo: courtesy Airborne Research Australia].

Aerial photographic and multi-spectral survey

We undertook hyperspectral airborne imaging of Turtle Reef and surrounding islands on a large spring tide [0.2 m] on 12 September 2010 at 0810. Coincidently, we also took LIDAR, Tri-colour scanner and high resolution digital photographs of the study area. These data provide a high resolution digital base map that can be further interrogated for detailed spectral information and, in the case of LIDAR, vertical height data to 15 cm accuracies.

Ground truthing was undertaken with the aircraft being directly overhead, to allow for end-member determination via a spectral library and the associated atmospheric correction. Contoured images, derived from the LIDAR data, are presented for two of the survey transects to give a first impression of the relative altitude of the reef platform.

A brief history of coral reef science in the Kimberley

In the narrative of his Kimberley surveys aboard the hydrographic survey vessels *Mermaid* and *Bathurst*, British hydrographer Philip Parker King made mention several times of corals and coral reefs (King 1827). He published a list of 20 species of corals in his Appendix B, three of which he collected at low tide on a reef at the Midway Islands near the entrance to Munster Water. Many biological samples collected by King and his crew found their way into the collections of the Natural History Museum in London but whether his corals were among them is unknown. If they still exist these specimens have considerable heritage significance as they may have been the first corals collected for scientific purposes in Australian waters.

John Stokes (1846) also noted the presence of coral reefs on the Kimberley coast in his narrative of the subsequent survey of the region by the *Beagle*. He had been asked by his friend Charles Darwin (they had been shipmates on the earlier *Beagle* voyage) to look for evidence of reef development and subsidence (Stokes 1846) but, unfortunately, he did not make any observations of that kind in the Kimberley (although he did in Queensland).

Coral collections were made by Bassett-Smith from Holothuria Bank, Baudin Island, Troughton Island in the north Kimberley and at Baleine Bank off Broome during the third Admiralty survey to the Kimberley aboard the *Penguin* in 1890 (Bassett-Smith 1899). English fisheries biologist W. Saville-Kent collected corals at the Lacepede Islands, King Sound and Roebuck Bay in 1894. The *Penguin* and Saville-Kent coral collections are preserved in the Natural History Museum (London) and were used extensively in subsequent taxonomic research.

E.J. Stuart (1923) reporting on findings of an exploratory expedition on the West Kimberley coast, published photographs of fringing reefs in Dugong Bay (an inner inlet of Talbot Bay). One of the Stuart photographs is reproduced here, scanned from the publication (Fig. 5).

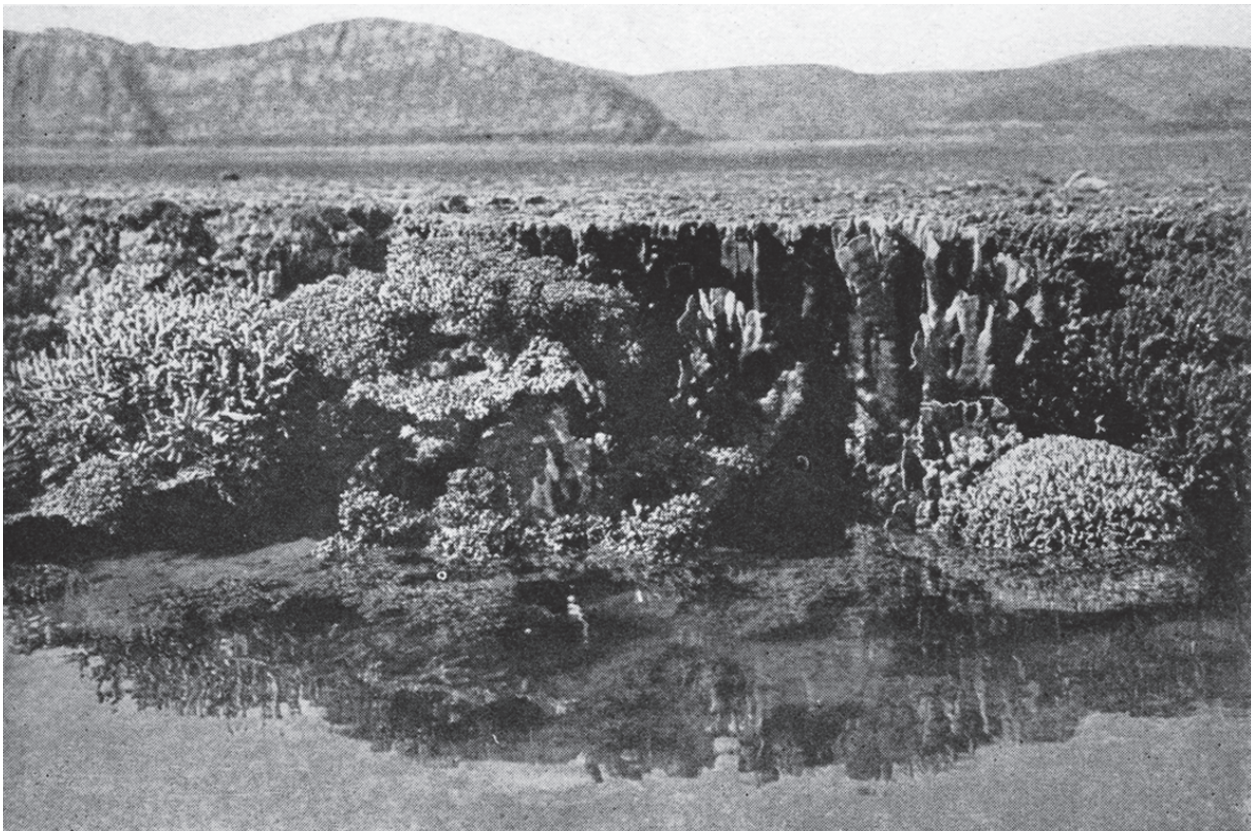


Figure 5. One of two photographs published by Stuart (1923) taken in 1917 at the reef edge at a site "*west of the entrance to Dugong Bay*". Stuart wrote that dynamite was used to blow away the outer wall to drain the water and allow this picture to be taken. [Scanned from the original publication, Stuart (1923)]

University of Western Australia geologists Curt Teichert and Rhodes Fairbridge (1948), working from military aerial photographs, described in detail the geomorphology of a large platform reef surrounding Adele Island. They also noted “ordinary fringing reefs … in great profusion around most of the offshore islands and on many parts of the mainland coast”. Following that work, Wilson (1972) distinguished between the shelf-edge atolls, offshore banks and platform reefs of the Sahul Shelf and the fringing reefs of the Kimberley coast as separate coral reef provinces.

A report on Western Australian corals by Veron & Marsh (1988) included an account of Kimberley corals, based mainly on literature references and collections made by staff of the Western Australian Museum. Coral species collected during later surveys of Kimberley coast were listed in unpublished W.A. Museum reports (Marsh, 1992; Blakeway, 1997). Those reports included the first descriptive accounts of the structure of fringing reefs of the region (Blakeway, 1997; Brooke, 1995, 1996, 1997). Subsequently, Dr Veron has provided preliminary data on the corals of the Kimberley coast in an on-line spatial database, *Coral Geographic*, dealing with the coral faunas of the world’s “coral bioregions”.

There is detailed information, most of it not yet in the public domain, on some of the extensive fringing reefs in the Bonaparte Archipelago, resulting from environmental assessment work in that area during the period 2006–2007 (RPS, unpublished reports to INPEX). That work included an intensive collecting program to document the coral fauna of the region. One paper on spawning of corals in the archipelago, resulting from those surveys, is in press (Rosser and Baird *Proceedings of the 11th International Coral Reef Symposium*, Ft. Lauderdale, Florida, 7–11 July 2008, Session number 11).

Regional geology and coastal geomorphology

The Yampi Peninsula is the intensely folded western end of the King Leopold Orogen (Yampi Fold Belt) a complex band of Proterozoic metamorphic and igneous rocks bordering the south-western side of the Kimberley Basin. Its elongate valleys were inundated by the last post-glacial transgression to form the rocky ria coast of the area and the adjacent islands of the Buccaneer Archipelago. Details of the geology of the Yampi Peninsula may be found in the maps and explanatory notes of the Bureau of Mineral Resources Yampi map sheet (Tyler & Griffin 1993).

The coastal geology of the peninsula is dominated by the Palaeoproterozoic metasediments and igneous intrusive rocks of the Kimberley Group. The geology of Talbot Bay, located on the northern side of the peninsula, is complex. The rocks of its shore-line comprise intensely deformed and highly resistant quartz sandstones of the Pentecost, Warton and King Leopold Sandstones, Elgee Siltstone and the Yampi Formation, with minor exposures of the tuffaceous Carson Volcanics.

Throughout the Kimberley Bioregion, there is no evidence of marine Pleistocene rocks or erosional notches on shore (Brooke 1995). Coral reefs appear to comprise upward growing coral and algal sequences, suggesting a significant thickness of Holocene limestone overlaying an unknown foundation and ultimately supported by a Palaeoproterozoic basement. The lack of exposure of Pleistocene reefs in the Kimberley Bioregion may be explained as a result of Late Quaternary subsidence. There is evidence that the northern part of the North West Shelf of Australia has undergone prolonged, tilted subsidence. Teichert & Fairbridge (1948) illustrated this notion with a diagram showing the modern inclined shelf, the shelf-edge atolls and outer shelf platform reefs as carbonate bioherms of considerable antiquity and depth, and the inner shelf platform and fringing reefs as shallow Quaternary carbonate deposits over the Proterozoic basement. Sandiford (2007) suggested that the northern continental margin has tilted and subsided since the late Neogene at significant rates. The combined effects of ongoing subsidence and sea level change during the Quaternary would have enhanced the development and growth of fringing reefs in the Kimberley through providing ‘accommodation space’ for upward growth.

Coral reefs of Talbot Bay

Coral reefs within the landlocked inlets of Talbot Bay were first noted by the veterinarian E.J. Stuart in 1923, however his descriptions and photographs remained un-reported by reef scientists until now. Indeed, due to the extreme macro-tidal and turbid water conditions of this environment, the presence of significant and flourishing accumulations of coral framework would appear to contradict established models for coral reef formation. The geomorphology of these reefs appears to be unique. Turtle Reef alone is over 25 km^2 in area, comprising a high carbonate platform in the middle-upper littoral zone (Figs 1 and 2) representing very large depositions of material that require an explanation.

The shores of Talbot Bay are predominantly rocky, steep and cliffed (Fig. 4) and the high relief of the landforms are matched by extremely complex subtidal bathymetry in bays and passages, with depths changing abruptly from shoals to channels that are over 30 m deep in places. Navigation is hazardous. At high tide the shoals and reefs are invisible because of the turbid water. The complex bathymetry and extreme tidal range result in exceedingly strong tidal currents, local shears and whirlpools, particularly during spring tides. The shoals include scoured rock reefs, coral reefs, sandbanks and mudbanks. There are several small freshwater streams that seasonally drain into the bay, but overall fluvial input is negligible. Sandy beaches are lacking. Most of the bays are lined with mudflats and a mangrove fringe, with several extensive mangal environments developed on mudbanks, the largest (Mangrove Island) supporting some 2.5 km^2 of mangroves.

Fringing coral reefs are prolific around the islands and peninsulas through the centre of Talbot Bay from the mouth of the inner Dugong Bay to the cluster of islands and banks (called the Mangrove Islands by our party) that lie across the main entrance from the open sea. There are also numerous and very dangerous small patch reefs scattered throughout the bay that emerge at low spring tide.

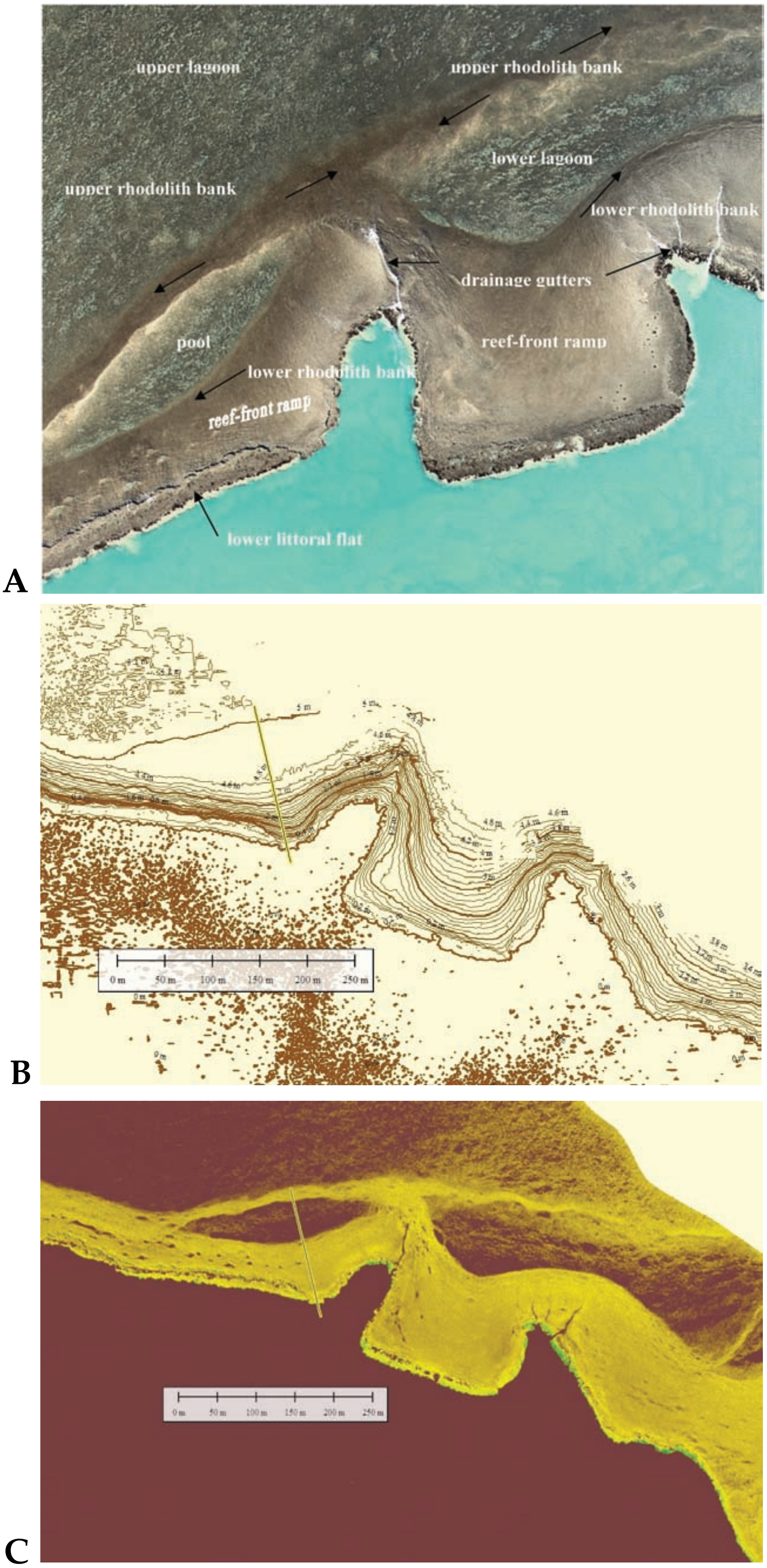


Figure 6. Transect 1, southern margin of South Turtle Reef. A) High resolution digital photograph of the lower portion of the transect from the lagoon, across a double rhodolith bank with a shallow pool between, the reef-front ramp and a narrow lower-littoral flat at the water's edge. Note small drainage gutters across the ramp and the narrow lower-littoral flat, just a few metres wide, at its base. B) Contour map of the same area derived from LIDAR data. C) NDVI image of the same area showing areas of intense photosynthetic activity. [Images: courtesy Airborne Research Australia].

The 1917 site of Stuart

In his narrative of the 1917 Kimberley expedition, Stuart (1923) described and photographed a coral reef, rich in coral species and other marine life, west of the entrance to Dugong Bay. On the mainland shore at this location there is a high, north-facing hill of Pentecost Sandstone and several small rock islands nearshore, with a wide, intertidal rock platform extending north-east along the shore for some distance.

On September 13, 2010 a landing was made by our party on the rock platform (co-ordinates 16°17.801'S; 123°50.293'E). From the profile of the mainland skyline to the south (Fig. 5) this was judged to be close to the site where the Stuart photographs were taken of the coral-rich reef edge (Fig. 3). At the time this reef was inspected by the WAMSI party the tide was half way in. The exposed platform surface, judged to be in the mid-littoral zone, was hard pavement with a cover of crustose algae and a sparse algal turf. Only a few small coral colonies were present. The reef edge was not visible but soundings indicated an abrupt step to a subtidal terrace and then another abrupt step to the seabed at around 30 m (below MSL). For historical reasons a repeat visit to this location would be worthwhile, during a period of low spring tide when the reef edge could be inspected and compared with Stuart's photographs.

Turtle Reef (Figures 1, 2, 4, 6 and 7)

For working purposes the survey team referred to the platform north of Molema Island as North Turtle Reef and the platform south of it as South Turtle Reef, although the two platforms are not connected. From the LIDAR data contour maps, contour maps and pictorial images have been prepared for the areas of the reef surrounding Transects 1 and 3 on South Turtle Reef (Figs 6 and 7). Summaries of observations made along the transects are given in the Appendix. The following are general notes on our field observations.

Reef structure

There were no exposures of the basement rock of the reef, the entire surface being covered by recent carbonates, comprising extensive rhodoliths, corals, sand, rubble or mud. Given the horizontal nature of the coral platforms which abut the steeply dipping Proterozoic rocks along the sides of the adjacent islands, it is assumed that basal layer is flat-lying and has a sedimentary origin but its nature and age are unknown. The several possibilities are discussed below.

Reef form

North and South Turtle Reefs are very large, high, platforms on either side of Molema Island, connecting that island on its northern side with the outer peninsula (Fig., 4) and on its southern side with smaller un-named islands about in the centre of Talbot Bay (Fig., 1). The total area of the reef platform is estimated at over 25 km^2.

The platform top appears more or less level, perhaps slightly undulating and a little higher on the southern side, and positioned close to the middle/upper-littoral boundary. On South Turtle Reef the heights of the reef crests were measured (from the LIDAR data) as 4.3 m at Transect 3 and 5 m at Transect 1. The height of the platform overall, with its shallow lagoon, is estimated to be about 4.5 m above Spring Low Tide level.

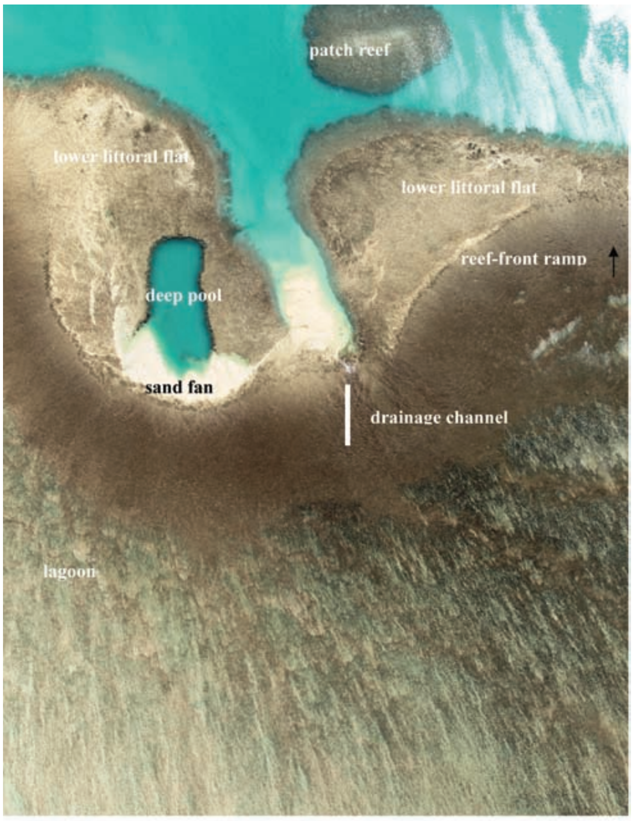
The outer perimeter of the platform is defined by a steep, convex ramp with a succession of small terraces constructed by crustose algae (Fig. 8). The ramp slope varies from about 25° (*e.g.*, at Transect 3) to about 10° (*e.g.*, at Transect 2). It lacks significant coral growth except for a few small prostrate, mainly faviid colonies (< cm diam.). Our survey party was not equipped to investigate the depth of the algal crust but it seemed to be superficial.

Around the reef perimeter there are low areas in the ramp functioning as drainage channels. Some of these are wide with violent cascades of water run down them off the impounded lagoon of the platform above (Fig. 8). Others are minor rivulets or narrow gutters incised into the ramp surface (*e.g.*, at Transect 1; Fig. 6A). There are usually fans of sand and rubble deposits along the base of the ramp, especially where minor drainage channels spill onto the lower terraces (Fig. 7A).

The top of the ramp is defined around much of the reef perimeter by one or more crustose algal ridges and sometimes bands of rhodoliths that impound the water on the reef platform. This is interpreted as the equivalent of the reef crest of most fringing reefs but is atypical – it is very high in the intertidal profile and there is no boulder zone. At some locations, for example on the north-eastern margin of North Turtle Reef the rhodolith bands along the crest are configured into inter-lacing patterns enclosing networks of small lenticular pools (Fig. 9). It appears that the rhodoliths are mobile and that their arrangement probably changes constantly with flux of the tide. At some locations (*e.g.*, Transect 1) the reef crest is divided into two prominent rhodolith banks with a shallow pool between them (Figures. 6A and 6C). In these regards the Turtle Reefs are very like Montgomery Reef.

Around the margin of most of the reef, at the base of the ramp there are low flats at around the zero tide level. They are between five and fifty metres wide and exposed only briefly at extreme low tide. Along the southern margin of South Turtle Reef the low terrace is only a few metres wide in most places (*e.g.*, Transect 1, Fig. 6Aa). On the northern margins of South and North Turtle Reefs, the lower littoral flats were usually much wider and represent a lower littoral reef flat (*e.g.*, at Transect 3, Fig. 7A). At both transects, there is a small but distinct erosional escarpment at the base of the ramp, 10 to 30 cm high, marking the edge of the lower flat. Coral growth is prolific in this lower zone wherever this structure is present, clearly resulting in outward growth of the reef, and it is interpreted as the equivalent of the coral-rich reef-front of most fringing reefs. The fore-reef below the lower terraces is very steeply inclined or vertical and soundings of more than 30 m were taken close to the reef at many locations.

There are deep holes (> 5 m) in the lower terraces at several locations (*e.g.*, at Transect 3, Fig. 7A) with very rich coral growth around their edges and vertical walls. The site of the Stuart photographs near Dugong Bay was probably a structure of this kind. (He described blowing out the wall with dynamite to drain out the water so that the corals were suitably exposed for his purpose!). These deep holes are assumed to be the outcome of coral



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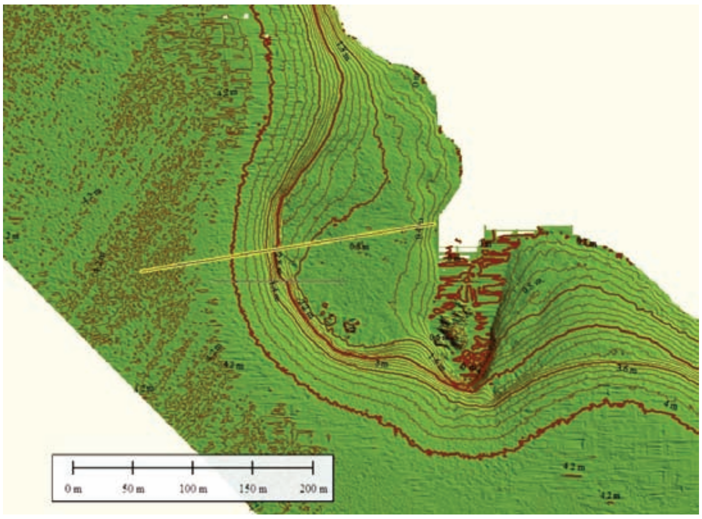

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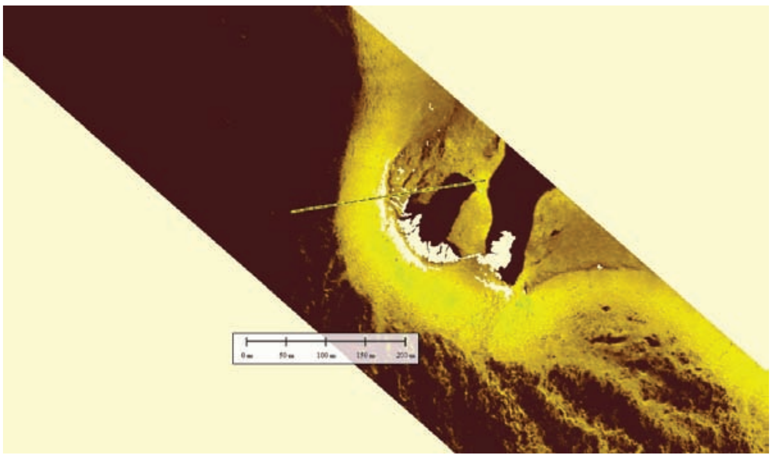

Figure 7. Transect 3, northern margin of South Turtle Reef. A) High resolution digital photograph of the lower portion of the transect from the lagoon and across the reef-front ramp and a wide lower-littoral flat at the water's edge. B) Contour map of the same area derived from LIDAR data. C) NDVI image of the same area showing areas of intense photosynthetic activity. [Images: courtesy Airborne Research Australia].

Figure 8. Western end of South Turtle Reef. One of many low-tide waterfall cascades down the ramp [Photo: S Blake, WAMSI].

Figure 9. Eastern side of North Turtle Reef, looking north across the peninsula to the open sea. Showing rhodolith banks enclosing lenticular pools behind the ramp, abutting a mudbank [Photo: courtesy Airborne Research Australia].

Figure 10. Mud bank on-lapping the eastern margin of South Turtle Reef (see aerial view of the same place at Figure 2). [Photo: S Blake, WAMSI].

Figure 11. *Porites* micro-atolls in-filling pools on the high reef platform, close to Transect 3, South Turtle Reef. [Photo: S Blake, WAMSI].

growth across drainage channels or embayments in the reef margin. In Figure 7A at Transect 3 there is a deep hole alongside a deep drainage channel and is easy to imagine that the hole was an earlier drainage channel now enclosed by coral growth.

On the eastern side of the Turtle Reefs, both North and South, there are huge mud banks which overlay the edge of the reef (Figs 2 and 10). The mud is very soft and it was impossible to walk on it without sinking down to the waist. At the sharply demarcated margin of mud and reef there is evidence of the former overlapping the latter but it is not clear whether it is advancing or retreating. The interaction between these two major ecosystems is clearly dynamic.

Biotic assemblages

On top of the platform, the shallow impounded lagoon is divided into a mosaic of pools, around 20–30 cm deep at low tide, separated by ridges of sand, coral rubble and rhodoliths. There are seagrasses (*Thalassia hemprichii)* in the sand, tufted *Sargassum* and other leafy algae on coral stones and rubble, patches of rhodoliths and a variety of scleractinian corals. Live coral cover may be as high as 30%. The corals are moderately diverse with mainly small colonies of *Acropora, Merulina, Galaxia, Seriotopora, Pocillopora, Fungia,* a lobate *Porites* and a variety of faviids and mussids. Rubble and sand derived from these corals and the rhodoliths is clearly in-filling the pools. In some places these sediments and *in situ* coral skeletons have consolidated and formed a new rock platform surface. In such places *Porites* micro-atolls grow and are an important part of the in-fill process (Fig. 11). There are also some sandy cays on the platform, inhabited by burrowing crabs and molluscs that are characteristic of the upper-littoral zone.

The steep outer ramp has very few corals – live coral cover being less than 2%. The coral colonies present, mostly faviids, are invariably small and prostrate. Crustose and turf algae dominate the pavement of this zone. However, the lower reef flats at the base of the ramp are rich in corals with live coral cover as high as 90% (Figs 12 and 13). Several kinds of fleshy sponge are common among the corals of the lower flat. *Tridacna squamosa* is also common there. Other molluscs and invertebrates are rare. The corals in this lower-littoral zone are smothered, to greater or lesser extent, by mud but flourish none-the-less. Coral species diversity in this zone is high. A collection made from several localities has not yet been identified but was estimated to include at least sixty species. Massive faviids and mussids are most common but there is usually a narrow band of *Acropora* along the reef edge (Fig. 13). The fore-reef below the reef edge slopes steeply into the subtidal zone and, from what could be seen of it, is rich in foliose and other corals. Sea whips and sponges also feature strongly in the subtidal zone.

Nearby patch reefs in Talbot Bay

Landings were made on several small patch reefs:

- south of Mangrove Island (Transect 4);
- in the channel of the NW corner of Molema Island (Transect 6);
- in the channel SE of South Turtle Reef.

Figure 12. Edge of a small patch reef south of Mangrove Islands (Molema Island in the background) at extreme low tide showing a species-rich coral assemblage, mainly massive faviids and mussids with an *Acropora* sp. fringe [Photo: S Blake, WAMSI].

Figure 13. Edge of a narrow fringing reef on a small island bordering the main navigation channel southwest of Molema Island at extreme low tide showing the *Acropora* sp. fringe [Photo: S Blake, WAMSI].

These reefs are all less than 100 m in diameter, flat and exposed only briefly at extreme low tide. They are all heavily affected with mud but support profuse growth of live corals. The coral assemblages appear to be the same as those on the lower reef-front flats of Turtle Reef with massive faviids and mussids behind a narrow band of *Acropora* at the edge, and rich growth of foliose corals, sea whips and sponges on the vertical, subtidal fore-reef walls. At the centres of the larger of these patch reefs, there are unusual accumulations of *Acropora* and other coral rubble in a mushy mud matrix. Soundings around these reefs found precipitous drop-offs to at least 30 m indicating that the coral growth is atop cliffed pinnacles or ridges, presumed to be high points of submerged terrestrial landforms.

Discussion

The prolific growth and species-richness of coral in these mud-dominated conditions is noteworthy. Further study is needed to identify the species present, to assess their assemblages and compare them with lagoonal and reef-front assemblages of fringing reefs around the islands of the Buccaneer Archipelago in more open sea conditions.

Coral growth at Turtle Reef is prolific in three zones:

- the high, upper-littoral lagoon impounded by algal terraces and rhodolith banks;
- the lower-littoral, reef-front flats (below the ramp) at extreme low tide level;
- the steep to vertical subtidal fore-reef walls.

There is very little coral growth on the reef-front ramp and in this respect Turtle Reef is unlike the fringing reefs of the North Kimberley, but resembles Montgomery Reef. The reef-front ramp is analogous to the 'algal cap' noted on the rim of many platform reefs, however we believe that its thickness on Turtle Reef may be an order of magnitude greater than algal caps observed in meso to microtidal conditions, due to the extreme tidal range in the Kimberley.

Crustose algae and algal rhodoliths play an important role in the construction of terraces and banks at the top of the ramp that impound shallow water over the vast reef platform in the middle/upper-upper littoral zone. Biogenic carbonate production by corals and calcareous algae in the lagoon is active. Corals are the principal producers of carbonate on the lower littoral flats and fore-reef slopes, supplemented by carbonate sediment delivered by water flow from the lagoon, and there is outward reef growth.

There is a dynamic, inter-active relationship within Talbot Bay between the massive mud banks and coral reefs. Both the deposition of mud and the connectivity and recruitment of coral communities, and the complex spatial distribution of these habitats, must be determined by the complexities of tidal currents. As far as these authors are aware, such a situation has never been described and would be a worthy subject for future study.

The high, massive platform with its impounded lagoon and very steep, convex and barren ramp are unusual features. Rather than wave exposure, it appears that a complex interaction between ebb and flood tidal currents is responsible for the reef's large-scale morphology. There are many similarities in these regards to Montgomery Reef. Further survey is needed to determine whether reef structures of this kind are more widely distributed in the Buccaneer Archipelago.

The geology and origins of the Turtle Reef platform (and others in Talbot Bay) remain unknown. Assuming the basal (Pleistocene and older) rock is sedimentary, key questions are what kind of sediment is it, what are its origins and what is its age. The platform might be:

- Of Holocene age, constructed entirely of marine biogenic carbonate. If that were the case, very rapid and voluminous carbonate production would be indicated.
- A pre-existing marine biogenic structure, built prior to the last transgression, with a veneer of modern reef growth. In this case it might be of Pleistocene age and the first example of an onshore Kimberley reef built in that period. Interpretation of these massive reefs in this way would need to take account of Neogene-recent subsidence.
- A pre-existing structure that is not of marine biogenic origin. It could comprise Tertiary to Pleistocene clastic alluvial and colluvial terrestrial sediments deposited in the valley floors between the folded ridges of the peninsular, its surface populated by reef building corals and algae, with marine sedimentary processes following subsidence and inundation by the post-glacial transgression.

This matter can be resolved only by drilling. Whatever the origins and age of the Turtle Reef platform, and of others like it in the vicinity, a carbonate structure of this scale supporting modern biogenic growth in a land-locked, macro-tidal, mud-dominated embayment is a highly unusual if not unique feature of the Kimberley. Both the geology and the contemporary biology of these reefs are worthy of intensive study.

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Appendix – Reef transects

The following field notes were made on site. Photographs taken at 1 m intervals along the transect tapes and voucher specimens of invertebrates are to be lodged with at the Western Australian Museum for future analysis and reference.

Transect 1 – 7 September 2010

South Turtle Reef (south of Molema Island) southern margin of reef (Figs 5a–c)

Start point (0 m): 16°17.667′ S; 123°54.156′ E. (Position on the lower part of the ramp; tide not low enough to see the reef edge.)
Finish point (120 m): 16°17.605′S; 123°54.141′E. (Position in the high lagoon).

Ramp steep, about 10°, with small, irregular ridges of crustose alga, very low algal turf and rhodoliths in shallow pools. Coral diversity and abundance very low; small, prostrate colonies only, mostly faviids. Small *Tridacna maxima* common. Change of slope at 35 m with a bank of rhodoliths about 12 m wide; then a pool (*c.* 30 cm deep) before a second, slightly higher rhodolith bank at 60 m and behind that the shallow lagoon on the top of the platform, estimated at about 5 m above low tide level.

Pool in between the rhodolith banks with abundant rhodoliths, some coarse sand and rubble, abundant fungiids and some other corals, and a few small patches of *Thalassia.*

The upper lagoon 10–50 cm deep, with sand and rubble, patches of *Thalassia* and leafy macro-algae; about 20% live coral cover, mostly faviids but a moderate diversity. Low diversity of associated invertebrate fauna. Gastropods: *Tectus pyramis, Trochus fenestrata, Astralium rotularia, Angaria delphinus, Pseudovertagus aluco, Drupella rugosa; Melo amphora*; bivalves: *Fragum unedo, Tellina staurella*. These are typical of intertidal reef assemblages in the Kimberley Bioregion.

Transect 2 – 8 September 2010

South Turtle Reef (northern side of reef)

Start point (0 m): 16°16.746′S, 123°54.332′E (16:38)
Finish point (60 m): 16°16.777′S, 123°54.337′E

Transect began on a low flat, about 30 m wide, just emergent at low tide, muddy but rich in live corals, with an *Acropora* fringe and diverse massives behind, mainly faviids. Live coral cover estimated at *c.* 80%.

Ramp very steep, *c.* 15°, convex, no distinct crest but "rolls over" a rhodolith bank with the high lagoon behind. Height of the platform estimated at about 4.5 m above water level at low tide. Pavement of ridged crustose algae and very low algal turf; very few corals, all tiny, mainly prostrate faviids and *Porites. Angaria delphinus, Astralium rotularia* the only common molluscs.

Lagoon with rhodoliths and abundant and diverse corals (70–90% live cover) including *Acropora* and branching *Porites* close to the rhodolith bank. Further back with more sand *Thalassia* and leafy algae. Large *Tridacna squamosa* common; *Hippopus hippopus* present also. Few other molluscs.

Transect 3 – 9 September 2010

South Turtle Reef (northern side of the reef. Figures 6a–c)

Start point (0 m): 16°16.675′S, 123°54.064′E
Finish point (180 m): 16°16.697′S, 123°53.927′E

At this site there was a lower-littoral flat between the reef edge and the base of the ramp, approx. 100 m wide, with an elongate deep hole at its centre. The ramp was very steep (around 25° at the base) and convex, without a distinct crest but marked at the top by a rhodolith bank about 30 m wide, containing a shallow lagoon on the upper platform, perched a meter at least above the water level of the channel. The platform above the ramp was estimated to be about 4.5 m above the low tide water level.

The lower flat had live coral cover of about 90% along the reef-front margin, with an *Acropora* fringe and mainly massives behind but with diverse other corals including three species of fungiid and several kinds of sponge. The pavement between the corals was mud and coral rubble. Coral growth around the rim of the deep pool was particularly vigorous, like that of the reef-front, and its sides bore total cover of foliose corals.

There was a low (*c.* 10 cm) sharp-edged escarpment along the base of the ramp, a fan of white sand and a band of rubble and old tridacna shells. The pavement on the ramp was of ridged crustose algae with a sparse, low algal turf. Live coral cover was sparse (< 2%) comprising very small prostrate forms. At the back of the crest the ramp merged into the lagoon. In this zone there was a diverse coral assemblage with about 10% live cover. The lagoon was 20–40 cm deep with a sand/rubble floor and *Thalassia,* tufted leafy macro-algae, rhodoliths and patches of diverse massive and branching corals with live cover estimated at 15–20%. *Tridacna squamosa* was common but there were few *Hippopus hippopus.* No holothurians or other echinoderms were seen. This habitat appeared to cover much of the high platform.

Transect 4 – 10 September, 2010

Southern margin of Mangrove Island.

Three short parallel transects were made across the reef-front.

4 a) Start point (0 m): 16°13.472′S, 123°51.881′E
Finish point (30 m): 16°13.456′S, 123°51.879′E

4 b) Start point (0 m): 16°13.476′S, 123°51.872′E
Finish point (30 m): 16°13.461′S, 123°51.866′E

4 c) Start point (0 m): 16°13.480′S, 123°51.864′E
Finish point (30 m): 16°13.448′S, 123°51.856′E

This is a low reef sloping up to a mud bank in front of the mangrove fringe. The reef-front slope, exposed at extreme low tide, was muddy but carried a diverse coral assemblage with an *Acropora* fringe in front of a 20 m wide band of massive, foliose and encrusting corals. Other invertebrates sparse, the most obvious being a few very large *Tridacna squamosa.*

Transect 5, 12 September, 2010

Western margin of North Turtle Reef, south of large drainage channel.

Start point (0 m): 16°14.467 ′S, 123°54.739 ′E. (Position at reef edge of lower reef flat.)
Finish point (256 m): 16°14.602 ′S, 123°54.721 ′E. (Position in high lagoon.)

The reef edge was just exposed at low tide (0.7 m). Rich growth of foliose corals, sponges, sea whips on the vertical fore-reef wall. Reef-front muddy; est. 20% live coral; no *Acropora* bank but clusters of those species along the margin; Band about 10 m wide along the margin of diverse coral assemblages, mostly faviids and encrusting species – no field of massive domes. About 50 m from the reef edge to the base of the ramp – rear part muddy rubble with *Halophila and Caulerpa* and abundant fungiids – *Cycloseris, Fungia* and (?) *Herpolitha.*

Ramp solid, about 35 m wide, *c.* 10° slope, elevation estimated at about 5 m above the water level at the reef edge; with crustose algal surface and low algal turf; many small ridges forming mini-terraces on the slope. Corals sparse, colonies small and prostrate, < 5% cover, mostly faviids and *Porites*. Only common molluscs *Angaria delphinus* and *Tectus pyramis.*

Ramp levelled out at the crest to a higher flat; some shallow pools with faviids, *Pocillopora, Galaxia;* also *Tridacna squamosa* and *Hippopus hippopus.*

At 165–180 m there was a ridge or second crest with a narrow sand fan along its lower edge; its surface rough, crustose algal pavement with low algal turf and meandering algal terraces, few rhodoliths. Many shallow (*c.* 10 cm) pools, sandy with rubble and leafy macro-algae, some *Thalassia* and *Caulerpa*, grey and green flabellate sponges, some patches of rhodoliths; scleractinian corals sparse. Off the transect line to the east, along the side of a major drainage channel, the pools became cresentic with abundant rhodoliths – presumably the result of strong run-off tidal currents.

At 210–256 m (end of transect) the platform became a flat pavement with low algal turf and dead coral slabs; areas of shallow, sandy pools (< 10 cm) with *Thalassia* (sometimes in patches with 10–30% cover), scattered rhodoliths and sparse corals, mainly small faviids, *Galaxia* and *Porites* micro-atolls; dead coral slabs heavily bored by the lithophagids (*Lithophaga teres* and *Botula fusca)* some higher rocks with rock-oysters, chitons and barnacles indicating a position at the base of the upper-littoral zone. This seemed to be the condition of the reef platform beyond the end of the transect to the south.

Transect 6

Small patch reef in channel, NW end of South Turtle Reef;

Start (0 m): 16°14.886'S, 123°51.948'E
Finish (44 m): 16°14.903'S, 123°51.931'E

This was one of two small patch reefs in the channel; each about 100 m diam.; exposed at 0.7 m tide. Horizontal, entire surface covered with dense coral assemblage, *c.* 80% live coral cover with interspaces of mud and coral rubble. Dense *Acropora* bank around the reef-edge margin at water level; corals atop mainly massive faviid and mussid domes but with diverse other encrusting and foliose species and some soft corals. Very few other invertebrates – one green crinoid and one echinoid (*Phyllacanthus* sp.) seen under coral slabs. No tridacnids seen. A representative collection of corals was made at this site (see also Peter Strain's photographs numbers 1 – 17).