Journal of the Royal Society of Western Australia, 94: 121–132, 2011

Kimberley beach and barrier systems: An overview

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Manuscript received November 2010; accepted January 2011

Abstract

The 4340 km long Kimberley coast is dominated by usually steep rocky shores, which occupy over 80% of the open coast. It also contains extensive areas of mangroves particularly in embayments and 1360 generally sandy beaches, which occupy 713 km (16%) of the more exposed open coast. Because of the high tide ranges (3–11 m) and generally low short waves (H_b = 0.1 m, T = 3–5 sec) most beaches have a relative tide range > 10 and consequently are predominately tide-dominated (71%), with 25% fronted by coral and rock flats, 3% tide-modified and only 1% wave-dominated. Beach location and length is controlled by the geology, with most bounded by rock headlands and backed by rocky slopes and with an average length of only 0.5 km. Only 31% of the beaches are backed by some form of barrier development. In these low regressive barriers dominate with 264 consisting of beach ridges, 35 backed by usually low stable foredunes, while usually minor dune transgression backs only 70 beaches.

Keywords: Kimberley coast, beach, beach types, barriers, dunes

Introduction

The Kimberley coast borders the rugged Kimberley Plateau and extends from the Dampier Peninsula in the west to Cambridge Gulf in the east. It has a predominately rugged, bedrock-dominated highly irregular shoreline that consists of over 4000 km of more open coast, with a total shoreline length of over 13 000 km, much of the shoreline in crenulate sheltered inlets. This paper is concerned with the more open shoreline, which is exposed for the most part to ocean waves together with the meso- to mega-tides of the region. While the coast is bedrock dominated, it is potentially rich in sediments derived from both terrigenous and biological sources. Where suitable these sediments have been deposited in 1360 generally small beach systems (Table 1), with only 32% backed by some form of barrier development, usually low beach ridges and foredunes, with only 70 beaches backed by transgressive dunes. The beach and dune systems provide a different morphology to the bordering rocky terrain and as a consequence a very important habitat for both turtles and crocodiles and for a wide range of flora and fauna.

The Kimberley beaches are a product of the available sediments, the usually low waves, high tides and generally light to moderate winds, all set in a tropical-monsoonal climate. The beaches are physically constrained by the bordering bedrock headlands, islands, islets and reefs, while many are also fronted by fringing coral reefs. As such they represent a suite of beach-barrier systems, with both similarities to other northern Australian tropical beaches, yet distinctive in the controls exerted by both the bedrock, which results in short embayed beaches with lower waves; and the high tides which result in predominately tide-dominated beaches. This paper presents an overview of all 1360 Kimberley beach and barrier systems located between Broome and the Western Australian–Northern Territory border.

Geology and bedrock control

The geology of the Kimberley region is dominated by the Kimberley Basin, bordered to the west by parts of the Canning Basin and King Leopold Orogen, and to the east by the Bonaparte Basin. Beginning in the west, the Canning Basin is characterized by deeply weathered shallow marine sediments, blanketed by longitudinal dunes. It forms the low lying Dampier Peninsula which at the coast is characterised by scarped red bluffs exposing the pindan soil, and low rocky headlands, including the red sandstone cliffs of Cape Leveque. The Canning Basin underlies King Sound and is bordered on the east by a narrow band of heavily folded rocks of the King Leopold Oregon, which forms the rugged terrain between the eastern entrance to King Sound and Walcott Sound and extends west to include the islands of the Buccaneer Archipelago.

Table 1

Northern Australia beach-coast characteristics. Modified from Short 2006b.

	Number beaches	Sandy coast (km)	Total coast (km)	Sandy %	Mean beach length (km)
Kimberley	1360	702	4340	16	0.52
Northern Territory	1488	1902	5029	18	1.28
Cape York	641	1509	2501	60	2.35
Northern Australia	3489	4114	11 869	35	1.17

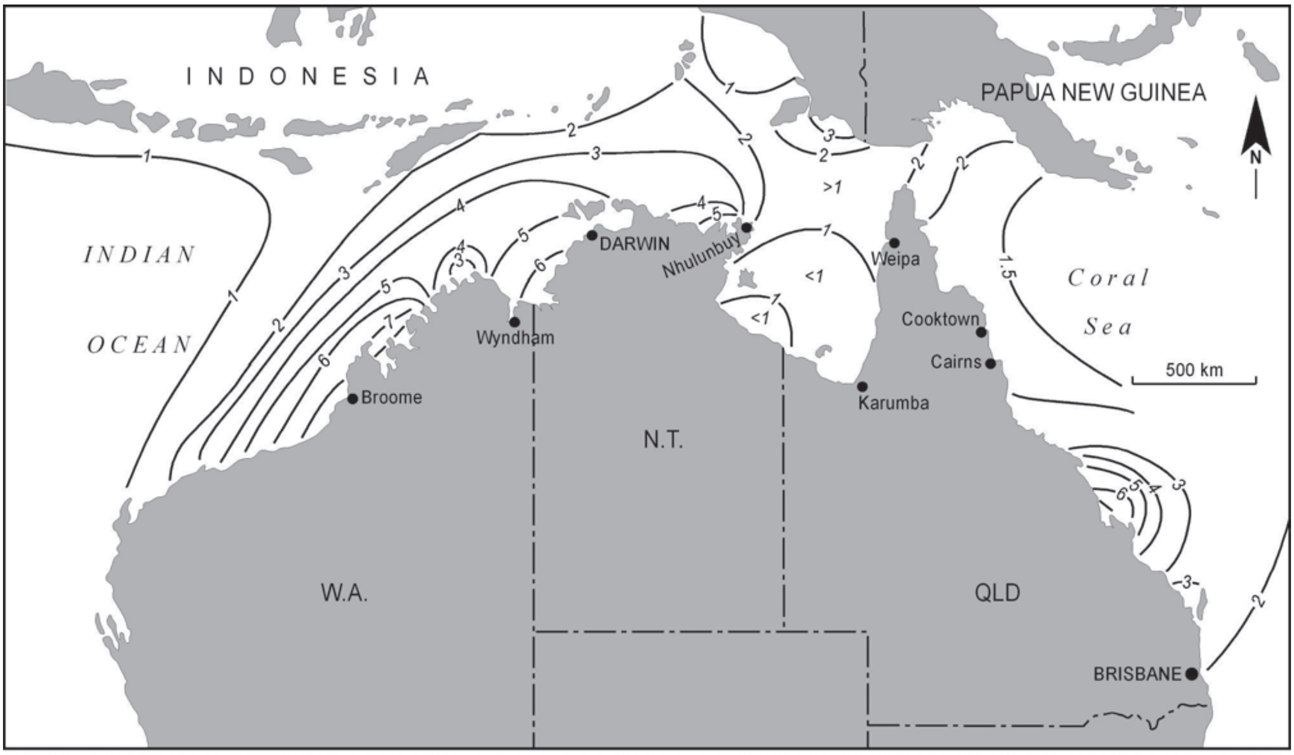
Figure 1. Faint Point in the western Kimberley is composed of Proterozoic sandstone. This view shows the joint-controlled bedrock ridges and typifies the over-riding role of bedrock along the Kimberley coast (A D Short).

The Kimberley Basin forms most of the Kimberley shoreline and consists of two dominant units. Horizontally bedded sedimentary rocks form the core of the basin, and while dating between 1800 to 1650 Ma they have experienced only minor faulting and warping. The sandstones are capped and replaced in places by extensive basalt deposits that date to 1800 Ma. Both units have however been uplifted and subjected to deep weathering and erosion along joint lines that trend roughly 10° (NNE-SSW) and 280° (WNW-ESE). As a consequence, all creeks and rivers parallel these joints in places for 10's of kilometer, such as the Prince Regent River. The jointing control is also prominent along the coast forming many elongate joint-aligned inlets and valleys (Fig. 1). At the coast the plateau forms often steep cliffs a few tens of metres high but ranging up to nearly 200 m in height in the north at sandstone Cape Torrens (183 m), and basalt Cliffy Point (186 m) and Crystal Head (191 m). Most of the coast and cliffs are however dominated by sandstone with the basalt more prevalent in the interior like the Mitchell Plateau, and only dominating along parts of the northern coast around Port Warrender, Cape Bougainville and east of cape Londonderry.

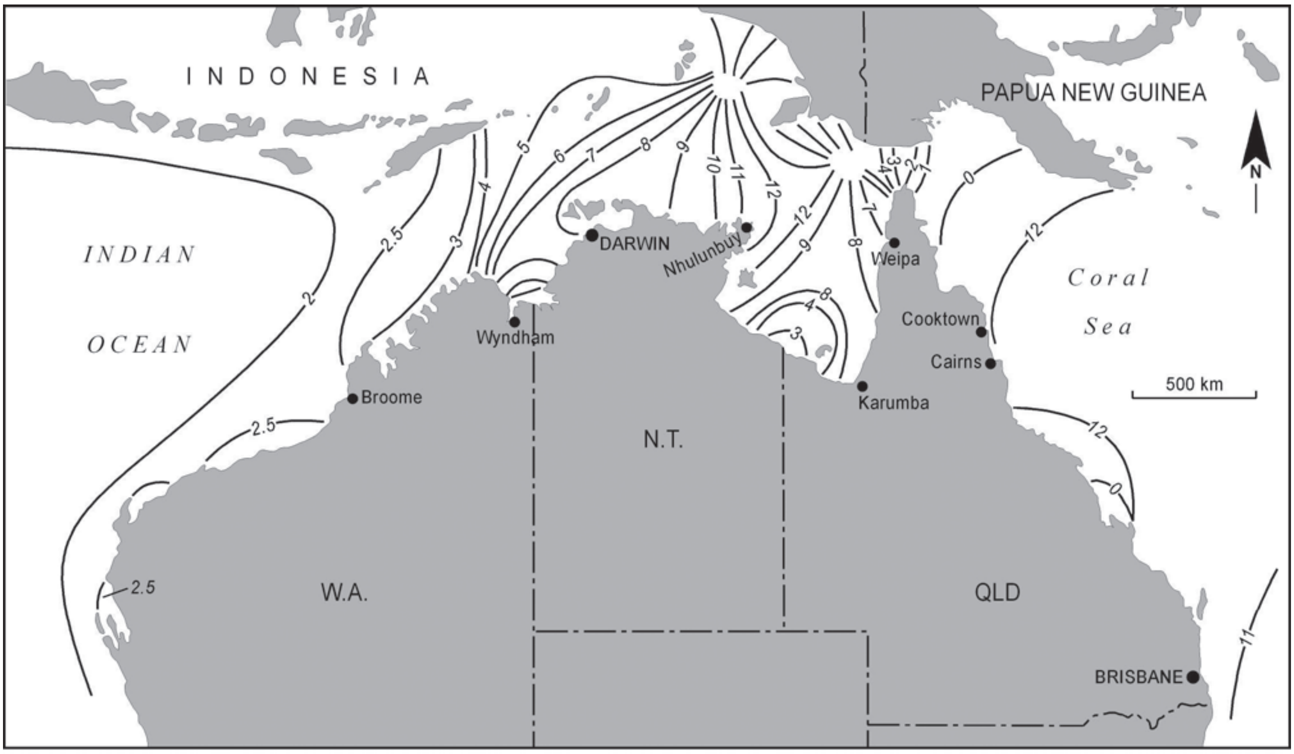
Cambridge Gulf marks the abrupt boundary between the rugged sandstone coast and the low-lying sediments of the Bonaparte Basin, which occupy the eastern shores of the gulf. The low sandstone Cape Domett marks the eastern entrance to the gulf, with the shore extending 75 km east to the Northern Territory border at Pelican Island. The final 30 km consists of a series of low barrier islands that extend to border, and then beyond to the extensive tidal flats of the Victoria River delta.

Coastal processes

The Kimberley coast is dominated by its by meso- to mega-tide ranges (Fig. 2). Spring tides reach 10 m at Broome, 11 m at Derby, 9 m at Hall Point and 8 m at Wyndham, with the lowest spring ranges being 3 m at Napier Broome Bay and Lesueur Island. The Kimberley coast has the third highest tide range in the world and the highest in Australia. In contrast, waves are predominately low short (3–5 sec) wind waves (Fig. 3), which are further lowered through wave refraction and attenuation into the bays and across the shallow inshore (Short 2010b). As a consequence, 50% of the beaches receive waves averaging only 10 cm, 30% 20 cm waves, 10% 30 cm, while the maximum average wave height of 1 m reaches less than 1% of beaches. The wind regime is low to moderate in velocity and seasonally bi-directional. The moderate velocity winter southeast trades blow offshore along much of the coast, with lighter onshore northwesterly winds accompanying the summer wet season. Only occasional tropical cyclones produce extreme conditions with strong winds, rain, storm seas, flooding and storm surges. However, because of their low spatial and temporal frequency they do not impact the modal coastal conditions. They can, however,



Co-range



Co-tidal range

Figure 2. Co-range and co-tidal lines for the northern Australian coast. In the Kimberley spring tides range from 3 to 11 m, while the co-tide lines show the west to east propagation of the tide wave. Source: Short, 2006b.

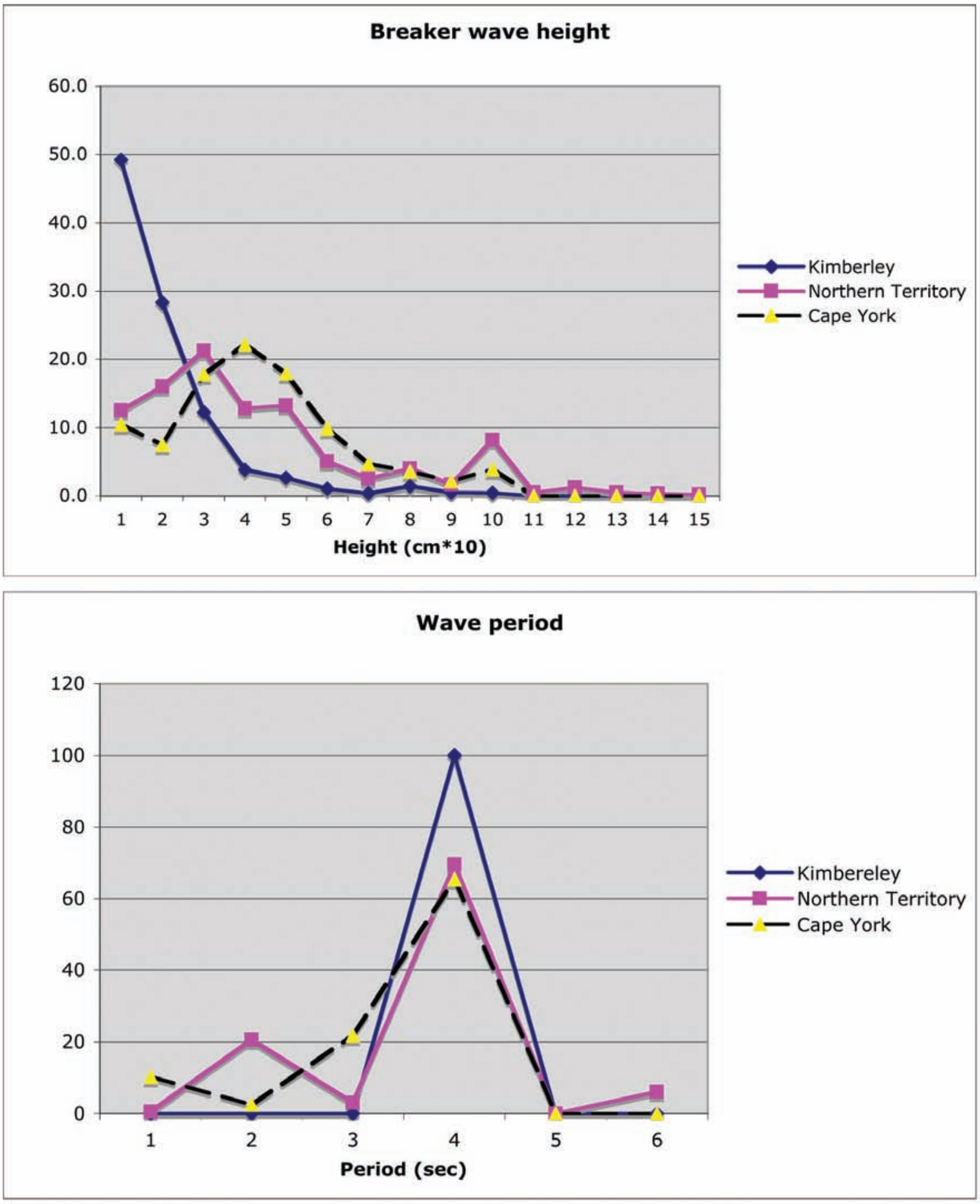


Figure 3. Breaker wave height and period across northern Australia. The Kimberley region has the lowest waves averaging 0.1 m, and typical short period, a product of the short seas and protection afforded most Kimberley beaches.

overwash the low beaches and beach ridges and leave storm deposits in suitable locations (Nott 2006). The coast can therefore be classified as tide-dominated, with only a few sections of more east-facing coast receiving enough onshore wind and accompanying wave energy to be classified as tide-modified to wave-dominated.

Methodology

This paper reports on the results of a long-term project to study all Kimberley beach and barrier systems (Short 2006b). The author first visited the Kimberley in 1980 as part of a University of Sydney team that undertook an intensive study of wave-tide-beach process on Cable Beach, Broome. The site was selected because of its high tide range, yet moderate wave activity (Wright *et al.* 1982a, b). Fieldwork for this project was undertaken by vehicle to the Dampier Peninsula in 1992, by plane to photograph every beach in 1997, and by small boat to facilitate beach landings between Wyndham and Broome in 2001. Additional information was sourced from large-scale maps (1:50 000 and 1:100 000), aerial photographs and Google images of the entire coast.

Beach systems

Beach systems can be classified based on their breaker wave height (H_b), wave period (T), sediment size or fall velocity (W_s) and tide range (TR). The relative tide range

$$\mathbf{RTR = TR/H_b}$$

is used to delineate between waved-dominated (RTR<3), tide-modified (RTR 3-10) and tide-dominated (RTR > 10) beach types (Short 2006a). Within each beach type the dimensionless fall velocity (Ω)

$$\mathbf{\Omega = H_b/T\ W_s}$$

is used to classify beach states between the dissipative (Ω>6) to reflective (Ω<1) end of each beach type, resulting in six wave-dominated, three tide-modified and four tide-dominated beach states around the Australian coast. In addition, some high tide beaches are fronted by either intertidal coral reef or rock flats and comprise a separate type, bringing the total to four beach types with fifteen beach states (Short 2006a; Short & Woodroffe 2009).

Table 2 provides the mean breaker wave height, tide range and RTR for all northern Australian beaches (Broome to Cooktown). Note the overall low breaker wave height and average meso- to macro-tides, and resulting range in RTR. The wave-dominated beaches have an RTR=<4, the tide-modified between 3 and 9, and the tide-dominated between 7 and 28, in general agreement with Short (2006a).

Barrier/dune systems

Beaches are commonly backed by longer-term deposits called barriers, the sediments comprising the barrier derived from the beach or former active beaches. Barriers can be grouped into stable barriers which usually consist of a beach backed by a single stable beach ridge or foredune; regressive barriers where a positive sediment budget has resulted in shoreline progradation and the deposition of a series of beach and/or foredune ridges; and transgressive barriers where the foredune has been destabilized and sand blown inland as transgressive dunes in the form of blowouts, parabolic dunes and transverse dunes. Barriers can range in size from very small systems a few tens of metres in dimensions to massive systems extending longshore and inshore for many kilometres (see Short and Woodroffe, 2009).

Kimberley beach systems

This section provides an overview of the Kimberley beach systems, followed by a review of the barrier systems that back 30% of the beaches. Full details of every one of the 1360 Kimberley beaches are provided by Short (2006b), while the barriers are incorporated in an overview of all Australian barrier systems in Short (2010a).

The 1360 beaches average only 0.52 km in length (standard deviation (σ) = 1.16 km), the longest at Cape Baskerville is 14 km long, followed by 12 km long Cable Beach. There are only four beaches greater than 10 km long, 62 greater than 2 km, 110 greater than 1 km, the remaining 1242 all 1 km or less in length, with eleven of these only 20 m in length.

The Kimberley coast has the shortest beaches and smallest barrier systems in Australia. This is a product of the short bedrock-controlled length of the beaches; their low wave energy which limits onshore sediment transport and deposition; and the generally low velocity and commonly offshore trade winds, which limit coastal dune development. The beaches can be classified into the four types, but with an overriding dominance of tide-dominated and to a lesser extent beaches fronted by coral reef or rock flats. Table 3 lists of the beach types and their states by number and length of coast they occupy. The only wave-dominated beaches are 14 reflective beaches located, two near Cape Leveque, a couple in the north, and ten reflective boulder beaches (Fig. 4) most

Table 2

Mean wave height, tide range and RTR associated with northern Australian beach types. Source: Short 2006b.

	Beach type[1]	H_b (m)	Tide Range (m)	RTR
Wave- dominated	1	0.55	2.15	4
	2	0.87	1.40	2
	3	1.33	1.40	1
Tide-modified	7	0.64	2.99	5
	8	0.90	2.44	3
	9	0.66	5.88	9
Tide-dominated	10	0.40	2.70	7
	11	0.28	4.02	14
	12	0.16	5.03	31
	13	0.16	4.54	28
Beach + rock flats	14	0.42	3.64	9
Beach+ reef flats	15	0.26	4.32	17

[1] see Table 3 for names of each beach state (1–15).

Table 3

Kimberley beach states by number and length of coast. Modified from Short 2006b.

No.	Beach state	Number	%	km	%
1	Reflective (R)	14	1.0	9.8	1.4
2	Low Tide Terrace (LTT)	0	0	0	0
3	Transverse bar & rip	0	0	0	0
4	Rhythmic bar & rip	0	0	0	0
5	Longshore bar & trough	0	0	0	0
6	Dissipative	0	0	0	0
7	R+LTT	21	1.5	20	2.8
8	R+LT rips	3	0.2	7.1	1.1
9	Ultra dissipative	22	1.6	78.2	11.1
10	R+sand ridges	25	1.8	12.8	1.8
11	R+sand flats	417	30.7	181.7	25.9
12	R+tidal flats (sand)	418	30.7	208.7	29.7
13	R+tidal flats (mud)	105	7.7	42.8	6.1
14	R+rock flats/platform	172	12.6	99.3	14.1
15	R+coral reef	163	12.0	41.8	6.0
	Total	1360	100	702.2	100

Figure 4. Cobles and boulders form the beach near The Funnel (Collier Bay). It is composed of locally derived platey sandstone. Vegetation debris (left) marks the high tide limit (A D Short).

Figure 5. The beach at Cape Dussejour is fronted by 500 m wide ridged sand flats, similar in extent to those that front most Kimberley beaches (A D Short).

around Bare Hill on the western entrance to Cambridge Gulf. These are all characterized by a relatively steep high tide beach, with no inter- to sub-tidal platform.

Tide-modified beaches total only 46, with about half located on the more exposed Dampier Peninsula including Cable Beach, north of Broome, a few around the northern Curran Point, Cape Talbot and Berkeley River, and the remainder east of Cape Domett. The eastern Kimberley tide-modified beaches are all located in more exposed locations that receive higher wave generated by the southeast Trade winds or the summer northwesterly winds. Twenty one have steep high tide beaches fronted by low tide terraces, 22 are wide long gradient ultradissipative like Cable Beach, and just three, on the exposed Cape St Lambert beaches, have low tide rips. These are the only persistent beach rips in the Kimberley another indication of the low wave conditions.

Tide-dominated beaches dominate and occur right around the coast from Crab Creek, near Broome, in the east to Pelican Island in the west, and on 71% of the beaches in between. They grade from the slightly higher energy ridged sand flats (2% Fig. 5); with decreasing wave energy to those fronted by sand flats (31%); tidal sand flat (31%), and with 8% fronted by mud flats. In all cases they consist of a low energy usually coarse shell rich high tide beach, fronted by the intertidal flats. The 900 plus intertidal sand and/or mud flats range in width at from 10 m to 2.5 km, with a mean width of 250 m (σ = 290 m) (Fig. 5).

A substantial number of beaches (25%) consist of a high tide beach and fronting fringing coral reef (6%) or intertidal rock flats (14%). The fringing reefs (Fig. 6) are a product of the tropical climate, while the rock flats are another example of the overriding role played by bedrock and in some location beachrock in influencing beach morphology.

The Kimberley beach and dune sediments characteristics are provided in Table 4. Sediments located on the intertidal sand flats are the coarsest (0.9 mm) and highest in carbonate (61%). Size and percentage carbonate decrease slightly into the high tide swash zone (0.8 mm and 59%). The foredune and transgressive dunes have the finest sand (0.6 mm) though quite coarse for dune sand, and the lowest carbonate (51%). The sorting is the opposite of what would be expected, with the sand flats and swash moderately well sorted, though both with large standard deviations, while the dunes sand are poorly sorted, though with a smaller standard deviation. Both the coarseness and poorer sorting of the dune sand can probably be explained by the fact many of the dunes are low and prone to occasional wave overwashing that may deposit coarser shells in the finer matrix.

Another interesting features of the sediment characteristics is the predominance of carbonate sediments on a coast with an abundance of river supplied terrigenous sediments. The source for the carbonate sediments is the fringing coral reefs, sand flats and seagrass meadows, all located in shallow water close to

Figure 6. Fringing coral reefs fronting a series of beaches east of Cape Londonderry. The beaches are backed by sandstone bluffs (A D Short).

Table 4

Kimberley beach-dune sediment characteristics

Position	Sample number	Carbonate %	Carb. σ	Mean diam (mm)	Mean σ (mm)	Sorting	Sort. σ
Sand flats	132	61	33	0.9	0.33	0.76	1.14
Swash	247	59	33	0.8	0.36	0.90	1.11
Dune	117	51	33	0.6	0.2	1.51	0.57

the shore. The massive volumes of terrigenous sediment supplied to the coast by the rivers and creeks is generally deposited in low energy bays and gulfs, and unable to be supplied to the shore because of its embayed location and low wave energy. Major beaches and barrier deposits are only present at the mouths of the Drysdale, King George and Berkeley rivers, each containing high to very high proportions of river derived sands. Beauty Point on the western side of the Drysdale has 5 km wide series of five successive beach ridge barriers contain 90% river derived sands, together with intervening mangrove filled inter-barrier depressions; The King George has a series of multiple sandy beach ridges and recurved spits on the eastern side of its bedrock-controlled mouth which contain 99% terrigenous sands (Fig. 7); while down wind of the Berkeley at Cape St Lambert, is the most extensive transgressive sand dunes in the Kimberley and composed of 99% river-derived quartz sand.

Kimberley barrier systems

The Kimberley coast region has the fewest and smallest barrier systems in Australia (Short, 2010a). This is a result of a number of factors beginning with the dominance of low, short waves that are only capable of transporting small amounts of sediment to the shore at low rates; second, is the wind regimes, with the strong trades blowing offshore on most beaches, with dunes only forming on some of the most exposed east-facing beaches; third is the generally coarse nature of the sediments which precludes their providing a source for coastal dunes; and finally is the steep bedrock coast which provides only limited accommodation space for beaches to form. Hence, while there is an abundance of terrigenous and carbonate sand available in the subtidal zone, most remains there with insufficient wave energy available to move it shoreward, and insufficient wind energy to produce substantial coastal dunes.

Barrier systems back 369 of the 1360 Kimberley beach systems, with the remaining 73% of the beaches of insufficient size to be termed a barrier, many backed by rocky slopes (Fig. 8). The barriers can be divided into three types: stable, regressive and transgressive (Table 5). Eight of the barriers consist of a stable boulder beach ridge (Fig. 4). There are 228 sandy beaches backed by a single beach ridge, while 28 consists of multiple beach ridges averaging seven ridges, but ranging from 2 to 40 ridges (Fig. 9). Ninety percent of the beaches and beach ridges (1227) are therefore solely wave deposited, with no backing aeolian dune deposits, most also fronted by the sand and tidal flats described above.

Aeolian activity resulting in the deposition of a foredune or transgressive dune on or in lee of the beaches and beach ridges backs only 105 of the beaches (8%). Most consist of a single usually low stable foredune (32) (Fig. 10). Only seven have regressive foredune ridges, consisting of usually 2 to 4 ridges (Fig. 11), with one system at Cape Talbot having 15 ridges. Sixty-nine beaches are backed by transgressive dunes, of which 40 have limited dune activity, while 29 have moderate to major dune activity, the most extensive extending 1–2 km inland around Red Bluff on the Dampier Peninsula (Fig.

Figure 7. The bedrock controlled mouth of the King George River with a series of sandy beach ridges extending to the east. The sediments for the ridges have been derived from the sandy river mouth shoals (A D Short).

Figure 8. A narrow high tide beach at Sanderson Point is backed by sandstone bluffs and fronted by intertidal beachrock. It illustrates the overriding role of bedrock in controlling beach and barrier morphodynamics (A D Short).

Figure 9. A small grassy rock and mangrove-bound beach ridge plain near Truscott. The 300 m wide plain contains multiple small, low beach ridges (A D Short)

Figure 10. A solitary foredune is squeezed in between beach and backing bedrock slopes at a beach near Gibson Point (A D Short).

Figure 11. A series of foredune ridges back this beach east of The Needles near the Northern Territory border (A D Short).

Figure 12. Transgressive dunes have extend up to 800 m inland either side of the Dampier Peninsula's Coulomb Point (A D Short).

Table 5

Kimberley barrier types and number

	No barrier	Beach ridge	Foredune	Minor transgression	Mod-major transgression	Total
No barrier	991	–	–	–	–	991
Boulder	–	8	–	–	–	8
Stable	–	228	32	–	–	260
Regressive	–	28	4	–	–	32
Transgressive	–	–	–	40	29	69
Total	–	1255	36	40	29	1360

12), and 0.5–1 km inland around Cape St Lambert. All of the more active dune are located either on the Dampier Peninsula (33) or on section of the more easterly facing east Kimberley shore, particularly around the Berkeley River mouth (29), with only seven in between.

Summary and Discussion

The Kimberley coast has a bedrock-dominated shoreline. The several large river and numerous smaller rivers and creeks tend to flow into deeply embayed joint-controlled valleys depositing their terrigenous sediment well inland from the open coast where extensive tidal flats and mangrove forests dominate the depositional shores. Only three rivers – the Drysdale, King George and Berkeley have significant wave deposited beaches adjacent to their mouths, the beaches composed of river-derived sediments.

The 1360 Kimberley beach systems occupy only 16% of the 4333 km long open coast, with the remainder of the coast dominated by bedrock. The beaches remain largely bedrock-controlled with an average length of only 520 m, the smallest in Australia. Further the beaches are predominately low energy tide-dominated systems. The typical beach is backed and bounded by bedrock slopes, has a single beach ridge and is fronted by sandy tidal flats averaging 250 m in width. Overall the combination of low wind waves and high tide ranges provide predominately tide-dominated beaches (63.5%), with only 15.3% tide modified and only one wave-dominated beach state (reflective) occurring on only 14 more exposed beaches. In addition, coral reefs fringed 12% while 13% are fronted by intertidal rock flats, the latter also a result of the bedrock dominance.

The barrier systems reflect the low level of wave and wind energy, as well as the generally coarser beach sediments. Most beaches abut backing bedrock and have no barrier. On the 360 barrier systems, most are single beach ridges (228) or foredune ridge (32), with a few regressive beach ridge (28) and foredune ridge (4) plains, again confirming the lack of available sediment. Regressive barriers capped by active dune transgression only occur on 69 barrier, 40 of which experience only

Table 6

Characteristics of Kimberley and Australian barrier systems (modified from Short, 2010a)

	Coast length km	Barrier length km	Number barriers #	total barrier area km^2	unstable area km^2	unstable %	barrier volume km^3	barrier mean vol m^3/m	Holocene rate supply $m^3/m/yr$
Kimberley	4333	456	368	223	66	17.8	1.0	2205	0.4
Australia	30671	12175	2476	23455	2765	11.7	281	22662	3.6

minor transgression, with the most extensive dunes extending up to 1 km inland and all located either on the more exposed Dampier Peninsula or east facing sections of the East Kimberley coast.

Table 6 summarises information on the Kimberley barriers. While the coast represents 14% of the Australian open coast the barriers contribute only 4% of Australian barriers by length of coast, 1.5% by number and 0.5% by volume. With a total Kimberley barrier area of 223 km^2, just over 80% are vegetated and stable the reminder experiencing either dune and/or overwash instability. The barriers have a mean volume of 2205 m^3/m, the smallest in Australia, and have been supplied with sediment at an average rate of 0.4 $m^3/m/yr$, again the lowest rate in Australia.

Whilst the Kimberley beaches and barriers are a secondary component of the coastal geomorphology, they do provide very important sites for landing and habitats for people and the native flora and fauna. The author observed turtle fin prints on almost every beach that was landed on, even on coarse cobble beaches, suggesting many beaches provide a nesting site for the turtles. Fresh crocodile foot prints were also a common sight on many beaches, again indicating they are used for resting and sunbaking. The beaches also provide the only easy landing for small boats at high tide and thereby access on an otherwise usually rugged coast. The beach ridges and dunes also offer a habitat for a range of coastal dune plants including coastal grasses *Spinifex longifolius, Ipomoea brasiliensis, Salsola kali, Fimbristylis cymosa, Fimbristylis sericea, Cyperus bulbosus* on the beach ridges, incipient foredune and foredune. Low shrubs *Acacia bivenosa, Lysiphyllum cunninghamii, Canavalia rosea, Triodia pungens* cover the larger foredunes; with dense shrub community of diverse plants, including some *Pandanus spiralis* grow on the hind dune and hollows, which then grade into pindan or rocky vegetation.

Conclusion

The Kimberley coast is a bedrock-dominated and controlled coast located in a humid monsoonal environment, with seasonal rainfall and several large river delivering substantial amounts of terrigneous sediment to the coast. Most of this sediment is deposited in drowned river valleys and the subtidal, with little available for onshore deposition by waves. Wave energy is low and tides are high resulting in a predominance of tide-dominated beaches (64%), followed by beaches fronted by either reef or rock flats (20%), then tide-modified (14%).

The barrier systems, similarly, are few and reflect the dominance of tide-dominated systems, with most consisting of solitary beach or usually low foredune ridge (74%), while only 10% have experienced shoreline regression resulting in a few ridges. Limited transgressive dune activity in the form of coastal dunes occur on 16% of the barriers mainly on the most exposed Dampier Peninsula and parts of the east Kimberley coast.

The beaches and barriers are however an important component of the otherwise rocky open coast, providing sites for landing and turtle nesting, as well as a range for dune based ecosystems.

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