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Stratigraphic patterns in coastal sediment sequences in the Kimberley region, Western Australia: products of coastal form, oceanographic setting, sedimentary suites, sediment supply, and biogenesis

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Abstract

Coastal sediments in the Kimberley region occur in generally macrotidal environments with variable wave energy, reside in different coastal forms, and illustrate various styles of facies development and sedimentation leading to varying types of stratigraphic packages. The sedimentary patterns and stratigraphic patterns are determined by the coastal setting in terms of coastal morphology, oceanographic factors such as tide-dominated or wave-dominated prevailing conditions, or cyclone generated conditions, sediment delivery, and the dominance of gravel *versus* sand *versus* mud. The main stratigraphic packages range from gravel-dominated sequences and sand-dominated sequences, to shoaling sand-to-mud sequences to mud-dominated sequences, with local variations such as sequences with embedded sand lenses (buried spits/cheniers), and thin sediment sequences on rocky pavements. Bouldery shores, tempestites, sandy beaches, and sandy beach-ridge systems represent one extreme of the stratigraphic patterns, with gravel and sand dominated systems. King Sound and Cambridge Gulf represent an intermediate pattern, with sand-to-mud sequences, reflecting shoaling from low tidal to high tidal sedimentation. Port Warrender and the Lawley River Delta and local mud-filled embayments represent the other extreme of the patterns, with sediment sequences dominated by mud. In ria and embayment coastal settings, the most complex array of facies occur, representing the intricacy of sedimentation in sedimentologically diverse embayments; these include tidal-flat sediments, tidal creek sediments, sand underlying spits/cheniers, high-tidal alluvial fans, and beaches. Biogenesis can be a major factor in facies development, with effects ranging from mangrove-influenced sedimentation to fauna bioturbation and skeletal contribution.

Keywords: Kimberley Coast, tropical coast, coastal sediments, coastal stratigraphy

Introduction

The geographic coastal region of the Kimberley, encompassing the natural geomorphic coastal sectors of the Kimberley Coast, King Sound (including Stokes Bay), and Cambridge Gulf (Fig. 1), presents a globally unique ensemble of sedimentary packages set in a tropical (generally) macrotidal cyclone-influenced environment with variable wave energy (Brocx & Semeniuk 2011). These sedimentary packages range from shoaling sequences of tidal flat sediments, to beaches, prograded beach-ridge systems, tempestites, to bouldery shores. While shore boulder deposits comprise the most extensively developed sedimentary unit, and many other sediment suites, such as sandy beaches and spits, occur throughout the Kimberley region in site-specific areas such as coves and mouths of embayments, tidal flat sediments comprise the largest accumulations of sediments at any given site, occurring in the headwaters of large rias and embayments and in many of the smaller sheltered inlets and ravines. Prograded tidal flat sediments, as laterally extensive flats, form distinct coastal landforms, adding to the geomorphic character of the Kimberley region, and form the habitats for mangroves and benthic tidal-flat fauna. In their various coastal settings, the other sedimentary suites, though volumetrically less significant site-specifically than tidal flat deposits, also form distinct coastal landforms, and add to the diversity of the coastal forms, sedimentary deposits, and habitats in the region.

To date, there have been a limited number of sedimentologic studies in the coastal zone of the Kimberley region; these include Gellatly (1970), Semeniuk (1981a, 1993), Lees (1992); Nott (2006), and Short (2006). Given the vastness of the area, understandably there have also been a limited number of studies that have involved stratigraphic analyses of the coastal sedimentary deposits of the Kimberley region. The main stratigraphic studies, to date, have been: Jennings & Coventry (1973) who investigated the spits in northern King Sound; Jennings (1975) who studied the relationship of tidal sediments to underlying red desert sand that comprise the linear dunes that adjoin the eastern shore of King Sound; Thom *et al.* (1975) who provided a stratigraphic cross-section of southern Cambridge Gulf across the tidal flats; Coleman & Wright (1978) who studied the sedimentation and stratigraphy from the alluvial plain to the tidal delta in Cambridge Gulf; Semeniuk (1980, 1981a, 1981b) who provided stratigraphic profiles of the tidal zone in King Sound, relating them to modern sedimentary facies and earlier Holocene sequences; and Semeniuk (1983, 1985) who provided stratigraphic profiles of mangrove-vegetated coasts in the Mitchell River and Port Warrender area. Apart from Short (2006) who described the various sandy and pebbly beaches of the Kimberley region, relating them to waves, tides and their local coastal setting, there has been little published on coastal sediments of the Kimberley region that provides an integrated explanation of the variety of sediments types and the types of stratigraphic packages that they may develop.

This paper is a description of coastal sediments of the Kimberley region, their occurrences in relation to coastal setting, the processes leading to their development, the types of stratigraphic sequences generated along the various coasts, and a perspective of their significance globally. Details of sedimentary structures, sedimentary interrelationships, and the processes of sedimentation at the smaller and fine scales (*cf.*, Semeniuk 1981a) are beyond the scope of this paper and the objective is to provide a large scale view of the variety of sedimentary systems and stratigraphic packages that occur in the region and relate them to the main coastal processes and coastal settings.

The sedimentary environments and stratigraphic sites described in this paper are based on field work, involving boat-work, land-based vehicle, aerial surveys by fixed wing aircraft, and helicopter. Sampling sites are shown in Figure 1. All surveys were accompanied by documentary photography. Additional work was carried out by desktop aerial photographic studies. On-site studies involved describing coastal setting, determining stratigraphy by augering, coring, and from cliff exposures, and sampling of sediments from stratigraphic profiles and the sediment surface. Details of sampling Quaternary stratigraphy and sediments are provided in Semeniuk (1980, 1981a, 1983, 1985).

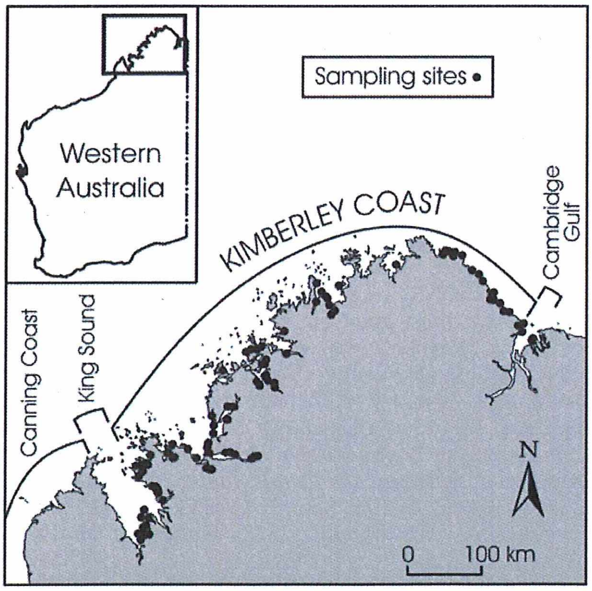


Figure 1. Location map showing King Sound, the Kimberley Coast, and Cambridge Gulf. The climate setting of the region is adapted from Gentilli (1972), and location of sampling sites.

Definition and limits to the Kimberley Coast and the Kimberley region

In this paper, the region of the Kimberley, is divided into three natural coastal units, following Semeniuk (1993) (Fig. 1):

1. the Kimberley Coast,
2. King Sound (including Stokes Bay), bordering the Kimberley Coast to the south-west, and
3. Cambridge Gulf, bordering the Kimberley Coast to the east.

The Kimberley Coast is the sector of ria shores cut into the Precambrian massif of the Kimberley Basin and King Leopold Orogen that (onshore) forms the Kimberley Plateau of (mainly) sandstone and (some) basalt. The Kimberley Coast (*sensu* Semeniuk 1993) is a rugged, dominantly rocky coastline with local sedimentary accumulations. Its geomorphic structure is dominated by medium and short rivers that have incised deep valleys into the sandstone and basalt regional plateau. As described in Brocx & Semeniuk (2011), the geological grain, faults, and boundary between geological units, such as between the Precambrian rock massif and Phanerozoic rocks, have been selectively eroded to form major valley tracts of the Fitzroy, May, and Meda Rivers and the Pentecost, Durack, and King Rivers. The southern to south-eastern margins of the Precambrian massif also have been incised by short rivers that form north-deriving tributaries to these larger rivers. The complex of larger rivers form the large gulfs, partly filled with sediments, *i.e.*, King Sound, Stokes Bay, and Cambridge Gulf. These rivers and their tributaries have delivered voluminous sediment to the gulfs from their respective large drainage basins. The short rivers, with smaller drainage basins, that incise and radially rim the Precambrian rock massif along its south-western, western, northern, north-eastern coastal margin, form the architecture of the ria shores of the Kimberley Coast.

King Sound (including Stokes Bay) and Cambridge Gulf are large funnel-shaped gulfs whose southern parts are composed of tide-dominated deltas of the Fitzroy River, and the combined May and Meda Rivers, and (for Cambridge Gulf) the combined contribution of the Pentecost, Durack, and King Rivers. King Sound is located between Dampier Peninsula (composed of Mesozoic rock overlain by Quaternary linear dunes), and to the north by folded rocks of the Precambrian King Leopold Orogen and north-east by a field of Quaternary linear dunes. From the south, it is dissected into two subsidiary gulfs (King Sound proper, and Stokes Bay) by a peninsula of Mesozoic rock that is mantled by Quaternary dunes. Cambridge Gulf is bordered by the rocks of the Kimberley Basin to the west, by Phanerozoic rocks to the east, and by faulted and folded Precambrian rocks of the Halls Creek Orogen to the south. As large embayments, King Sound and Cambridge Gulf have been carved out by the large rivers in the regions and, as such, are the depositional basins for the fluvially-derived sediments of these drainage basins. The sedimentary deposits are concentrated to the south within the gulfs, and the accumulations effectively are the deltaic deposits of the contributing rivers. Tidal processes have shaped these deposits into north-south oriented linear elongated shoals, some of which are high-tidal emergent. As such, the deltas of the Fitzroy River, and the combined May and Meda Rivers, and for Cambridge Gulf the combined contribution of the Pentecost, Durack, and King Rivers are tide-dominated deltas.

Climate, oceanography, and coastal processes of the Kimberley region

The Kimberley geographic region is located in a tropical climate, with the coastal zone spanning several climate regions, *viz.*, following Gentilli (1972), tropical subhumid in the Cambridge Gulf area, tropical humid centred on the Port Warrender area, tropical subhumid from Prince Regent River to northern King Sound, and tropical semi-arid in the King Sound area. The significance of the climate is that coastal rainfall influences local freshwater seepage, the extent that saline high-tidal flats are developed, and the development of beach rock, and evaporation determines the extent that saline high-tidal salt flats are developed. Wind in the region is variable regionally in direction and strength. It is instrumental in generating wind waves that affect shore processes, in mobilising sand into dunes, driving landward migration of parabolic dunes, and in evaporation from the high-tidal salt flats.

The climate of the hinterland inland from the coast is also relevant in that rainfall in the drainage basins of the Kimberley Plateau determines the extent of run-off into the rivers which, in turn, determines the amount of freshwater and sediment delivered to the coast. Generally, the drainage basins of rivers and creeks that deliver freshwater and sediments to the coast are largely in a subhumid climate. Across the region, the variability in size of drainage basin, the lithologies where the drainage basin resides, and the rainfall result in variation of sediment volumes and particles types delivered to the coast. Quartz sandstone terrain yields quartz sand particle types, while felspathic quartz sandstone and interlayered sandstone and siltstone yield quartz sand and mud-sized particles, and basalt terrains and laterite-capped basalt terrains yield mud–dominated sediment.

The coastal zone of the Kimberley region is subject to four main oceanographic processes (Fig. 2): semi-diurnal tides, seasonally determined wind waves, prevailing swell, and seasonal and inter-annual cyclones. All these influence sedimentary processes but some are environmentally/geographically restricted and some, as

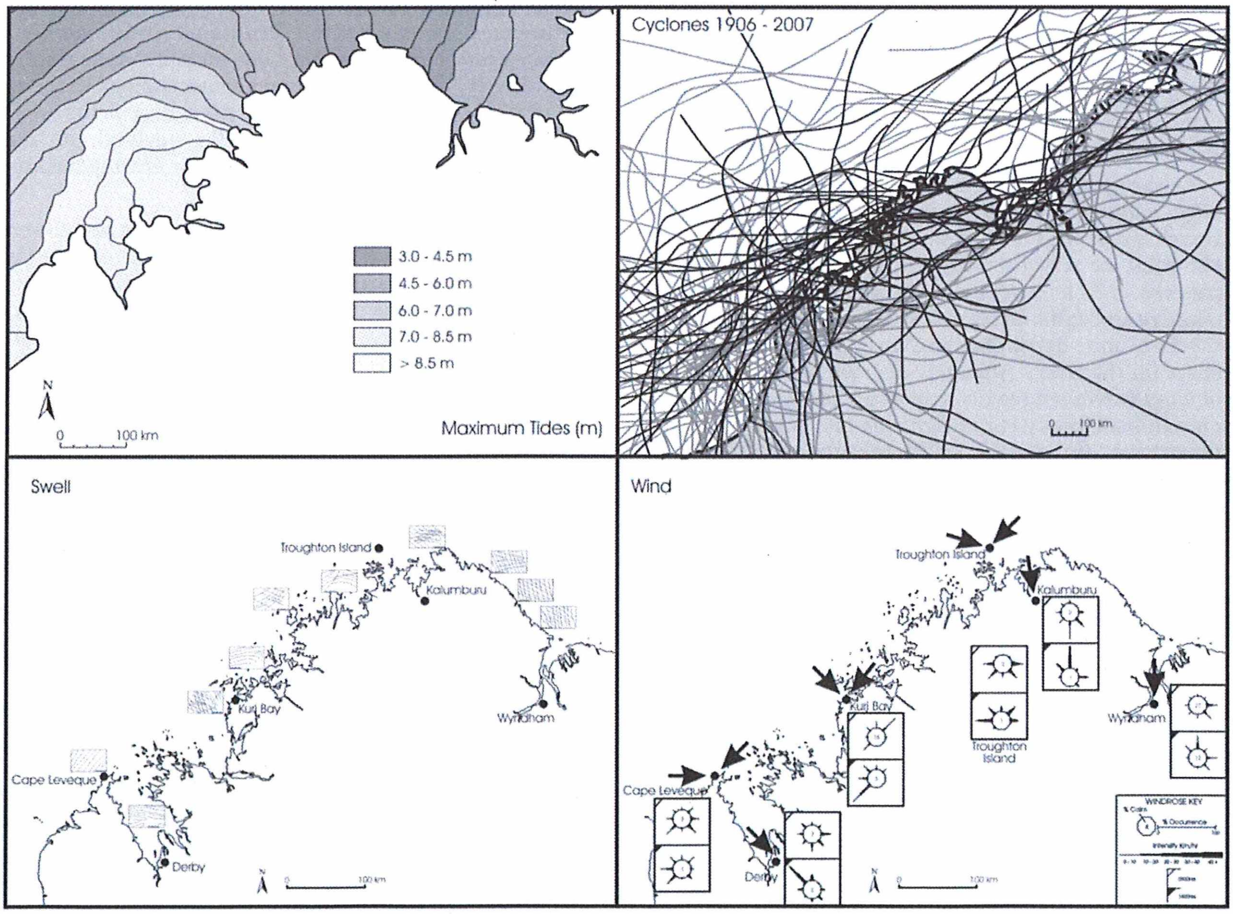


Figure 2. Swell patterns, wind, and wind wave directions, tide ranges, and cyclone paths in the Kimberley region. Swell patterns are shown for small representative sections of the coast. Wind roses are derived from the Bureau of Meteorology (2010) for the locations shown; the large arrows show the summarised directions for a given location, which will determine wind wave directions that will impinge on the coast.

noted, are seasonally specific. As such, they are variable in their coastal effects across the region. Additionally, the Kimberley Coast is highly indented and comprised of south-facing, west-facing, and north-facing inlets and embayments which, in many instances, are nearly wholly isolated from the open sea, being connected only by narrow channel-ways or waterways. While the latter are subject to inundation only by high tides, storm surges and cyclone-induced high-water, they are protected from the action of swell, wind waves, and storm waves.

The coast of the Kimberley region is macrotidal, with maximum tides ranging from 11.5 m in King Sound, to 10 m at Koolan Island, 8 m at Port Warrender, to 8 m at Cambridge Gulf, though tidal range decreases to mesotidal in the Berkeley River area. In fact, semi-diurnal large tides are a daily and pervasive dominant feature that affects the coast regardless of its geometry, degree of shelter, and orientation. Tidal waters and tidal currents are regionally pervasive even where tides penetrate into protected inlets and lagoons. As such, all portions of the coast from large open embayments to narrow secluded ravines, to tidal lagoons receive mud-bearing waters, and are subject to a varying degree to tidal currents. In particular, scour-lag and settling lag processes (see later) result in mud accumulating at the high tidal interval in embayments, lagoons, near-landlocked inlets/ embayments, and where tidal waters can invade on high tides. In this paper, EHWS = equinoctial high water spring tide, MHWS = mean high water spring tide, MHWN = mean high water neap tide, MSL = mean sea level, MLWN = mean low water neap tide, MLWS = mean low water spring tide, and ELWS = equinoctial low water spring tide.

Oceanographically, the next important processes to affect sedimentation are wind waves and swell. Wind waves are pervasive even in areas sheltered from swell, but are more seasonal, reflecting the seasonality of wind patterns and, in particular, sea breezes. They are most effective in coastal processes where coasts are relatively exposed and, depending on fetch, they have variable effect on the coast. Although the sedimentologic effects of wind waves are region-wide, they have most influence on sedimentation where headlands and coves face wind directions, and where small islands act as foci for development of cuspate forelands and tombolos. Swell is an all year phenomenon, deriving from northerly, north-westerly, north-easterly to south-westerly sectors, and impinges on exposed coasts facing these directions. Swell is refracted and dampened interacts with the shelving near-shore environment, and as it enters deeply embayed rias. However, swell is not a major wave form in the region.

Cyclones are inter-annual and seasonally determined phenomena (Lourensz 1981; Lough 1998), but highly localised in their effects on shore development. Cyclones result in elevated sea level, large waves, and storm surges. With cyclones there is winnowing of existing sedimentary deposits, transport and emplacement of sedimentary deposits above and well above the high tide mark, and coastal erosion. Cyclones also result in massive influx of freshwater into the coastal zone, and concomitant sediment delivery from rivers/creeks to the high-tidal alluvial fans.

Geology, landscape, rivers and valleys as architecture to the Kimberley coastal region, and ancestral topography and the coastal forms host to coastal sediments

Coastal forms in the Kimberley region have developed by marine inundation of onshore landforms and rivers, creeks, their tributaries and other valley tracts (Brocx & Semeniuk 2011), and by accumulation/erosion of Holocene sediments (Semeniuk 1981b). The main onshore landscape feature of the region is the Kimberley Plateau, a terrain underlain by rocks of the Kimberley Basin (mainly of fractured/faulted sandstone with some basalt). The Kimberley Plateau is deeply incised by rivers, creeks, and their tributaries forming trellis and dendritic drainage patterns as controlled by the geology. As a result, there are steep-sided ravines, with bluffs and cliffs, which at the coast result in steep rocky shores and cliffs, steep bouldery shores, narrow to open embayments, fracture-aligned gulfs, inlets, narrow ravines, archipelagos, and ocean-facing cliffs. The King Leopold Orogen, a tightly folded sequence of rock with fold axes oriented WNW, forms ridge-and-basin topography. Marine inundation of this topography has formed prominent WNW-striking peninsulae, inlets, linear embayments and lagoons, and chains of islands (as archipelago complexes), isolated or near-isolated linear high-tidal marine enclosures and, where fracture influences cross-oriented drainage, trellis-shaped embayments and inlets. Onshore ancestral topography thus directly determines coastal geomorphology in terms of size, shape, and orientation of embayments, and whether they have been fluvially derived, or are indented coasts, and if they grade into or are adjoined by an archipelago.

Following Brocx & Semeniuk (2011), there are eleven coastal forms in the Kimberley region that determine (or influence) the nature and style of sedimentary accumulations; these are (Fig. 3): 1. large funnel shaped gulfs; 2. large narrow v-shaped gulfs; 3. large broad embayments; 4. medium-sized to small narrow v-shaped ravines and valleys; 5. medium-sized to small embayments and coves; 6. isolated inlets and lagoons; 7. rectilinear to rhomboidal intersecting embayment/ inlet complexes; 8. archipelago-and-embayment complexes bordering the Kimberley Basin; 9. archipelago-and-inlet complexes bordering the King Leopold Orogen; 10. straight rocky shores; and 11. scattered islands in an archipelago.

Depending on the orientation and the oceanographic aspect of these coastal forms, there is a gradation of wave and tidal energy: coasts may be exposed to wind waves and prevailing swell and thus subject to the high energy of waves and tides; or relatively protected from prevailing wave action and subject mainly to tidal currents; or fully protected from wave action and only inundated on the highest tide at times of near slack-water and slack-water. The nature of the coast, how much of it is subject to waves and tidal currents, and how much sediment is delivered to or generated at the site will determine the style of sedimentary accumulation that will develop.

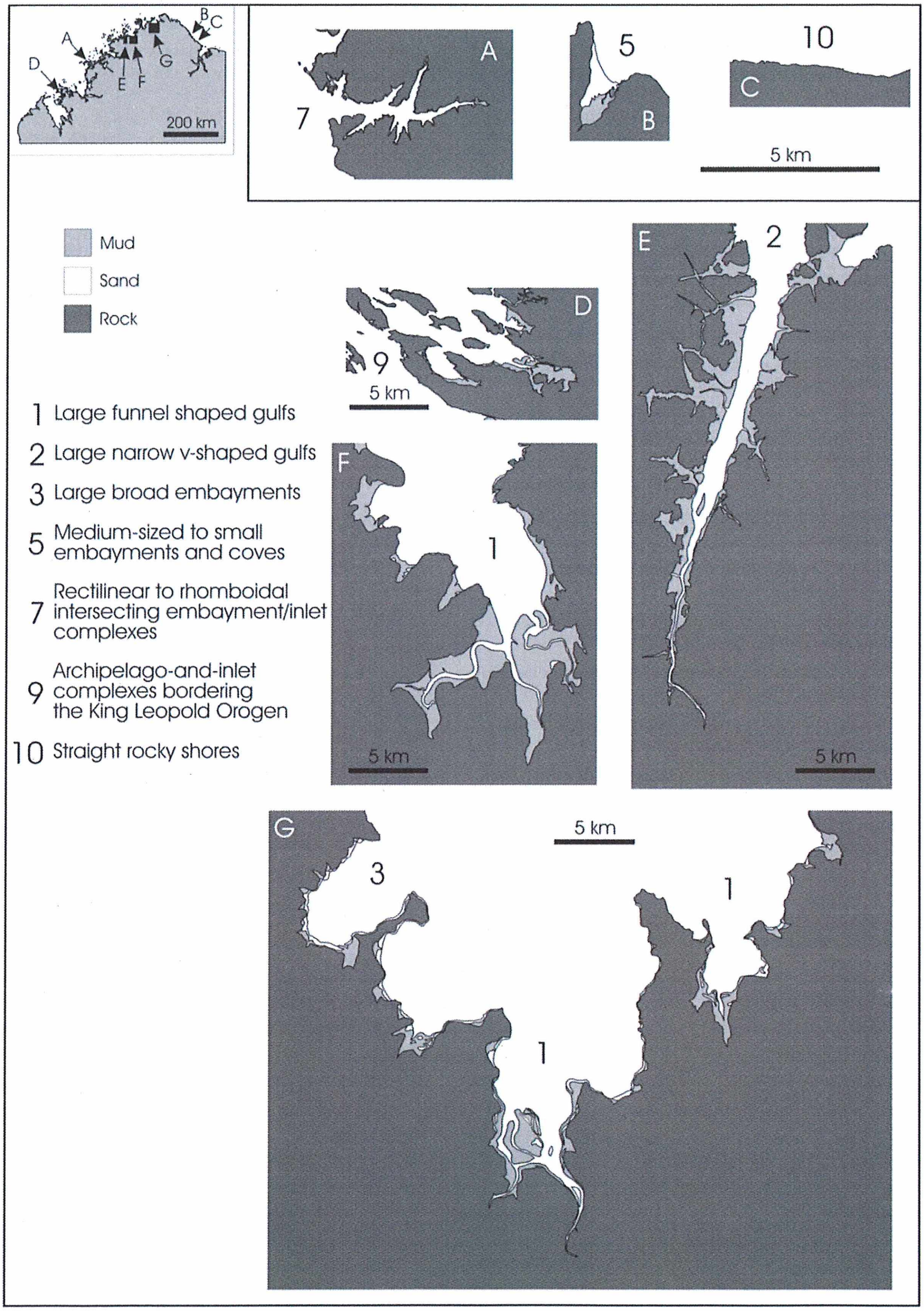


Figure 3. Coastal forms in the Kimberley region that determine (or influence) the nature and style of sedimentary accumulations (after Brocx & Semeniuk 2011). Bar scale for A, B, C, D, E, F & G is 5 km. The numbers refer to one of the eleven coastal forms mentioned in the text, and the letters A, B, C, etc. show the location of the example along the Kimberley Coast.

Processes of sedimentation

To provide a context of how sediment is transported to, along, and within the coastal zone, the main processes of sedimentation in the coastal zone, and those processes that result in sediment being delivered to the coastal zone, are briefly outlined here, drawing on local and international literature. The main processes of sedimentation that result in sediment accumulating in the coastal zone, from land to marine environment, are:

1. Long distance fluvial transport involving traction loads and suspension loads
2. Short distance fluvial transport involving traction loads and suspension loads
3. Sheet-wash on terrestrial slopes
4. Mass wasting along cliff lines contributing blocks, boulders, cobbles, and sand
5. Aeolian transport of drying high tidal sand on beaches to form dunes, and its further inland transport as parabolic dunes
6. Wave action driving sand and gravel shoreward
7. Storm surges driving sand, pebbles, and boulders shoreward
8. Longshore drift driven by oblique prevailing wave action or storm waves
9. Wind-driven currents mobilising suspended mud and sand alongshore and shorewards
10. Tidal currents that transport sand by traction and mud in suspension
11. Scour-lag and settling-lag resulting in mud accumulation in high-tidal zones
12. Biological activity (*e.g.*, mangrove detritus, shell contribution)

These processes and their relevance to sedimentation in the coastal Kimberley region are described in Table 1

Sediment sources and styles of supply

Sediments in the Kimberley coastal zone are derived from six sources: 1. nearly *in situ* ancestral gravel and sand; 2. locally derived gravel and sand; 3. distally river-delivered derived sand, mud, and gravel; 4. reworked sediment from earlier Quaternary deposits and relict sediment; 5. biogenic sediment; and 6. locally derived intraclasts. These are described below in terms of sediment granulometry and composition, and in terms of the processes that deliver the sediments to the coast.

Gravel and sand, that is nearly *in situ*, contribute to the sediments in the coast zone. The rocky ranges, ridges, hills, slopes, and scree slopes of the Kimberley massif mainland are mantled with gravel and sand, and the valley tracts cut into the fracture-dominated Precambrian massif are floored with gravel and sand. These materials formed the ancestral topography and sediments and soils prior to the last post-glacial transgression. After the last glacial period, with sea level rising to its near-present position some 10,000–7000 years BP, the various materials mantling the ranges, ridges, hills, slopes, and valley tracts formed the sedimentary materials of the shore-lines. Those materials that were inundated and remained largely *in situ* formed boulder shores and sandy bouldery shores and gravelly shores. Those that were inundated and local reworked by waves, storm waves and cyclone-induced wave actions and surges, developed bouldery and gravelly shores, with rounded boulders and gravel, and bouldery shores showing imbricate structure. The extent that such deposits are *in situ* or reworked is dependant on the extent that the shore is sheltered from wave action. In many protected areas of the Kimberley ria shore and embayments, slopes and hill-sides subaerially covered in gravel scree descend directly into the tidal zone to form a steep bouldery shore. Where wave action is prevalent, the slopes and hill-sides subaerially covered in gravel scree descend directly into the tidal zone and the boulder and gravel deposits are reworked into mid to high-tidal ribbon

Table 1

Processes of sedimentation and their products

Process	Sedimentation products
Long distance fluvial transport	Long distance fluvial transport involving traction loads and suspension loads
Short distance fluvial transport	Short distance fluvial transport involving traction loads and suspension loads
Sheet-wash on slopes	Sheet-wash on terrestrial slopes
Mass wasting along cliff lines	Mass wasting along cliff lines contributing blocks, boulders, cobbles, sand
Aeolian transport of beaches to form dunes	Aeolian transport of drying high tidal sand on beaches to form dunes, and its further inland transport as parabolic dunes
Wave action driving sediment shoreward	Wave action driving sand and gravel shoreward
Storm surges driving sediment shoreward	Storm surges driving sand, pebbles, and boulders shoreward
Longshore drift	Longshore drift driven by oblique prevailing wave action or storm waves
Wind-driven currents mobilising sediment	Wind-driven currents mobilising suspended mud and sand alongshore and shorewards
Tidal currents transporting sediment	Tidal currents that transport sand by traction and mud in suspension
Scour-lag and settling-lag	Scour-lag and settling-lag resulting in mud accumulation in high-tidal zones (Postma 1961)
Biological activity	Biological activity (*e.g.*, mangrove detritus, shell contribution)

deposits, becoming more rounded, and imbricated. The scree and the shore-line deposits are composed of large platy boulders. Where the shoreline rocks, particularly well-bedded sandstone and siltstone, have been fragmented by terrestrial erosion, salt weathering, and wave erosion to pebble-sized clasts, they form pebble shores along the rocky coasts, and can be transported to form pebble beaches, and pebble cheniers, tombolos, and barriers.

Locally derived gravel and sand is similar to that described above but has been transported to the shore by sheet-wash, mass wasting, or small creeks and rivulets active during the wet season. The latter deliver gravel and sand to rocky shores, to high-tidal deltas, or into ribbons of gravel and sand along the interface between the upland slopes and the tidal flat. Mass wasting along cliffs contributes blocks, boulders, and sand as chaotic masses, or as talus cones, both of which are reworked, transported and subject to rounding and attrition.

Sand, mud and gravel also are supplied by rivers. The medium sized and large rivers, such as the Fitzroy River, the Lawley River, the Prince Regent River, amongst others, have delivered, and continue to deliver much sedimentary material to the coastal environment. Thus, this sedimentary material has a distal origin. Because of the size of the drainage basins and the diversity of rock types at the source, some rivers deliver a diversity of particle types mineralogically and granulometrically. Quartz sandstones yield gravel and quartz sand, quartz/felspathic sandstones yield gravel, quartz sand and clays, basalt and lateritised basalt yield gravel and clays. Once delivered to the coast, wave action and tides partition the sediments into sand, muddy sand and mud lithofacies, and gravel.

In many locations of the Kimberley coastal region, there is erosion and remobilisation of pre-existing Quaternary sediments, including relict earlier Holocene sediment. Pre-existing Quaternary sediments and relict Holocene sediment include: 1. early to middle Holocene tidal mud formed under mangrove cover (with reworking, in the late Holocene to modern setting, of voluminous amounts of mud that is redistributed to mid-high tidal environments); 2. alluvial plains of the pre-transgression surface; 3. Pleistocene tidal flat deposits (these generate mud, quartz sand, and carbonate lithoclasts); 4. relict earlier Holocene sediment of shelly muddy sand, or muddy sand; and 5. Quaternary red sand dunes. The reworking of earlier deposits has resulted mainly in remobilisation and accumulation of mud and sand, with minor gravel. In some instances, the sediments are not remobilised, remaining in subtidal areas as relict sediment.

Biogenesis contributes sedimentary particles to and/or develops biogenic rock along the Kimberley coastal region. Biogenic materials include: 1. coral reefs along the shore zone; 2. calcareous algal reefs (biolithites, or boundstones) along the shore zone (Brocx & Semeniuk 2011); 3. calcareous algal encrustations on lithoclasts, shells, or corals to form rhodoliths; 4. coral fragments as gravel and coarse sand, derived from fringing coral reefs that border the low tidal zone of rocky shores, and transported shorewards by wave action along high energy coasts to form coral gravel deposits as spits, cheniers, and beaches; 5. oyster and barnacle skeletons as gravel and coarse sand, derived from rocky shores, transported alongshore and shorewards by wave action along high energy coasts to form shell gravel deposits as spits, cheniers, and beaches; 6. benthic molluscs that inhabit tidal and subtidal sand and mud substrates, which remain *in situ* to contribute shell to the sediment, or are winnowed and transported alongshore and shorewards by wave action or tidal currents to contribute particles to the sand deposits; 7. benthic and epibiotic foraminifera of tidal and subtidal environments that contribute sand-sized skeletons, transported alongshore and shorewards by wave action or tidal currents to contribute particles to the sand deposits; 8. diatoms in tidal environments that contribute mud-sized skeletons, that are transported alongshore and shorewards to contribute particles to the mud deposits, or remain *in situ* in the local mud accumulations; 9. plant material as leaves (detritus), branches, logs, which break down and contribute to the organic-matter-rich muds, or to the development of pyrite-impregnated muds; and 10. plant material as *in situ* roots and trunks embedded in the mid to high-tidal mud deposits (Semeniuk 1980, 2008), which break down and contribute to the organic-matter-rich muds, and to the development of pyrite-impregnated muds. The range of biogenic skeletal particles in the sediments, as gravel to sand-sized grains derived from various extant biotopes, include: entire bivalves and their fragments, entire gastropods and their fragments, foraminifera tests and fragments, (encrusting) calcareous algal fragments, segments of articulated calcareous algae, rhodoliths, bryozoans, echinoderm test fragments and spines, coral gravel and sand-sized fragments, sponge spicules, barnacles and their fragments, and hydrozoans.

Cementation in the tidal zone of beaches develops beach rock (slope-parallel indurated beach sand, shelly sand, or gravel). Fragmentation and reworking of beach rock generate intraclasts (intra-formational clasts; Folk 1959) which range in size from boulders (as slabs), to pebble-sized to sand sized calcarenite fragments and slabs of coquinite.

The coastal stratigraphic packages in varied oceanographic/drainage basin settings

From the descriptions above, it is apparent that there is variability in the coastal sedimentary patterns in relation to processes, sedimentary particles, and sediment types throughout the Kimberley region. The distribution and characteristics of the coastal sedimentary systems in the Kimberley region are complex and vary in response to coastal geomorphic setting, method of emplacement, and geometry of sedimentary bodies. They also vary in terms of their granulometry and composition, and their lithotope and stratigraphic interrelations. Because of the diverse origins, multiplicity of processes, and diverse granulometric characteristics of the coastal sediments, it is not possible to devise a strict hierarchical system for their grouping or classification. For instance, storm deposits (or tempestites) may be coral gravel, rock clast gravel, or shell gravel (and they can be monomictic, oligomictic or polymictic; *cf.* Semeniuk 2008), or beach-rock slab boulder deposits. This renders difficult a systematic classification of sediments based, in the first instance, on grainsize, or grain composition, or sediment geometry, or sedimentary origin.

The coastal sediments of the Kimberley region form stratigraphic packages that are grouped into a simplified system of eleven suites, reflecting their coastal setting and hence geometry, and some specific granulometric properties related to origin, sediment types therein, processes of formation, stratigraphy, and complexity of stratigraphy. The stratigraphic packages are:

1. Tempestites
2. Block, boulder and gravel shore deposits
3. High-tidal alluvial fans
4. Tombolos and cuspate foreland deposits
5. Beach cove deposits
6. Barrier sand/gravel deposits
7. Beach-ridge deposits
8. Sand-and-mud tidal flat systems
9. Mud tidal flat systems
10. Ria and embayment systems
11. Bar-and-lagoon systems

The classification is largely genetic, based on formative processes and on coastal setting, recognising that some lithologies (such as sand, or gravel) transcend the classification categories, and some stratigraphic units or some stratigraphic sequences will occur in more than one classification category. Of the list, for instance, categories 1–9 represent simple stratigraphic packages and form a quasi-gradational series from high energy to low energy. Each category is more or less internally homogeneous and, as such, they are listed in general granulometric order. Categories 10 and 11 represent coastal sedimentary packages that are ensembles of sediments that occur in definite coastal facies arrays within a coastal setting such as an embayment. The wave and tide energy spectrum is more complexly distributed in the ria and embayment systems and bar-and-lagoon systems. In this classification of stratigraphic packages, the emphasis is on coastal sediments and not on *biogenic rock* that also is generated along the coast in the tidal zone but which is outside the scope of this paper (Brocx & Semeniuk, in preparation).

Figure 4 illustrates the plan view of some of these stratigraphic packages. Figure 5 illustrates the occurrence of some of these stratigraphic packages: sandy coves, barriers, and beach ridge plains are generally on the wave exposed outer margins of the ria coast, and the sand-and-mud systems and mud systems are in the interior of embayments.

In terms of stratigraphic complexity, tempestites and block, boulder and gravel shore deposits are relatively simple systems, consisting usually of a single lithology. Tombolos and cuspate foreland deposits, beach cove deposits, barrier sand/gravel deposits, and beach-ridge deposits, though dominated by sand, show shoaling systems of various sandy lithology. Similarly, mud tidal flat systems though dominated by mud, show shoaling systems of various mud lithology. High-tidal alluvial fans and sand-and-mud tidal flat systems are more complicated in that they show vertical and lateral lithological changes from gravel to sand to mud. The most complicated stratigraphy occurs within the ria and

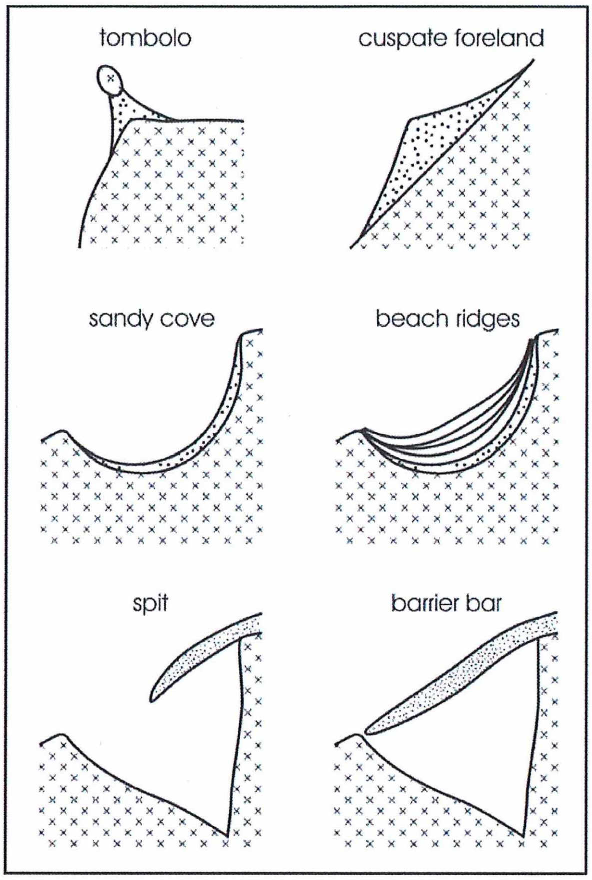


Figure 4. Diagrammatic plan of some selected sedimentary packages.

embayment systems and bar-and-lagoon systems. It should also be noted that the simple stratigraphic (geomorphic) units such as spits, or cheniers, high-tidal alluvial fans, boulder and gravel shore deposits, or tempestites can occur and do occur as stratigraphic units within ria and embayment systems and bar-and-lagoon systems. As such, while most of the sedimentary systems listed above form relatively internally homogeneous packages, even if manifesting shoaling sequences, the ria and embayment systems and bar-and-lagoon systems are sedimentologically the most complex as they have a suite of sediment types (or lithofacies), each with their own specific internal stratigraphic sequence.

While the various sedimentary packages have been separated as categories in this paper, in fact, the tombolos and cuspate forelands, beach coves, barrier sand, and beach-ridge systems form a gradational series of coastal deposits geomorphically and a gradational series of stratigraphic packages. Tombolos and cuspate forelands, while attached to the mainland or to islands, are deposits that project into the marine environment, whereas beach cove deposits are shore-conforming (shore-hugging deposits), essentially narrow, parallel to, and attached to a broadly indented mainland or open bay, and barrier sand/gravel systems are spits or barriers of sand or gravel located at the mouth of a more deeply indented embayment and form a single barrier across or nearly across the mouth of the embayment. The beach-ridge

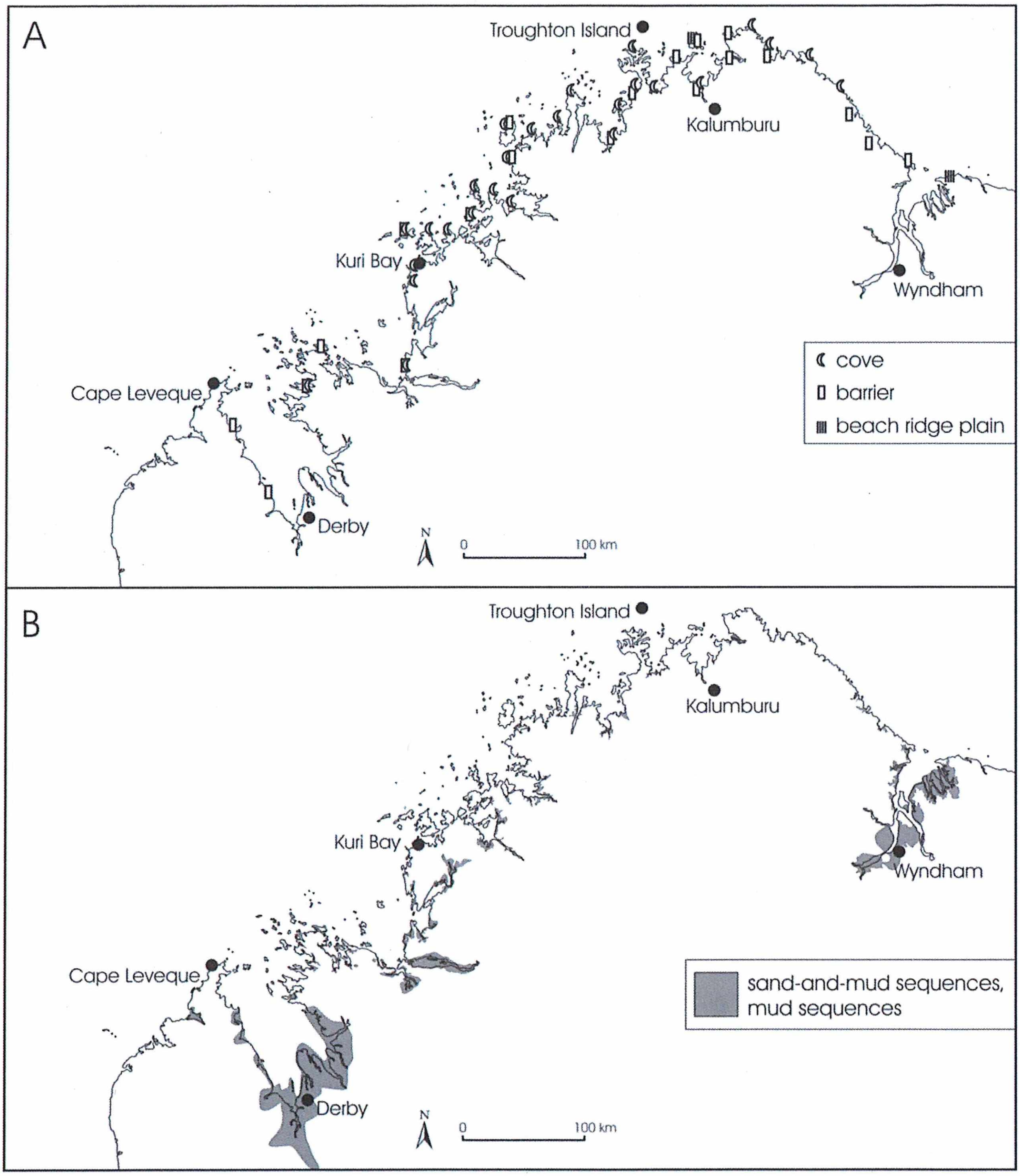


Figure 5. Maps showing occurrences of sandy coves, sand barriers, and beach ridge plains in the wave exposed outer margins of the ria coastal system, and both the sand-and-mud systems and mud systems are in the interior of embayments and gulfs.

systems are similar in setting to the beach cove systems and barrier sand systems, except that the deposits have prograded to form a narrow beach-ridge plain as a prism of sand (usually as a barrier to an embayment).

The sand-and-mud tidal flat systems and mud tidal flat systems generally comprise the tide-dominated deltas of large funnel shaped gulfs such as King Sound, Stokes Bay, and the Lawley River delta in Admiralty Gulf.

A selection of stratigraphic packages is illustrated in Figure 6, and aerial photographs and on-ground photographs of some of the sedimentary systems are shown in Figures 7 and 8.

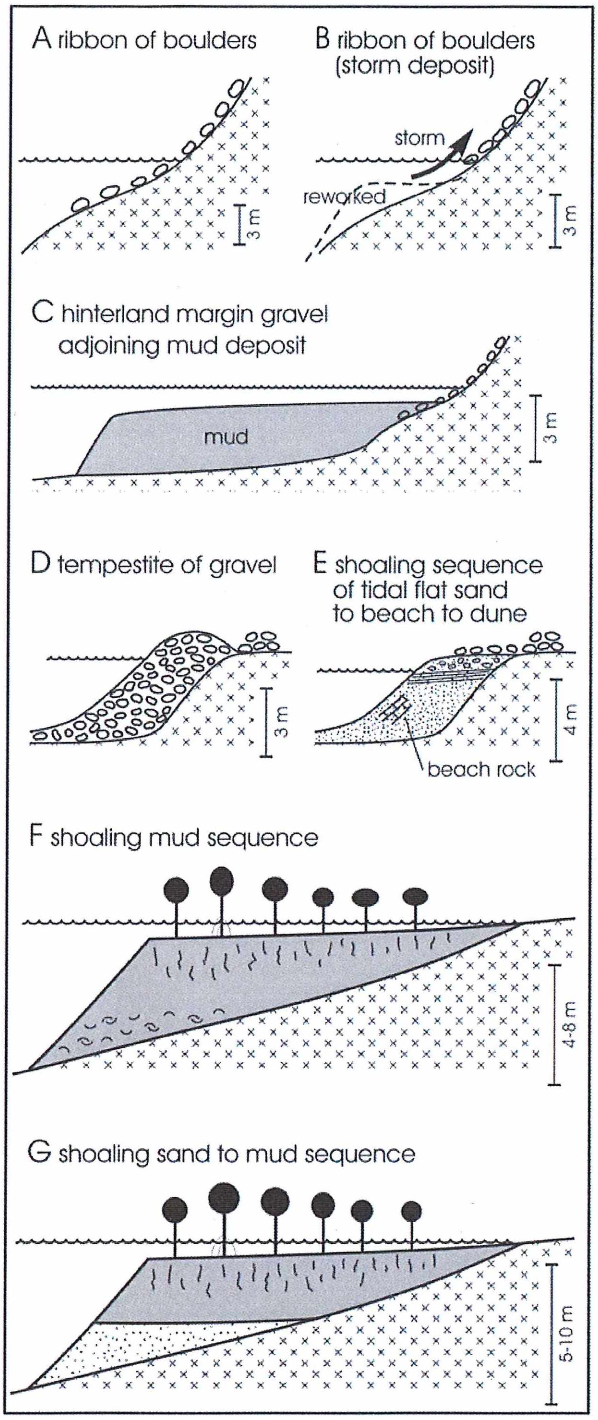


Figure 6. A selection of stratigraphic packages from accretionary systems in the Kimberley region showing their lithologic sequence.

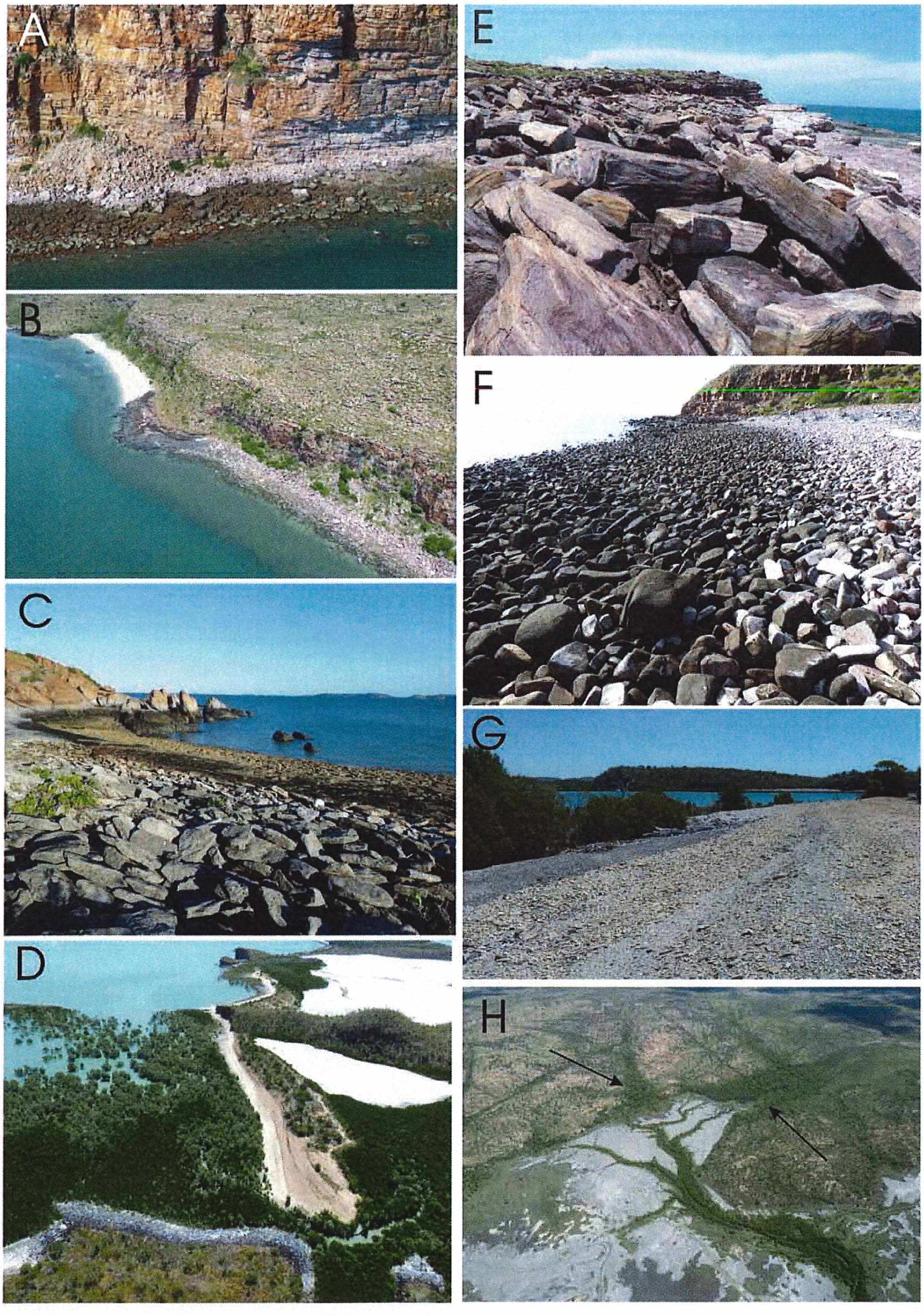
Tempestites

Tempestites are formed by storm processes such as cyclones, during times of high wave energy and generally elevated sea level, resulting from storm surges and low pressure systems. Their emplacement is by shore-directed wave action, or by longshore drift. With the latter, the tempestites commonly emanate from a rocky headland. Tempestites are located in a number of coastal settings and, as such, they comprise a variety of sediment types, but generally, all are located 1–1.5 m above the level of high tide and, locally, 2–3 m above the level of high tide. Compositionally, four types are recognised: Precambrian rock clast tempestites, beach-rock slab tempestites, shell-gravel tempestites, and coral-gravel tempestites.

Along bouldery shores bordering Precambrian rock, Precambrian rock clast tempestites form high level boulder deposits of rock slabs, rock boulders, and equant rock blocks, ~ 30 cm to 75 cm in size, with some cobble and pebble-sized gravel, but local deposits can be composed of blocks up to 2 m in size. Adjacent to sandstone cliffs or basalt cliffs, the deposits are composed of sandstone blocks and basalt blocks, respectively. Adjacent to sandstone and shale cliffs, the deposits are composed of sandstone blocks and platy shale pebble-sized clasts. Tempestites are ribbon-shaped, several metres wide, and up to 2 m thick, and perched on a rock pavement or rocky slope. Some tempestite deposits, adjacent to sandstone cliffs where joint-controlled blocks of sandstone occur along the rocky shore, are composed of blocks over 2 m in size. These latter tempestites form ribbon deposits several metres thick, and tens of metres wide. Tempestites also form gravel spits emanating from headlands and, as such, can bar embayments. Stratigraphically and lithologically, tempestites generally are structureless deposits, with randomised blocks and cobbles, but locally, there is interlayering exemplified by boulder shapes, and sizes, or layers of pebbles, or (minor) interstitial shell gravel. They have been emplaced by storm-reworking of bouldery shores, or storm-wave alongshore transport. Gravelly tempestites (as "gravel ridges") were also noted in the Kimberley region by Nott (2006).

Where there is beach rock in mid to high tidal areas, the cemented beach sand can be fragmented and transported shorewards during storms to form tempestites composed of beach rock slabs (*cf.* Semeniuk 2008 for the Canning Coast). Stratigraphically and geometrically, these tempestites are ribbon-shaped, several metres wide and up to 1 m thick, and slope towards the beach. Generally they are structureless deposits, composed of randomly oriented to weakly imbricated slabs of calcarenite or shelly calcarenite or shell gravel (reflecting the variable composition and layering of the parent beach rock), usually 30–45 cm in size and 10–20 cm thick. At above-tide levels in any

Figure 7. Aerial photographs of some of the sedimentary systems along the Kimberley Coast. A. Ribbon of boulders and pebbles along a bouldery shore. B. Ribbon of boulders along a bouldery shore and, to the left, a pocket beach (sandy cove). C. Ribbon tempestite composed of slabs of beach rock (located above the high tide level). D. Bars of coarse sand (as tempestites) as barriers to lagoons and, in foreground, a shore-fringing ribbon of gravel (tempestite). E. Tempestite comprising boulders of sandstone located above the high tide level. Structural benches cut into the sandstone in the inter-tidal zone are evident to seaward of the tempestite. F. Rounded cobbles and pebbles mainly of basalt (and some sandstone) adjoining a cliff where sandstone overlies basalt. G. Tempestite located above high tide level, composed of platey pebbles of sandstone and shale and oyster gravel; the tempestite shows lithological differentiation across the accretionary zones. H. High-tidal alluvial fan debouching onto the high-tidal flat. ▶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locations, where they have been emplaced into the lithosome of dune sands and beach ridges, interstitially, aeolian sand forms a matrix to the boulder frame.

Where molluscan shell has been winnowed, concentrated and transported shoreward by waves, and where oysters, other rocky shore molluscs, and barnacles have been eroded and reworked from rocky headlands, local shell gravel deposits can accumulate. During storms and cyclones, these shell deposits are concentrated, transported, and emplaced in high tidal levels to form shell gravel tempestites above the level of high tide. Though dominantly composed of shell, there also may be a mixture of some pebble-sized sandstone and shale rock fragments where there is local bedrock outcrop. As such, this shell gravel can be monomictic (composed dominantly of one mollusc species), oligomictic (composed dominantly of a few mollusc species and coral), or polymictic (composed of many mollusc species, and with coral and rock fragments). Stratigraphically and geometrically, these tempestites are ribbon-shaped, several metres wide and up to 1 m thick, and usually perched on a beach sand deposit further up the beach slope. Internally, they are layered deposits, with oriented shell and platy gravel.

Beach areas landward of coral communities have coral gravel tempestites. During storms and cyclones, coral gravel is concentrated, transported, and emplaced in high tidal levels to form these tempestites above the level of high tide. Though dominantly composed of gravel-sized coral fragments, there is also local shell, and some pebble-sized sandstone and shale rock fragments, and as such, the gravel can be monomictic, oligomictic, or polymictic. Stratigraphically and geometrically, these tempestites are ribbon-shaped, several metres wide and up to 1 m thick, and usually perched on a beach sand deposit further up the beach slope. Internally, they are structureless to weakly layered deposits, with oriented shell and aligned coral gravel.

Block, boulder and gravel shore deposits

Block, boulder and gravel shore deposits form along rocky shores bordering Precambrian terrane. They are shore-blanketing deposits of rock slabs and equant lithoclasts, generally ~ 30 cm to 75 cm in size between high water and subtidal levels. Usually, because of wave action at the shore, the rock clasts are rounded. Composition of clasts reflects local provenance. Sandstone cliffs and basalt cliffs produce sandstone clasts and basalt clasts, respectively; adjacent to sandstone and shale cliffs, the deposits are sandstone blocks and platy shale pebble-sized clasts. The deposits are ribbon-shaped, usually blanketing the entire tidal interval, and hence are up to tens of metres wide; they are usually thin (a few 10–30 cm thick). Block, boulder and gravel shore deposits are generally structureless, and may have some admixed shell, and interstitial sand and/or mud. Block, boulder and gravel shore deposits have formed locally by the erosion and reworking of rocky shores and terrestrial scree slopes, that have been inundated by the post-glacial marine transgression. Wave processes result in abrasion and rounding of the clasts, and in transport of sand into the lithosome. Mud accumulates interstitially by tidal current processes.

High-tidal alluvial fans

Where creeks and streams and some small rivers enter high tidal flats or the marine environment, high-tidal alluvial fans develop (Semeniuk 1985). These are usually located at EHWS but can topographically descend to levels of MHWS. In plan, they are fan-shaped to digitate deposits, up to 500 m long, and 100–200 m wide. In down-dip cross-section, they are usually asymmetrically lens-shaped, thin at their landward part, thickest in central parts (1–2 m thick), and thinning seawards. At their seaward margin they interfinger with, or underlie high tidal mud deposits. Stratigraphically and lithologically, they comprise interlayered gravel and sand and some mud (usually at high tidal parts, or at levels of EHWS and above), or interlayered sand, muddy sand and mud. Compositionally, the gravel is rock clasts, the sand is quartz, and the mud is terrigenous clay and silt. They may have some admixed shell derived from the resident high-tidal molluscs. This lithosome is maintained by fluvial processes delivering gravel, sand, and mud as an alluvial fan, with mud also being transported into the site on the highest tides.

Tombolos and cuspate foreland deposits

Where there is a shoreline supply of sand and wave action, nearshore islands adjacent to the mainland coast and clusters of islands act to accumulate sand in the relatively protected leeward zone, as tombolos or as cuspate forelands. Wave action is the dominant sedimentary process. These deposits accumulate essentially in high wave energy settings and sand forms elongate to triangular bodies in shoaling sequences. Sediment is supplied from alongshore or from offshore, and is composed of quartz sand, fragmented skeletal biota, and some shell gravel. The stratigraphy of the deposits is a shoaling sequence of burrowed to layered sand (equivalent to low tidal zones), laminated sand (mid tidal zones), and layered sand and shell sand and local shell gravel (equivalent to high tidal zones).

Beach cove deposits

Beach cove deposits are shore-conforming (curved) ribbon-shaped sand and/or gravel deposits that are narrow and parallel to (and attached to) a broadly indented mainland or open bay. The deposits accumulate in high wave energy environments and the sand and/or

◀ **Figure 8.** Aerial photographs of some of the sedimentary systems along the Kimberley Coast. A. Mouth of a river with barrier bars and leeward lagoons. Seaward of the river mouth is a fan-shaped ebb-tidal delta. B. Tombolo joining a bedrock island to the main shore. C. Barrier of sand barring a narrow ravine. D. Barrier of gravel barring a lagoon (formerly an open embayment). E. Mud deposits filling an series of broad open embayments. F. Aerial photography showing a range of sedimentary features: (1) sandy cove; (2) and (3) barrier of sand composed of parallel beach ridges barring a small lagoon; (4) older spits emanating from headland; (5) older spit barring a muddy lagoon; and (6) mud-filled channel-way vegetated by mangroves and incised by a meandering tidal creek. G. Sand bars and intervening mud-filled lagoons at the mouth of a river outlet. H. Accretionary lobe of mud (with zone mangrove vegetation cover) in a mud-dominated sedimentary system. I. Beach cove system; from left to right, bioturbated sand in the low tidal zone, laminated sand in the tidal zone, and cross-laminated and structureless (vegetated) sand in the supratidal dune zone.

gravel form deposits parallel to the shore. If composed of sand, aeolian transport mobilises sediment from high tidal parts of the beach to form dunes. For sand, the stratigraphy of the deposits shows a shoaling sequence and comprises four units: a low tidal burrowed to layered sand, a mid-tidal mainly burrowed sand, high-tidal layered to structureless sand and shelly sand (and local layers of shell gravel), and a supratidal aeolian structureless to root structured sand. For gravel, the stratigraphy of the deposits is generally a structureless gravel aggregate, but clasts may be imbricated or be aligned if the clasts are platy. Supratidal parts of the system may have a stratigraphic capping of tempestite, which often has interstitial aeolian sand.

Barrier sand/gravel deposits

Barrier sand/gravel deposits are spits or barriers of sand or gravel located at the mouth of a deeply indented embayment, forming a single barrier across the embayment. The deposits are prism-form or shoe-string in geometry, but the process of formation, and sedimentary accumulation is similar to that outlined for the beach cove systems. The stratigraphy of the sand deposits shows a shoaling sequence comprising four units: a low tidal burrowed to layered sand, a mid-tidal mainly burrowed sand, high-tidal layered to structureless sand and shelly sand (with local shell gravel), and a supratidal aeolian structureless to root structured sand. As for the beach cove deposits, supratidal parts of this system also may have a stratigraphic capping of tempestite, which commonly has interstitial aeolian sand. Barriers composed of gravel are mainly rock gravel deposits that are internally structureless or imbricated. Barrier sand deposits along the Kimberley Coast were also noted by Short (2006).

Beach-ridge deposits

Beach-ridge systems are similar in setting to (sandy) beach cove systems and barrier sand systems except that they have prograded to form a narrow beach-ridge plain as a prism of sand. The processes of sedimentation, dominated by wave and aeolian transport, are also similar. Progradation is manifest by shore-parallel linear beach ridges separated by narrow swales. Geometrically, overall, the beach-ridge systems are prism-shaped deposits that stratigraphically show a shoaling sequence of four units: a low tidal burrowed to layered sand, a mid-tidal mainly burrowed sand, high-tidal layered to structureless sand and shelly sand (with local shell gravel), and a supratidal aeolian structureless to root structured sand. Supratidal parts of the beach-ridge system may have a local stratigraphic capping of tempestite, with interstitial aeolian sand, with ribbons of tempestites commonly buried by later deposits of aeolian sand.

Sand-and-mud tidal flat systems

Sand-and-mud tidal flat systems are located in gulfs and embayments where there is riverine influx of sand and mud into a gulf, or tidal transport of sand and mud into an embayment. They comprise some of the tide-dominated deltas in the region (Semeniuk 1981a; Brocx & Semeniuk 2011). The sediments include sand and shelly sand, muddy sand, and mud. Sediment types are strongly related to tidal level. Low tidal areas are dominated by sand and some shelly sand. Processes here are strong tidal transport by traction, to form megarippled sand and plane-bed sand, and reworking by waves on the rising and falling tide when water depths are < 1 m, to form wave ripples. Biota contribute shell, and where this is concentrated by winnowing, shelly sand and shell gravel accumulate. The only common burrowing organism is the sand bubbler crab and sand-tube worms. Low-tidal to mid-tidal areas are underlain by muddy sand, or interlayered sand and mud. Tidal currents transport sand, and mud is deposited from suspension during slack water at high tide, resulting in alternating sand and mud layers. Infauna puncture this layered sequence with burrows, but where the sediments are thoroughly burrow-mixed, muddy sand is formed. Mid-tidal to high-tidal areas are dominated by mud deposits that accumulate from suspension on slack water during high tide, and by processes of scour lag and settling lag. The mid tidal to high tidal interval also is the zone of mangroves, which contribute organic material and whose roots structure the sediment. Skeletal organisms, such as molluscs, contribute skeletal material and burrowing organisms, such as crabs, bioturbate the sediment. With progradation and shoaling, the sedimentary facies form a relatively simple sequence of a lower unit of rippled and laminated sand, overlain by interlayered sand and mud, or by muddy sand that, in turn, is overlain by mangrove-structured mud. In King Sound, where the best example of this sequence occurs (Semeniuk & Brocx 2011), the total stratigraphic package is ~ 11 m thick. Since the various sedimentary units are strongly related to tidal levels, the thickness of the sediment units within the stratigraphic package have thicknesses broadly related to tidal intervals, with sand at the base ~ 2m thick, the unit of interlayered sand-and-mud or muddy sand 3–4 m thick, and the mangrove-structured mud ~ 5 m thick. The delta of the Drysdale River is also relatively large, the largest in the Kimberley Coast sector, and its ocean-facing distal margin manifests numerous spits and cheniers.

Variation on this general sequence occurs where cheniers of sand and shelly sand are developed at levels of MHWS. These bodies are tens of metres long, several metres wide, and 1–3 m thick. They occur perched on or embedded in the mangrove structured mud, often on an eroded base.

Mud tidal flat systems

Mud tidal flat systems are located in embayments, protected inlets, lagoons that have some tidal connection, gulfs where riverine influx is dominantly mud, or there is tidal transport of mud into an embayment. They underlie some of the tide-dominated deltas in the region where mud dominates the sedimentary suite. Locally, mud also accumulates to form "tombolo-like" coastal sediment structures, in mud-dominated areas, extending from a rocky headland or muddy linear shoal to a nearby rocky island. Muddy sediments range from laminated mud, shelly mud, biostromal mud, burrowed mud, and mangrove-structured mud. These sediment types are strongly related to tidal level. Low tidal areas are dominated by burrowed mud and shelly mud. Biota contribute shell and, where this is concentrated by winnowing, shelly mud and shell gravel accumulate. Burrowing organisms are common. Low tide to mid tidal areas are underlain by laminated mud, biostromal mud (with mussel beds embedded in the mud), and burrowed mud. The mid tidal to high tidal interval is the zone of mangroves, and they contribute plant material and their roots structure the sediment. Skeletal organisms, such as molluscs, contribute skeletal material, and burrowing organisms, such as crabs, bioturbate the sediment. At all tidal levels, dominant processes are strong tidal transport, with accumulation of mud on the slack water at high tide. During rising and falling tides, and during storms, the mud is reworked, and shell can be concentrated into layers. With progradation and/or shoaling, the sedimentary facies form a relatively simple sequence of a lower unit of mud and shelly mud, overlain by laminated, burrowed and biostromal mud which, in turn, is overlain by mangrove-structured mud. In the embayments of the Port Warrender area (Semeniuk 1983, 1985) and in the Lawley River delta and the Charnley River delta (in Collier Bay) where the best examples of this sequence occur, the total stratigraphic package are ~ 8 m thick, but the thickness of the package will depend on the depth of the basin setting where the mud has been accumulating. In the embayments of the Port Warrender area and in the Lawley River delta, since the various sedimentary units are strongly related to tidal levels, the thickness of the sediment units within the stratigraphic package have thicknesses broadly related to tidal intervals, with the lower mud unit ~ 2 m thick, the middle mud unit 2–3 m thick, and the mangrove-structured mud ~ 3 m thick.

Ria and embayment systems

Ria and embayment stratigraphic systems form in coastal settings that are narrow, v-shaped to open ravines and embayments, or bay-like embayments (Semeniuk 1985). The main features for development of sedimentary packages within the rias and embayments are that: 1. the rias and embayments are relatively protected to accumulate mud in their interiors, or barriers of sand as spits partially bar the embayment to create the protected low energy environment for mud to accumulate through scour-lag and settling-lag processes; 2. the accumulations of mud are incised by meandering tidal creeks which, through bank erosion, and sediment redistribution, develop shoaling point bars deposits and shoaling mid-channel shoal deposits; 3. headlands, bordering the mouth of the embayment, subject to wave action, develop rocky shore bouldery deposits; 4. rocky headlands are sites where rocky-shore biota generate skeletal material as oyster shell gravel, rocky shore molluscan debris, and barnacle gravel; 5. skeletal material formed at the rocky shore headland, driven by wave action on the headlands, and by tidal currents, accumulate as spits emanating from the headland and migrate into the embayment; 6. there are buried colluvial slopes of the upland along the margins of the embayment, still fed by sheet wash from the upland scree slopes; and 7. upland creeks, streams, and small river systems continue to deliver fluvial gravel, sand, and mud to the shore to form high-tidal alluvial fans. Stratigraphically and geometrically, the embayment mud deposits are wedge-shaped, and composed of laminated sand or burrowed mud at stratigraphic levels of low tide, burrowed mud at levels of low to mid tide, and root-structured mangrove-bearing mud at stratigraphic levels of mid to high tide. The point bars along tidal creeks are lunate-lensoid shoaling accumulations, several metres wide and 2–3 m thick, of sand to mud, or mud, or mud-clast conglomerate (where creek bank erosion has yielded an abundance of mud fragments). The mid shoal deposits along tidal creeks, also several metres wide and 2–3 m thick, have similar stratigraphy to the point bars but have elongate lensoid geometry. Headlands bordering the mouth of the embayment have ribbons of boulders and gravel blanketing the shore, several metres wide and < 1 m thick. Spits emanating from the headlands are prisms or shoestrings of sand and shell gravel, several metres wide, several metres thick, and tens to a few hundred metres long; their stratigraphy, depending on location along the length of the spit, is crudely layered shell gravel, or skeletal and quartz sand resting on tidal flat mud, or a shoaling sequence of layered sand and shelly sand grading up to crudely layered shell gavel or skeletal and quartz sand. Colluvium along the margins of the embayment is ribbon-shaped, and a few metres wide and < 1 m thick; stratigraphically, it is most commonly a structureless or root-structured muddy pebble or muddy cobble deposit. High-tidal alluvial fans are tens of metres to hundreds of metres long and wide (depending on the size of the contributing creek, river, or rivulets), and stratigraphically composed of gravel and sand and mud at the proximal portions, which grade (often interfingering) into sand and mud, and then mud to seawards. The ensemble of alluvial fan sediments and subfacies therein are 1–3 m in thickness.

Bar-and-lagoon systems

Bar-and-lagoon systems form in embayment settings. The embayments can be open and bay-like, or narrow. The main features for development of this sedimentary package are: 1. the embayment is protected enough to accumulate mud in its interior; 2. there is a supply of material as sand, shell, or rock gravel transported by waves, storms, or tide, to bar the mouth of the embayment; and 3. there are rocky headlands to frame the lagoon and act as anchoring sites for the barrier bar. Driven by wave action on the headlands, and by tidal currents, skeletal material formed at rocky headlands accumulates as spits emanating from the headland, or sand is transported by waves and tides into the mouth of the embayment, or gravel is transported alongshore to form a gravel barrier spit. All these deposits function, however, to bar the embayment to form a lagoon. Where sandy, the barrier may accrete to the level where coastal dunes cap the (beach-derived) barrier. In this context, if active, the dunes may be landward-ingressing, and encroach into the leeward lagoon, burying mangroves and/or encroaching into and overlying the lagoonal deposits. At its contact with the rocky headland, the barrier bar often has a narrow tidal creek that exchanges tidal waters between the lagoon and the open marine environment, such that the lagoon is flooded on the high tides. These tidal creeks commonly have an ebb-tidal delta at their mouth. However, some lagoons of a bar-and-lagoon system are wholly isolated from the open marine environment. In many sedimentary respects, the bar-and-lagoon systems have a number of features in common with ria and embayment systems, *viz.*, rocky headlands with their source of skeletal and rock gravel material, high tidal alluvial fans, and buried colluvial slopes along the margins of the embayment. Except for an exchange channel at one end of the bar, tidal creek networks traversing the mud-filled lagoon are not a common feature of bar-and-lagoon systems, because there is not enough tidal exchange, and therefore tidal currents are not strong enough to generate them. Stratigraphically and geometrically, the mud deposits under the lagoon are wedge-shaped to lenticular units, and composed of mangrove-structured mud at levels of high tide to mid tide, underlain by burrowed mud at levels of mid tide to low tide. The stratigraphy of the barrier depends on its composition. Sandy barriers have a shoaling sequence of burrowed sand, laminated sand, and a capping of dune sands. Gravelly barriers are relatively homogeneous (structureless) or locally imbricated. Shell gravel barriers are layered. The barriers have two types of stratigraphic relationship with the lagoon deposits: 1. they have predated the accumulation of the lagoon deposits, the lagoonal muds onlap and (for sandy and shell gravel barriers) interfinger with the leeward margin of the barrier, or rock gravel barriers are onlapped by the lagoon muds on their leeward side; 2. the barriers postdate the initial accumulation of the lagoon deposits, and here the barrier deposits rest on the lagoonal muds. Where the barrier is in retreat into the embayment, lagoonal muds are exposed along the seaward base of the barrier deposits (Fig. 9). Ebb-tidal deltas are fan-shaped deposits underlain by laminated sand and shelly sand, and bioturbated sand.

The main stratigraphic units in the bar-and-lagoon system are: the barrier deposits, the lagoon deposits, and the deposits associated with the headland and embayment setting (such as colluvium bordering the upland slopes, the tidal creeks, the high-tidal alluvial fans), and the ebb-tidal delta deposits. The stratigraphic geometry and lithologic sequence in the barrier of the bar-and-lagoon system are similar to that described for the barrier sand/gravel system. The stratigraphic geometry and lithologic sequence in the lagoon generally are similar to that described for the tidal mud systems, but some lagoons are filled with sand and/or with mud, or interlayered sand and mud. The sand within the sand-filled lagoons derives from the fluvial sources that feed the alluvial fans at their head, or from aeolian input from the dune portion of the barrier that bars the lagoon. The stratigraphic geometry and lithologic sequence of the colluvium bordering the upland slopes, the tidal creeks, and the high-tidal alluvial fan within the bar-and-lagoon system are similar to those units described above in ria and embayment systems.

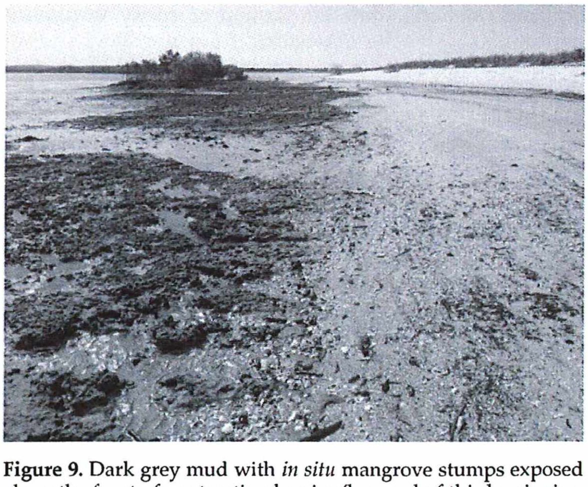

Figure 9. Dark grey mud with *in situ* mangrove stumps exposed along the front of a retreating barrier (leeward of this barrier is a mangrove-vegetated mud-filled lagoon).

Discussion and conclusions

Though marginal to a plateau underlain by an apparently repetitive sequence of sandstone and volcanic rock (the Kimberley Basin) and folded metamorphic, volcanic, and igneous rock (the King Leopold Orogen), and a relatively even expression of regional coastal geomorphology (*i.e.*, the array of rias, albeit in different sizes, shapes and orientation; Brocx & Semeniuk 2011), the coastal sedimentary environments of the Kimberley region, present a diverse system of stratigraphic suites that embody a variety of recognisable sediment types, source origins, and depositional style and settings. This variability is expressed in many ways: as the dominance at a given site of gravel *versus* sand *versus* mud; in the origin of gravel at the coast as locally derived *versus* distally derived; in the extent that biogenesis develops sedimentary particles and influences development of sediment types and sedimentary packages; and in the different oceanographic processes prevailing (such as tide-dominated, wave-dominated or cyclone generated conditions) that will sort, transport, shape and emplace the sedimentary bodies. This multitude of primary materials, provenances, and processes are superimposed on coastal settings that include large exposed embayments, smaller exposed embayments, protected embayments, coastal ravines, archipelago coasts, and straight coasts, that have varying orientation in relation to oceanographic aspect. As a result, the array of coastal sedimentary patterns and stratigraphic packages in the Kimberley region is considerable. In each case, the stratigraphy effectively and unequivocally reflects oceanographic setting, coastal setting and form, sediment types and supply, and biogenesis.

As described above, oceanographic factors and the oceanographic aspect of the coast play a large part in determining sedimentary style and type of stratigraphic package. The prevailing and ubiquitous oceanographic condition in the region is the extreme tidal range which results in the development of coastal geomorphic forms of all scales down to small/fine scale sedimentary features. Examples range from the large scale sedimentary accumulations such as the mega-scale tide-dominated delta of the Fitzroy River with its tidally-oriented shoals, to the ubiquitously developed meandering and ramifying tidal creek systems that are erosional on muddy tidal flats, to large fields of sand shoals and megaripples where sand dominates the low tidal areas, to tidal waters delivering mud to areas that are semi-enclosed or protected such that high-tidal mud deposits are ever-present except in wave-agitated areas. Wind waves and onshore wind effects are the next most important and prevailing coastal processes in the Kimberley coastal region, and here oceanographic aspect of the coast becomes a determinant of the sedimentary style and stratigraphic sequence. On exposed coasts, wind waves result in the development of sandy beaches, spits, tombolos, cuspate forelands, beach-ridge plains, wave agitated bouldery shores (with rounding of the boulders and pebbles), and dune fields. As such, the best developed sandy beaches, spits, tombolos, cuspate forelands, beach-ridge plains occur on the outer exposed parts of the ria shore complex. Cyclones and other storms also have an effect on the coast and, while at times their effects are extreme (*e.g.*, mobilisation of blocks and boulders to above the high tide level), they are not a prevailing process and tend to generate specific coastal forms and coastal deposits, namely erosional features such as mud cliffs along mangrove shores and sand cliffs along beach shores, and depositional features such as cheniers, spits and sand sheets, and the emplacement of block and boulder deposits or skeletal gravel at or above high tide levels as ribbon deposits. The effects of a given cyclonic event or storm event are not widespread, but tend to be more localised.

Sediment supply also plays a major part in determining sedimentary style and type of stratigraphic package. Where there is abundant sediment supply, there are large sedimentary accumulations that are subject to the oceanographic processes at a site. To illustrate, the Fitzroy River, with a large drainage basin, and abundant and diverse sediment supply, has large distal accumulations of prograded (tidal flat) sedimentary packages. At the other extreme, rocky shores that shed slabs, blocks and boulders of rock to the coast have a narrow ribbon of bouldery shore deposits, and alluvial fans, that are the distal accumulation of smaller rivers at the head of an embayment, have localised relatively small accumulations of gravel, sand and mud restricted to the high-tidal zone.

The geometry and style of sedimentary accumulations are strongly dependent on the coastal receiving basins (*i.e.*, "basin" geometry or the "basin" wherein the coastal sediments accumulate) developed in the Kimberley region which, in turn, are underpinned by geology of specific lithology and tectonic structure. The rocky coasts of the Kimberley region are controlled by geology, both in terms of rock types, rock structures, and the derivative geomorphology. The fractured rock system of the edge of the Kimberley Plateau, the folded rock system of ridge-and-basin of the King Leopold Orogen, and the landscapes derived from sandstone or basalt bedrock, directly result in a variety of coastal forms from narrow ravines, to narrow embayments, to cliffed shores, rounded shores, rounded embayments, to coastal inundated trellis drainage, fracture and fault oriented gulfs, ravines, and fractured rocks. The shape, size and orientation of the coast as a result of these foundational differences also play a large part in determining sedimentary style and type of stratigraphic package because coastal configuration and "basin" geometry in relation or orientation to coastal processes determine how much sediment accumulates at the coast, what type of sediment accumulates, and the geometry of the sedimentary package. For instance, basalt-based landscapes have developed a different coastal geometry to fractured sandstone based landscapes in terms of coastal forms developed, and type of the seacliffs or shore slopes.

Bedrock geology and the size of the drainage basins of the onshore hinterland have also determined the type and extent of sediment delivery. The largest rivers, axiomatically, have delivered the largest volumes of sediments to the coast, but the type of sediment granulometrically and mineralogically delivered to the coast will be determined by the nature of the source rocks in the drainage basin. Similarly, networks of drainage basins such as those emptying into Cambridge Gulf have delivered large volumes of sediments to the coast. However, leaving aside the largest rivers in the region (*viz.*, the Fitzroy, Meda, May, Prince Regent, Collier, and Lawley Rivers, and the network of the Pentecost, Durack, and King rivers), many of the other smaller rivers in fact are short rivers with relatively small drainage basins, and while they have an influence on coastal development, in that they have incised fracture-controlled gorges and ravines that have been inundated at the coast (forming narrow to open embayments or coastal ravines), they do not necessarily have associated large sedimentary volumes. Bedrock geology has an influence on sedimentary patterns in that sand is derived from landscapes underlain by sandstone, and mud is predominantly derived from landscapes that have a multiplicity of rock types at the drainage basin source (*e.g.*, the Fitzroy River drainage basin and the Pentecost, Durack, and King Rivers drainage basins), or have a basalt landscape (*e.g.*, the drainage basin of the Lawley River). Notwithstanding the influence of distal sedimentary provenance in determining lithology of coastal sediments, there is also the factor of the reworking of earlier Holocene sediments that can generate and deliver large volumes of mud into the modern sedimentary "basin".

The diversity of sedimentary deposits and their stratigraphic dissimilarity are the foundation for the variation and complexity of the coastal ecosystems that occur in the Kimberley region. The variation in coastal substrate types, tidal level of the substrate types, coastal groundwater aquifers and their hydrochemistry, tidal groundwater aquifers and their hydrochemistry, habitats, and the oceanographic processes that maintain the coastal sedimentary deposits and stratigraphic packages, underpin the ecological processes that maintain coastal biota.

The coastal region of the Kimberley, encompassing the Kimberley Coast as a ria coast, and King Sound (including Stokes Bay), and Cambridge Gulf, presents a globally unique ensemble of sedimentary packages. Ria coasts of the style represented along the Kimberley Coast are uncommon in the world (Brocx & Semeniuk 2011). The examples of coasts of comparable extent most similar to the Kimberley region are the indented coasts of Chile, Scotland, and northern Siberia, but these latter coasts actually are fjords (Brocx & Semeniuk 2011) and have a very different suite of sediments, coastal processes and climatic parameters (*e.g.*, coastal processes are underpinned by boreal and arctic climate processes, not tropical processes). In terms of ria coastal types developed elsewhere, the south-west coast of Ireland provides a quasi-comparable coast setting in geometric form, in that geological grain has controlled the form of the rias, but this setting is wholly different in terms of climate, sedimentary suites, and coastal processes. It is also of limited extent, *viz.*, *circa* 140 km in length of coast as compared to 700 km of the Kimberley ria coast. In this context, the sediment assemblages along the rias of the Kimberley Coast are globally distinct. The nearest equivalents to the Kimberley coastal region either in terms of gulf form or tide-dominated deltas of King Sound, Cambridge Gulf, the Lawley River Delta, and Charnley River delta in Collier Bay are the Colorado River delta on the western coast of the United States of America (Thompson 1969), the Klang-Langat Delta of Malaysia (Coleman *et al.* 1970), and the Brahmaputra River and Ganges River deltas (Allison 1996). The Colorado River delta is similar to the tide-dominated deltas of King Sound and Cambridge Gulf in that it is in a semi-arid climate and manifests salt flats, and is of comparable size. However, it is dissimilar in that it is mangrove-free (and hence lacks the mangrove-generated lithofacies), it is of a smaller tidal range, and doesn't contain the complex Holocene stratigraphy of the King Sound area. The Klang-Langat Delta and the Brahmaputra River and Ganges River deltas are mangrove dominated deltas with mud-dominated deltaic sequences and without the salt flats. In this context, the sediment assemblages along the tide-dominated deltas of the Kimberley region also are globally distinct.

The sediments of the Kimberley Coast are important natural history features of the region, but need to be viewed as ensembles of sediment packages expressed variably across the region. Located in gulfs, in tide-dominated deltas, rias, and with sedimentary suites ranging from cyclone-generated tempestites, to coastal sedimentary suites and mud-dominated sediment systems, and their associated stratigraphic packages developed by macrotidal and tropical conditions, they should be viewed as a heterogeneous and patchy response to the regional abiotic and biotic processes acting on the regional geological template. In other words, there is interplay between coastal processes, coastal forms, sediment supply, and sediment type. Viewed in this manner, the sedimentary packages of the Kimberley Coast as an integrated system are globally unique, and present a model that shows the inter-relationship of coastal morphology, oceanographic factors, sedimentation style and stratigraphic packages.

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