Coastal geoheritage: a hierarchical approach to classifying coastal types as a basis for identifying geodiversity and sites of significance in Western Australia

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Abstract

Identifying sites of coastal geoheritage significance begins with classification of coastal geology and geomorphology. However, classifying coasts for purposes of geoheritage is made difficult due to the complexity, intergradation, and different scales at which coastal features are expressed, with variation potentially present locally or regionally. Also, geoheritage must address geological content as well as coastal geomorphology expressed erosionally and/or sedimentologically, and Earth history as manifested in coastal erosional and stratigraphic products. While geological and environmental settings play important roles in determining regional variation in coastal form and coastal products, or expression of geological content, coasts at the local scale commonly are expressions of one or more of the main processes of (marine) inundation, erosion, and deposition, and/or of subdominant processes of biogenic activity and diagenesis. To address this coastal geodiversity for geoheritage and geoconservation in Western Australia, a three-level scalar hierarchical approach is used. Level 1 identifies the regional geological and environmental setting, *i.e.*, recognising major cratons and basins, and the climatic/oceanographic setting of a coast, which determine regional coastal forms. Level 2 identifies the main coastal types developed by coast-forming processes (*e.g.*, marine inundation of pre-existing landforms; coastal erosion; exhuming of older landforms; construction by Holocene sedimentation, coasts formed biogenically, amongst others), as well as coastal types that illustrate Holocene history geomorphically or stratigraphically, or manifest pre-Holocene rock sequences in sea cliffs. Level 3 identifies finer-scale characteristics particular to any coast within its regional setting to develop an inventory of features providing data within the context of the coastal types for comparative geoconservation purposes. All three levels need to be applied to fully categorise coasts for assessing geoheritage values and for geoconservation.

Keywords: coastal geoheritage, coastal types, geoheritage, geoconservation, geodiversity, coastal classification, hierarchical coastal classification.

Introduction

As the zone of intersection and interaction of land, sea, groundwater, and atmosphere, and the processes therein, the coast is one of the most complex environments on the Earth's surface, with a multiplicity of processes operating at a number of scales. With other matters such as lithology, structure, or geological framework being equal, the coastal zone generally results in greater geodiversity in processes and products than elsewhere (Brocx & Semeniuk 2009). As such, it is an environment where there should be a focus on geoconservation and to date, indeed, there have been many coastal locations of geoheritage significance identified at the global and national level (particularly rocky shores and cliffs with their exposures illustrating geological history, types sections, or geological principles). However, the coastal zone is one of the most difficult environments to classify into natural groups, for a number of reasons: 1. it is complex, spanning geology, geomorphology, biogenesis[1] and diagenesis; 2. there are features that are specifically formed at the coast that are not part of natural gradations or groupings (*e.g.*, diagenetic products); 3. good exposures of geological sequences of geoheritage significance in natural cliffs are *ad hoc* products of coastal erosion and not part of a coastal gradation or coastal system; and 4. there are various scales at which geological features are evident. This complexity has not been previously recognised in assigning geoheritage significance and undertaking geoconservation.

[1] *Biogenesis* has two meanings: in Geology it refers to the formation by organisms of products such as coral reefs, shells, or bioturbation structures (*i.e.*, formed biogenically), while in Biology it refers to the principle that organisms arise only by the reproduction of other organisms (Bates & Jackson 1987). The term is used more commonly in the realm of Biology. In this paper, we use *biogenesis* in the geological sense, but also *biogenic activity* and *biogenic process(es)* as more general process-oriented terms.

Coasts have been classified previously from a number of scientific perspectives and purposes and at different specific scales, and using a variety of approaches, and such classifications have resulted in an understanding of coastal forms or coastal evolution at global scale down to local scale, in models of sedimentation and stratigraphy oriented towards geohistory and/or resource exploration, in developing a framework for habitats, and in rational environmental management of the coastal zone. As such, there is a large body of literature dealing with categorisation of coastal forms based on their morphology, origin, evolution, and tectonic, oceanographic, or climatic setting (Johnson 1919; Valentin 1952; Bloom 1965; King 1972; Shepard 1973; Davies 1980; Kelletat 1995; Woodroffe 2002; Schwartz 2005). However, the various classifications developed to date have not lent themselves to be directly applicable to issues of geoheritage and geoconservation. For instance, genetic classifications provide an understanding of coastal evolution, coastal development, or coastal types but have not been useful in comparative studies for geoheritage and geoconservation in that they tend to be process-oriented.

Thus, while coastal classification systems abound, coasts have not been systematically classified for the purposes of recognising sites of geoheritage significance and for geoconservation. Moreover, geoheritage and geoconservation are relatively young endeavours compared to other established disciplines involved with the coast. For example, sedimentology is a long-established science (Wentworth 1922; Krumbein & Pettijohn 1938; Twenhofel 1939; Shrock 1948; Pettijohn 1949; Allen 1970), and sedimentologists have developed coastal classifications at regional scale (*e.g*. delta forms, barrier islands, amongst others), and an understanding of sedimentary sequences and sedimentary products at finer scales (Reineck & Singh 1980). Similarly, coastal geomorphologists have classified coasts (though occasionally somewhat differently to sedimentologists) generally at regional to large scales and, at a more detailed scale, rocky shore specialists, for example, have classified medium and small-scale erosional features along coasts. All such classifications have been directed to the objective of the specialist science and (axiomatically) not in a manner to provide information directly to identify sites of geoheritage significance or for geoconservation, though their information is useful for comparative geoheritage and geoconservation usually at small scales of reference. Locally, where researchers have attempted to address geoheritage of coastal zones, they have applied existing terms and established classification(s) of smaller-scale geomorphic and sedimentological features. This has resulted in an inventory of coastal features (*e.g*., Kiernan 1997) rather than a coastal classification for geoheritage purposes.

Whether it is species, ecosystems, or physical features, it is the differences (or diversity) in types of natural features, *viz*., biodiversity or geodiversity, as well as their rarity and representativeness that form the basis of selection of species, or of sites for conservation. Identification of coastal types, *i.e*., the "species of coasts", and their geodiversity, should form the prelude to identifying sites of geoheritage significance. To this objective, this paper presents a classification of coastal types as the first step in identifying sites of geoheritage significance for geoconservation and coastal management. We present here a hierarchical approach that identifies, in the first instance, "families" of coastal types, as a context and a prelude to identifying "species of coasts".

Coasts initially can be categorised according to geological setting, (*e.g*., Precambrian rock coast, Tertiary limestone coast, Quaternary limestone coast), climatic setting (*e.g*., tropical; humid or tropical arid coasts), and oceanographic setting. Thereafter, coasts can be separated on the basis of forms developed by marine inundation, erosion, sedimentation, biogenesis, or diagenesis (as will be described later) and then, if necessary, subdivided into finer scales that result in recognition of further forms and patterns. There can be variation along the coast in terms of processes and products and development of coastal types, and these can be present at different scales within a region, and across regions. Also, many coastal localities around the world have classic exposures of types sections, reference sections, fossil occurrences, geological features such as large nodules and columnar jointing, and exposures illustrating Earth history (exposing geohistorical sequences). As a zone of interaction of sea, land, atmosphere and groundwater, it can also be a zone of distinct diagenesis. In this paper, categories of coastal features or coastal types are classified in order to identify sites that may have geoheritage significance within a context of geological region and environmental setting (climate/oceanography). This approach to assessing sites of geoheritage significance will be developed further in future papers.

The coastline of Western Australia provides an excellent starting point for the development of a coastal classification for purposes of geoheritage and geoconservation as it manifests a wide variety of coastal forms along its 8000 km length and 22^{o} of latitudinal range, a length that transcends several geological regions (*viz*., the Kimberley region, the Canning Coast, through to the Eucla Basin), several climate zones (from tropical to near-temperate, and humid to arid), and various oceanographic and coastal settings (from macrotidal to microtidal, from wave-dominated to tide-dominated, from protected to wind-dominated).

In contrast, European countries, while trans-nationally complex, tend to involve only short segments of the subcontinental geological, climatic, and oceanographic variability as represented in Western Australia. A further contrast is provided by the western coast of the Americas, being a collision coast, while transcending a large latitudinal distance and climate belts, presents at the megascale a relatively uniform coastal form of uplift determined by tectonic plate collision.

Terms, scope and scale, involved in coastal geoheritage

The term *coast* is used to denote the modern environment separating land and sea, and generally occurring between high and low tide, and the term *coastal* is used to denote a variety of environments that are related to the interaction between oceanic and terrestrial processes (Brocx & Semeniuk 2009). As such, coastal zones will contain both land and ocean components, and have boundaries to the land and ocean that are determined by the degree of influence of the land on the ocean and the ocean on the land; and may not be of uniform width, height, or depth (Kay & Alder 1999). These environments may include the seaward margin of prograded coastal plains, or coastal dune belts (where they have been formed by coastal processes), or areas influenced by marine processes such as salt spray.

In this context, the term *coastal geoheritage* is used to denote geoheritage aspects of the coastal zone where the coastal zone is the shore, and where terrestrial and oceanic areas are, or have been, influenced by Holocene coastal processes.

Since coasts are Holocene, the emphasis on coastal geoheritage features is on Holocene forms, whether they are marine inundation features (formed by the last post-glacial transgression), erosional features cut into materials of Holocene, Pleistocene, or older age, or depositional landforms and sedimentary sequences developed during the Holocene. As such, Pleistocene coastal landforms, Pleistocene coastal sedimentary sequences, and other Pleistocene features (regardless of how closely they spatially are related to Holocene shorelines), and exhumed pre-Holocene former coastlines (such as exhumed cliffs or rocky shore pavements), are relegated to the category of ancient sequences. Stranded sea cliffs of Pleistocene age or earlier, are not included in this definition of coast or coastal.

The term *bedrock* is used in this paper to refer to rocks of sedimentary, igneous, and metamorphic origin, of Precambrian to Phanerozoic age (*e.g.*, the Silurian Tumblagooda Sandstone, and the Mesozoic Broome Sandstone), and not only to Precambrian basement rocks.

Following Brocx & Semeniuk (2007), the scope of geoheritage involves different categories of sites, all of which can be identified in the coastal zone.

- type examples, reference sites or locations for stratigraphy, fossils, soil reference profiles, mineral sites, and geomorphic sites, including locations for teaching research, and reference;
- cultural sites where classic locations have been described;
- geohistorical sites where there are classic exposures in cliff and outcrops where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed;
- modern, active landscapes where dynamic processes are operating.

Cliffs, or other types of coastal outcrops, that expose ancient sequences (ranging from Precambrian in age such as the sequences exposed in cliffs along the central Pilbara Coast, to cliffs exposing Mesozoic or Cainozoic sequences such as along the edge of the Sydney Basin in New South Wales, or the edge of the Nullarbor Plain, respectively, to cliffs of Quaternary limestones as exposed at Zuytdorp Cliffs, Western Australia) clearly represent the category of geohistorical sites in which there are exposures from which the history of the Earth or the processes within the Earth in the past can be reconstructed.

For the category of "modern, active landscapes", Sharples (1995) expanded the original idea of geoheritage to include areas of dynamic geological processes which could include environments such as mobile coastal dunes, or fluvial systems with annual or episodic floods. This notion is explored further here, as it is relevant to assigning coastal types to categories of modern, active landscapes, or to geohistorical sites. These two categories, in fact, can grade into each other.

Landscapes can gradationally vary from being very active (*e.g.*, mobile inland-ingressing parabolic dunes), to episodically active (*e.g.*, floods in riverine systems in arid zones), to largely now inactive, but intermittently active over the Holocene (*e.g.*, arid zone fluvial systems, or prograded coastal plains). Further, where there is a combination of active geomorphic, sedimentological and diagenetic processes operating in an area, one of the processes may be episodic, another intermittent, and the third ongoing, and each may have different rates and intensities when active, and various expressions in a gradient normal to the coast. For separating geohistorical sites from active modern landscapes, this temporal and spatial gradation in landscape activity and dynamism is further discussed in terms of what constitutes "dynamic process", and how far inland should the idea of "dynamic process" for coasts be taken.

The majority of coastal scientists would agree that mobile, landward-ingressing, coastal parabolic dunes accord with the notion of "dynamic". Similarly, relatively rapidly accreting coasts, such as the Gascoyne Delta (Johnson 1982) and Point Becher (Searle *et al*. 1988), or eroding coasts, retreating at, say, 1 m per annum, as recorded in cliffs cut into mud in King Sound (Semeniuk 1981a), along the sandy seafront of the Leschenault Peninsula (Semeniuk & Meagher 1981), and the retreating cliff along the edge of the Nullarbor Plain, with its continual development and erosion of shoreline talus (breccia and megabreccia) deposits, would also constitute dynamic environments where processes are extant. Slow retreat of limestone rocky shores, measured in rates of < 1 mm per annum (Hodgkin 1964), under the action of algae-grazing molluscs, other forms of bioerosion, wave abrasion, or chemical corrosion also could be considered as dynamic, albeit at reduced rates. In these latter examples, the coast is still actively eroding, but not so conspicuously. This poses the question of how rapid a process must be for it to be designated as "dynamic". For instance, for erosional coasts, various studies on different materials and rock types under different processes show varying rates of erosion (Hodgkin 1964; Gill 1973; Semeniuk & Meagher 1981; Semeniuk 1981a, May & Heeps 1985) and, conversely, for prograding coasts, there are varied rates of accretion (for deltas, cuspate forelands, and arid coastal sedimentation, see Fisk 1961, Searle *et al*. 1988, Semeniuk 1996a and Semeniuk 2008, respectively). In this paper, all extant processes at the coast are classed as dynamic, regardless of whether they are rapid and visually conspicuous, or extremely slow, but nonetheless effecting change in landforms through agencies of erosion or sedimentation, or where they result in diagenetic products. That is, it is Holocene coastal processes *in action* that constitute a dynamic environment, or it is where processes still contribute to an ongoing developing system.

Coastal processes can change in style, effect, and intensity, spatially and temporally. Spatially, they may be conspicuous and marked at the coast, and change inland because there is a gradient in hydrochemistry, or because of decreasing intensity (*e.g.*, decrease in seabreeze velocity), or change in processes (*e.g.*, marine water diagenesis giving way to fresh-water diagenesis). Dunes ingressing inland under the effect of coastal winds may be subject to marine/brackish water diagenesis at the coast and freshwater diagenesis in inland locations.

For modern, active (coastal) landscapes, the main ubiquitous processes include sedimentation, erosion, biogenic processes, and diagenesis, and these processes may be continually operating, or intermittently operating, or have the potential to be reactivated. In the case of prograding coasts, generally the most dynamic portion of the landscape is the seaward part or the seaward edge of a prograded/prograding plain, with a stranding of the earlier deposits inland, and a consequent decrease in activity of coastal processes towards inland. The attendant effect is that processes of sedimentation and erosion may/will progressively decrease inland. Three coastal landscapes and their processes are described below to demonstrate the extent that active processes may extend inland: a prograding tidal flat, a prograding beach-ridge plain, and coastal barrier dunes.

In the case of prograding tidal flats, the main processes are sedimentation, biogenic activity, and diagenesis. The seaward parts of tidal flats involve accumulation/accretion and biogenic activity on the low intertidal to high intertidal flats, with development of stranded flats that are inundated only on the highest (equinoctial tides) and by storm waters. But for such environments, while there will be annual inundation by the highest tides and storm water, these tidal flats also are subjected to on-going coastal hydrochemical, groundwater, and other processes (that are graded from the level of the low tidal level to that of the highest tide) that diagenetically imprint on the stranded flats (Logan 1974; Semeniuk 1981a, 1981b, 2008). In the case of prograding beach-ridge plains, the main processes are sedimentation, intermittent erosion, and diagenesis. With progradation, the beach surface shoals become incipient beach ridges, and beach ridges become emergent above the level of the highest tides and storms by vertical aeolian accretion of sand ridges (Searle *et al*. 1988; Semeniuk *et al*. 1989; C A Semeniuk 2007). Thus, in contrast to tidal flat systems, there is a decrease to some extent in coastal effects in regard to sedimentation and accumulation in stranded parts of such systems. However, with beach-ridge plains the coastal zone may later be subjected to coastal wind erosion and sand remobilisation (forming inland-transgressing parabolic dunes), originating from the coast zone itself, and still is within the realm of active coastal processes though this may be staggered in time and space. In this case, the entire package of seaward-edge processes of sedimentation and any concurrent mobilisation of dunes towards inland, the reactivation of inland ingressing dunes, wind erosion of stranded beach ridges and dunes are all part of the ensemble of "modern, active landscapes where dynamic processes are operating", as distinct from terrains of Quaternary limestone, or older rock sequences that have not been actively formed as part of the modern landscape. Similarly, any diagenesis effected on the beach-ridge plain is part of the same ensemble of "modern, active landscapes where dynamic processes are operating". The same principles apply to coastal barrier dunes. The most active zone is the seaward edge *and* the coastal zone immediate to the shore. However, for coastal barrier dunes, the coastal zone may later be subjected to wind erosion and sand remobilisation, forming inland-transgressing parabolic dunes, and still is within the realm of active coastal processes which may be staggered in time and space (Semeniuk & Meagher 1981).

For the examples presented above, prograded tidal flat and beach-ridge plains, as well as coastal barrier dunes, are considered to be modern landscapes with dynamic processes, and the plains in particular are the result of active edge-of-sea sedimentation. In older parts of such systems, modern diagenesis and reactivation of dunes still place these environments within the category of active and extant. However, on the oldest parts of such systems, the landscapes may change from being modern and active to geohistorical sites where there are exposures in cliffs and outcrops recording the history of the Earth, or the past processes within the Earth.

Scale should be a factor considered, even as a descriptor, in developing classification of sites for purposes of geoheritage and geoconservation, because significant features can be terrane size or crystal size, and both may be present in the same area (Brocx & Semeniuk 2007), and similar coastal features may be present at different scales (Semeniuk 1986). In the coastal zone, features can range from large systems such as deltas, to specific types of cliffs, to micro-pinnacles (= "lapiés" *cf*. Paskoff 2005) and tafoni. Most literature on coastal classification or on coastal evolution tends to deal with phenomena at one frame of reference and do not transcend scale. Scale is formally addressed in this paper in terms of frames of fixed sizes, using regional, large, medium, small, and fine scales (Semeniuk 1986), or megascale, macroscale, mesoscale, microscale, and leptoscale (C A Semeniuk 1987). Cross-lamination, sedimentary layering, bubble sand, shell layers, and tafoni, for instance, are evident within a 1 m x 1 m frame of reference, while cliff faces, shoreline benches and sandy spits are evident within a 10 m x 10 m to 100 m x 100 m frame of reference. Scales of reference for geomorphic/geoheritage features in this paper, for use as descriptors, are: regional scale (or megascale) within a frame 100 km x 100 km or larger; large scale (or macroscale) within a frame 10 km x 10 km; medium scale (or mesoscale) within a frame 1 km x 1 km; small scale (or microscale) within a frame 10–100 m x 10–100 m; and fine scale (or leptoscale) within a frame 1 m x 1 m, or smaller.

Global coastal classifications – and their potential applicability to geoconservation

There have been a number of classifications published for coastal systems, as summarised by King (1972), Schwartz (1982), Kelletat (1995), Fairbridge (2004), and Finkl (2004). They grade from over-arching and conceptual (*e.g.*, Johnson 1919, Valentin 1952, Bloom

1965; Shepard 1973), to those focused on providing systematic global to regional environment-specific classifications based on an inventory of determinative processes (*e.g.*, Coleman 1976; Reineck & Singh 1980 on delta forms; Fairbridge 1980 on estuaries; or Davies 1980 and Finkl 2004 on coasts globally), to those focused on regional to local details based on form and evolution (*e.g.*, Guilcher 1953; Schwartz 1972, 1973; Klein 1976), wherein, for example, rocky shores, sandy shores, and muddy shores are recognised and described (as summarised by Woodroffe 2002), or where coastal types at finer scales are recognised (*e.g.*, Semeniuk 1986). Many authors have focused on the details of coasts to the extent that there has been subdivision (classification) of coasts determined by geology, climate, oceanographic setting, and tectonic setting. Rocky shores in particular provide a good example of this. They have been studied and classified into types based on local determinative environmental factors, lithology, form and evolution (Bird & Dent 1966; Edwards 1941; Emery & Foster 1956; Emery & Kuhn 1982; Guilcher 1953; Hills 1949; Stephenson 2000; Sunamura 1992; Trenhaile 1974, 1980; Wentworth 1938), and limestone rocky shores specifically have been subdivided into numerous types based on lithology and morphology responding to climate and oceanographic setting. As Finkl (2004) points out, over-arching classifications are broad in scope but lack specificity, while specialised studies are narrowly focused and provide uneven coverage of coastal taxonomic units.

From a global perspective, the classification of coasts has been approached from that involving tectonics (and later, plate tectonics), with smaller-scale coastal features determined ultimately by their location in relation to tectonic plates, *viz*., collision coasts or trailing coasts (Inman & Nordstrom 1971), or that of submerging coasts, neutral coasts, and emerging coasts (Johnson 1919). They have also been categorised from a perspective of accretionary *versus* eroding coasts; and that of primary youthful coasts *versus* secondary coasts; amongst others. From a scaler point of view, classifications have been approached from the largest scale, as outlined above, to the smaller scales, with classification of shore types based on response to waves, tides, climate, and rock types (see specific studies presented in King 1972; Schwartz 1972, 1973; Klein 1976).

A review of literature indicates that while inventories of coastal features have been generated for purposes of geoheritage/geoconservation (*e.g.*, Kiernan 1997), and coasts of geoheritage significance have been identified at specific locations on an *ad hoc* basis (*e.g.*, a range of internationally- and nationally-significant coasts in the United Kingdom, cited in Soper 1984, Bennett 1989, and Sale *et al*. 1989; as well as locations in Australia such in Victoria, see White *et al*. 2003, and at Hallett Cove in South Australia, see Parkin 1969; Dexel & Preiss 1995), a classification of coasts for the purposes of identifying features of geoheritage significance, to date, has not been systematically undertaken. This is a difficult endeavour. Firstly, because of the reason of scale: large coastal tracts (*i.e.*, megascale features) may be of geoheritage significance, especially from a global perspective (*e.g.*, the ria shores of the Kimberley Coast of Western Australia), while at the other extreme, smaller-scale features, at crystal scale, also may be significant. Secondly, coasts may be simple in form, lithology and structure, or they may be complex, or may be multi-genetic. Marine erosion, for instance, may result in a wide range of coastal types and complex coastal forms: coastal erosion may be incising into fairly uniform bedrock resulting in a range of differential responses dependant on the lithology (*viz*., relatively resistant such as granite, or relatively soft such as friable limestone), but if rock types are heterogeneously distributed, the eroding coast results in a diverse suite of products and coastal forms. Marine erosion also may exhume landforms and geological features that were formerly buried: for example, a terrain of granitoid/gneiss inselbergs, surrounded by younger, softer sedimentary materials, through marine erosion, results in a headland-and-(sandy)-cove system where resistant inselbergs form large, rounded headlands, and the sedimentary materials, having eroded away, form the sandy coves. Thirdly, coastal types commonly are intergradational, with gradational lineages often being multidimensional, and this particularly renders classification complex. For instance, coasts grade from those wholly developed by marine inundation of the hinterland (with terrestrial forms still apparent) to eroded coasts with remnants of the original inundated morphology, to those dominated by erosional features, or a gradational suite of coasts ranging from recently-inundated to partly sediment-buried coasts to coasts wholly constructed by sedimentary processes. Complications in developing or applying a classification also arise because, depending on the scale of reference or observation, many features can be assigned to more than one category of coastal type.

Apart from some detailed work on rocky-shore types (cited above), the classification of estuaries (Fairbridge 1980), depositional forms such as beaches, coastal dunes, barriers, bars, and spits (Schwartz 1972; 1973, 2005) and tidal flats (Klein 1976; Reineck & Singh 1980; Semeniuk 1981b; 2005), which provide information on smaller-scale processes, products, and geodiversity, the classifications of coasts and coastal forms at the larger scale cited above have not been useful for categorisation of sites of geoheritage significance. They tend to be conceptual models developed to understand coastal setting and coastal evolution, and while they provide a framework for understanding the development of coasts, they are not product-oriented for smaller-scale features, and are not applicable for comparative geoheritage assessment at finer scales. For example, Davies (1980) provides a useful categorisation of coastal types based on integrating a range of features such as wave climate and tidal regime, distribution of shores types and climate, but the classification cannot be used at the site-specific scale.

A classification of coasts for purposes of identifying sites of geoheritage significance and for geoconservation has to be able to transcend a wide variety of coastal forms, from rocky shores and cliffs to depositional coasts, and their variety, to be able to encompass the variety of rocks types and materials presented at the shore, to deal with the variety of processes at the coast, and also to accommodate the variety of scales at which natural history features occur at the coast. It must also address that fact that a given tract of coast may be of geoheritage significance for a number of different reasons: for features of crystal size, to small-scale geomorphic features, to diagenetic products, to large-scale features of coastal form, or stratigraphy, or structure. None of the coastal classifications designed to date have been applicable in this manner.

The main processes leading to development of coastal types

To provide a context for the development of category-oriented coastal types for Western Australia, the main end-member processes that develop the different coastal forms and shore types are described. Identifying the main end-member processes ensures that all forms of coasts are captured at a high order level of classification.

In Western Australia, there are five main and ubiquitous end-member marine and coastal processes that develop coastal forms and shore types (Table 1); listed in generally decreasing scale, these are:

- marine inundation
- erosion
- sedimentation
- biogenic processes
- diagenesis

Globally, there are two other processes that can form coasts, though they are not strictly marine, *viz*., volcanism and glaciation. Volcanism builds islands (with their peripheral coasts), or through ash accumulation, cone accretion, or lava flows encroaching from a mainland into the sea, develops coasts constructed of volcanic materials. Glaciers can erode coasts (thus overlapping with erosion), deliver sediments to the coast (thus overlapping with sedimentation), or form ice cliffs. These additional processes do not occur in Western Australia, and are outside the scope of this paper, but are mentioned for completeness in the list of coastal types (to be described later).

Essentially in Western Australia, all coastal forms and products of (marine) inundation, erosion, sedimentation, biological coastal construction, and diagenesis are underpinned by the five end-member processes operating alone, in combination, or operating at different scales. A given tract of coast may have products of these processes developed to different extent and scale along the shore, and/or may have products of these processes alternating along the shore. These end-member processes are described below as to their significance in developing coastal types. The scales at which the processes operate are shown diagrammatically in Figure 1.

Marine inundation is a major factor in developing coastal landforms. If there has been no Holocene erosion or sedimentation, or only minor erosion or sedimentation superimposed on such coastal landforms, marine inundation would be *the* major determinant of a coast form. At the larger scales, where erosion and sedimentation are secondary factors in coastal development in that they influence the formation of smaller-scale products, marine inundation in fact is a primary deciding factor in the development of coastal forms. An idealised diagram showing coastal forms initially developed by marine inundation of a topographically variable fluvially dissected hinterland, and some of the more common coastal forms developed by variation in erosion and sedimentation is presented in Figure 2.

Erosion is a ubiquitous process along the shore, and is another major determinant in the formation of many types of coastlines. With waves, tides, currents, chemical solution, and bioerosion as drivers, it can be a major determinant of coastal form. Coastal erosion cuts into mud deposits (*e.g.*, King Sound tidal flats; Semeniuk 1981a), sand deposits (*e.g.*, sand cliffs cut into Peron

Table 1

The five main end-member processes and resultant coastal forms in Western Australia

Process	Examples of resultant coastal form or product
Marine inundation	coastal form reflecting pre-inundation topography (*e.g.*, fluvially-dissected landforms that will develop a ria coast, or shore-parallel limestone ridges which will develop a limestone barrier coast)
Erosion	straight-cliffed coasts, crenulated cliffed coasts, coves and embayments, headlands, stacks, benches, platforms, notches, lapiés, fissures
Sedimentation	deltas, beach-ridge plains, barrier islands, beach/dune shores, tidal deltas, spits, cheniers, fans, breccia/talus deposits
Biogenic processes	coral reefs, serpulid reefs, oyster reefs, stromatolitic reefs
Diagenesis	beach-rock ramps, cemented pavements, breccia pavements, gypsum pavements, gypsum crystal meshworks, sheets of gypsum rosettes, patina

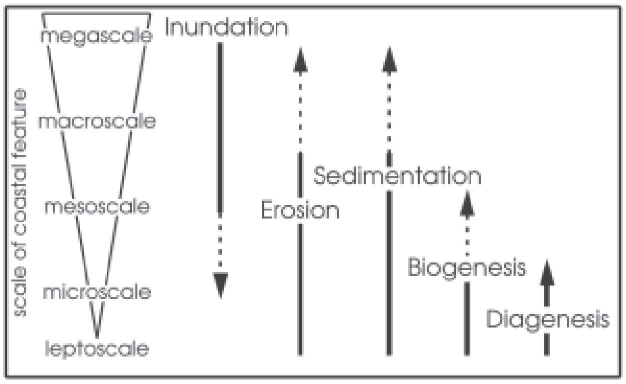


Figure 1. The five main end-member coast-forming processes in Western Australia with respect to scale. Marine inundation develops coastal forms mainly in the megascale to mesoscale range, and to a limited extent, at microscale. Erosion and sedimentation operate mainly at leptoscale to the mesoscale/macroscale, and to a limited extent, at megascale. Biogenic processes develop and influence coastal form mainly at mesoscale to leptoscale, while diagenesis develops and influences coastal form mainly at leptoscale and microscale.

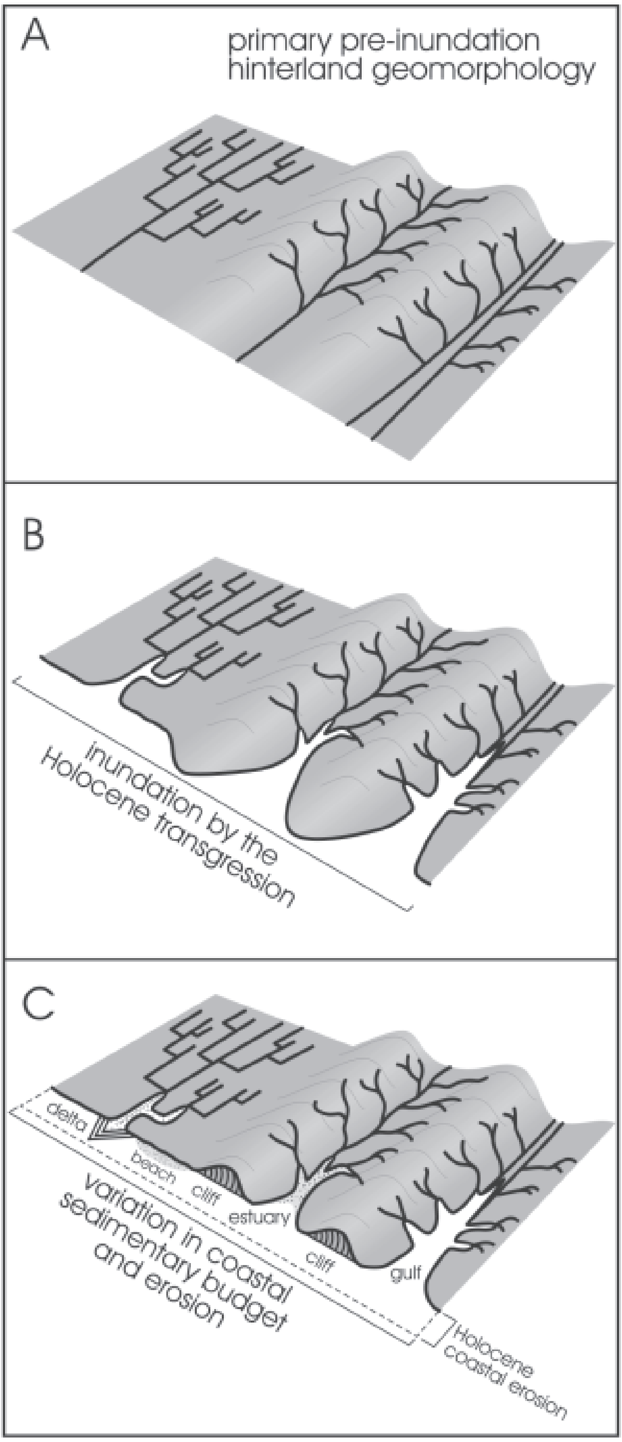


Figure 2. Diagram using a fluvially-dissected landscape as a template showing coastal forms developed by inundation and other processes, with the initial development of coastal form by inundation, followed by its modification by erosion and sedimentation. The same processes can, in principle, be applied to other landscapes. The juxtaposition of the three drainage basins are not meant to imply that such a situation exists in Western Australia or elsewhere, but to illustrate the range of hinterland forms that may be inundated by the Holocene transgression.

Sandstone; Logan *et al*. 1970), soft rock sequences (*e.g*., cliffs cut into the Toolinna Limestone along the Nullarbor Plain), hard rock sequences (*e.g*., cliffs cut into the Precambrian rocks along the Leeuwin-Naturaliste ridge), and into heterogeneous geological sequences (*e.g*., coasts eroding a plain comprised of Tertiary sediment and protruding granitic inselbergs such as the Esperance Plain). Erosion exposes formerly buried geological features, and if it is differential where it incises into a lithologically- and/or structurally-variable bedrock, it results in complexly shaped shorelines (*e.g*., the folded rocks of the King Leopold Mobile Zone in the southern Kimberley region). At one extreme, coastal erosion results in high rocky cliffs, with well-exposed geological sequences, and eroding sedimentary deposits at the other. It operates at the large scale to develop laterally-extensive cliffs such as the Zuytdorp Cliffs along the Carnarvon Basin Coast (see later), and the Baxter Cliffs along the edge of the Nullarbor Plain, and at the smaller scales to develop site-specific cliffs and local cliffs within a marine-inundated coastal terrain, or within a sedimentation-dominated coast.

Where sediment supply is adequate, regardless of whether it is marine-derived and directed shorewards, or land-derived and directed seawards, sedimentation can dominate the development of coastal form. It can be an extensive and ubiquitous process along the shore, developing many types of shores. For example, at the larger scales, sedimentation results in deltas, gulf and embayment fills as estuarine deposits, barrier dune systems, aeolian coasts, prograded beach/dune shores, and tidal flat systems. In Boreal and Arctic regions, coastal sedimentation can be driven by glacial processes. Sedimentation at the smaller scales, even if occurring within a dominantly eroding coast, results in shoreline spits and bars, pocket beaches, shoreline breccia deposits, and perched dunes. As such, sedimentation can be a major determinant of coastal form.

Erosion and sedimentation, alternating at various time frames from millennial, and greater than decadal, to daily, can result in a range of coastal forms. At large scales, it may be manifest in features such as channel switching in deltas, rows of cheniers on prograding tidal flats, truncation of beach-ridge lines, and development of inland-transgressing parabolic dunes on accreting sandy coasts. At smaller scales, it can result in complex geometry of recurved spits, talus or breccia deposits at the foot of cliffs, and the daily formation and destruction of beach cusps and rip channels (and their attendant stratigraphic and sedimentary products), amongst others.

Biogenesis involving biogenic processes and skeletal production can result in *resistant* shore-face biogenic structures, such as coral reefs, serpulid reefs, or oyster reefs, which may be expressed as extensive shore-face features, or as patch reefs. Generally, while many biologically generated resistant structures and accumulations (such as coral reefs) are subtidal features, and would not be strictly considered as "coastal", some are very shallow subtidal or may shoal into the low intertidal zone (being exposed at low tide), and form biogenic coasts. These can develop into fringing reefs that are border landmasses and islands. But while biogenic processes as coast-forming are included where reefs are concerned, we consider that most biological activity and contributions along the coast to be a subset of sedimentation, erosion, and diagenesis. For example, macrobenthos shell production, and other microfaunal and microfloral skeletal production, contribute materials to develop skeletal gravel and sand, or carbonate or siliceous mud, and form sedimentary deposits, with some shell production resulting in (sedimentary) biostromes. In this context, biogenesis (and biogenic activity) is part of sedimentation. The many other forms of biological activity in the coastal zone are subsets of erosion (*viz*., bioerosion), or diagenesis (*e.g.*, algal boring of carbonate grains, or biologically mediated blackening of grains) and clearly not part of the processes that form coasts and shore types.

Diagenesis is the chemical, physical, or biological alteration(s) effected in sediments after their initial deposition, and during and after their lithification (Bates & Jackson 1987). Chemically, it involves precipitation, solution, or chemical/mineral reactions. Diagenesis can result in the development of a diagenetic rock (or *diagenite*; Bates & Jackson 1987). It will also include alteration of sedimentary rock such as Quaternary limestone. As a process, it can be instrumental in developing coastal forms, especially at the medium, small and fine scales, and many coasts and coastal geological features are diagenetic in origin, or have formed as the result of erosion and/or sedimentation acting in combination with diagenesis. Diagenesis is particularly important in developing coastal features along tropical and subtropical arid coasts, where, for example, tidal cementation of sand develops indurated shoreline ramps of beach rock. Diagenesis in Shark Bay results in the cementation of high-tidal sediments to develop extensive crusts and breccia pavements that dominate the shore. In combination with erosion and sedimentation, it can form distinctive shoreline products (*e.g.*, beach sand cementation forming beach rock, followed by cyclone-induced erosion of the beach rock to form slabs, and shoreward transport of the slabs to form a high-tidal shoreline ribbon of boulder conglomerate and breccia; Semeniuk 2008).

While marine inundation, erosion, sedimentation, and some aspects of organic reef-building have been identified previously by other authors as coastal-forming processes, to date, diagenesis in developing coastal features has not been given enough emphasis, *and has not been previously described as a significant coast-forming process*. While recognised as a process in modifying sediments, particularly at the grain-scale and structure-scale, and is demonstrably a prevailing and ubiquitous process in the coastal zone, diagenesis can be secondary but important to the other coast-forming processes (*e.g.*, coastal erosion cutting cliffs in relatively porous limestone is accompanied by diagenesis: the splash zone and the interface between marine water and fresh water are zones of cementation that form hard bands manifest as pavements, platforms, and benches). Diagenesis can result in significant and extensive coastal features, and can influence the development of coastal form, and the evolution of a coast. For this reason, in this paper, products of diagenesis are included where they influence coastal form and coastal features.

Coastal classification can be complex because coasts are formed not by a single process but by a range of processes operating at different scales, and to differing extent. The five major coastal-forming processes outlined above largely can act alone, or in combination, and contribute to a different individual extent when in combination. Coasts geomorphically also can express a gradational trend in their process of formation: from (marine) inundational to erosional to depositional. This gradational trend is from inundated landscapes, where the primary pre-inundated landscape is still evident, regardless of the geological nature of the inundated hinterland, to those where erosional forms dominate the coastal morphology, to coasts that are partly erosional/depositional, and finally, to those which are wholly depositional.

Within any suite of coastal forms, sedimentation and/or erosion, and biogenic and/or diagenetic processes, can result in coasts that express geohistorical features useful to reconstructing the history of the Earth, from Holocene to the Precambrian (*viz*., Holocene stratigraphy underlying prograded coasts, or Holocene erosional morphology such as rocky shores with platforms and benches, or where erosion acting on older, pre-Holocene rocks have provided well exposed lithologies, structures, and stratigraphy, *e.g.*, sea cliffs exposing pre-Holocene stratigraphy).

Proposed hierarchical approach to the categorisation of coasts

While the approach to coastal classification designed in this paper is based on the Western Australian coast, if national and international comparisons are to be made for assessing geoheritage significance, it also needs to be applicable to other parts of Australia, and globally.

Coastal forms with their variable geological content and geomorphic expression are very different in various parts of the World dependent on geological setting, history of the landforms, type of hinterland geomorphology, and climate and oceanographic processes. For instance, solely from a geological perspective, a sea cliff of geoheritage significance in England, portraying Mesozoic chalk stratigraphy, palaeontology and ichnology has different attributes to a sea cliff cut into Mesozoic sandstone in Western Australia. Similarly, from a sedimentologic, climate and oceanographic perspective, mesotidal terrigenous mixed sand-and-mud tidal-flat deposits in sub-Arctic regions have very different sets of processes, products and detailed structures from those in mesotidal carbonate-dominated or mixed sand-and-mud tidal flat deposits in tropical arid regions (Reineck & Singh 1980). The mixed sand-and-mud tidal flats of Dampier Archipelago are different in tidal range, stratigraphy, small-scale products and sediment composition from carbonate-dominated tidal flats of the Canning Coast (Semeniuk & Wurm 1987; Semeniuk 2008). Coasts will respond to environmental settings developing different forms dependent on oceanography, tidal regimes, and climate. Thus, simply identifying a coastal form as a “sea cliff” or a “tidal flat” is insufficient to provide information for assessment and comparison for geoheritage and geoconservation purposes within a nation and certainly internationally. Clearly, classification of coastal features and coasts needs to address the global and national variation in coastal features in their geological, climate, and oceanographic setting.

At the next level, coasts develop various forms in response to the main coastal processes of marine inundation, erosion, sedimentation, biogenesis and diagenesis. These processes are instrumental in developing coastal forms and different types of coasts regardless of where the coast is located geologically, climatically or oceanographically. The coastal forms or coastal types generally will be ubiquitous and/or recurring, because the processes are ubiquitous.

Finally, there may be a range of smaller-scale features of a coast that are particular and peculiar to a given location, because of the context of geological, climate and oceanographic setting, and the type of coast developed by the dominance or combinations of the processes of marine inundation, erosion, sedimentation, biogenesis, and diagenesis acting on the shore. For instance, for rocky shores, regardless of where they are developed, there may be palaeontological or ichnological (palaeo) biodiversity exposed on a shore platform in different parts of the World. There may be region-specific, large nodules/concretions of calcite, or phosphate, or iron/ manganese, exposed on shore platforms. There may be petrified forests, or a range of sedimentary, igneous, deformational, or metamorphic structures well exposed on wave-washed rocky shores in different geological regions in different parts of the State, nation or the World. Similarly, in the arena of modern sedimentology, there is variation globally (Reineck & Singh 1980): the fine-scale sedimentary structures developed on a tropical arid tidal flat will contrast with those of Boreal or Arctic tidal flats (*e.g.*, the latter may contain ice crystal prints). Thus the more detailed, or finer-scale variation in coastal types will merely reflect the geological, climatic or oceanographical setting of the coast superimposed on the coastal types.

To address this State-wide to international variation, the classification of coasts for purposes of assessing geoheritage significance and for geoconservation is approached in a three-level system:

Level 1: identification of the setting of the coast, geologically, climatically, and oceanographically; geological setting and environmental setting will determine lithological range, structural orientation, and any significant geological content, as well as climate effects, and wave and wind patterns, and tidal range; it will also determine the type of hinterland geomorphology that is presented to the coast;

Level 2: identification/classification of the various coastal types developed by the processes of marine inundation, erosion, sedimentation, biogenesis, and diagenesis to provide consistent comparative information for coastal description and assessment, and to provide a framework for finer-scale coastal features in a consistent context for describing, comparing and assessing sites of geoheritage significance; this level also identifies *types* of coasts of geoheritage significance;

Level 3: inventory of finer-scale coastal features within the framework of coastal setting and coastal types identified by Levels 1 and 2.

Level 1 – locating the geological and environmental setting of coastal types regionally

In Western Australia, coasts are developed in different geological regions and different environmental settings, comprising latitudinally-varying climate and oceanography (Figure 3). In the first instance, geological region is a major factor underpinning what form a coast will develop in that it determines lithological range, structural orientation, and style of hinterland (*i.e.*, hinterland geomorphology) and the rock types exposed at the coast. Geological region also determines the tectonic and Holocene history of a region. Lithological sequences, and sedimentary, igneous, or metamorphic sequences in sea cliffs axiomatically will depend on the geological region being eroded, ranging, for example, from the interesting stratigraphy of a Silurian fluvial to estuarine system (*e.g.*, the Tumblagooda Sandstone at Red Bluff, Kalbarri) to Mesozoic fluvial to shallow marine systems (*e.g.*, the Broome Sandstone at Gantheaume Point, Broome) to Precambrian igneous rock sequences in the Dampier Archipelago, to complexly folded Precambrian rocks in the King Leopold Mobile Zone of the south-western Kimberley region (with fold structures determining coastal orientation and coastal form), to complexly folded and faulted metamorphic rock sequences in the southern coast regions. In this context, the geological, climatic and oceanographic categorisation of a coast is to some extent scale-determined as geological, climate, and oceanographic regimes are subcontinental features.

The five coastal-forming processes described earlier can be operating on varying types of hinterland geomorphology and geological materials (*e.g.*, marine inundation of a geologically-complex, high-relief, dissected hinterland, or inundation of a relatively geologically simple high-relief dissected hinterland, or inundation of a geologically complex relatively low-relief dissected hinterland, and so on), with inundation, or erosion, or sedimentation dominant.

In Western Australia we recognise eight coastal sectors, broadly corresponding to geological regions, that determine coastal form; these are the Kimberley Region (Kimberley Basin bordered by the Halls Creek Mobile Zone and King Leopold Mobile Zone), the Canning Basin Region (Canning Coast), the Pilbara Region (Pilbara Coast), the tectonically active horst-and-graben complex of the western Carnarvon Basin with its coastal ridges-and-gulfs, and then progressing southwards through a variety of geological regions such as the Perth Basin, the Leeuwin Complex, the south coast between Augusta, Esperance, and Israelite Bay (with Precambrian rocks of the Albany-Fraser Orogen and Yilgarn Craton, and sediments of the Bremer Basin), and the Eucla Basin (Geological Survey of Western Australia 1975, 1990; Playford *et al*. 1976; Myers 1994). Key aspects of the geology of the regions are summarised in Table 2 and Figure 3. The focus in Table 2 is not on Holocene coastal sediments and their geomorphic expression, as these may be repetitive in form and content, and change depending on oceanography and climate (from barriers with mobile parabolic dunes in the Leschenault Peninsula, to beach-ridge plains in the Rockingham area, to tidal flats along

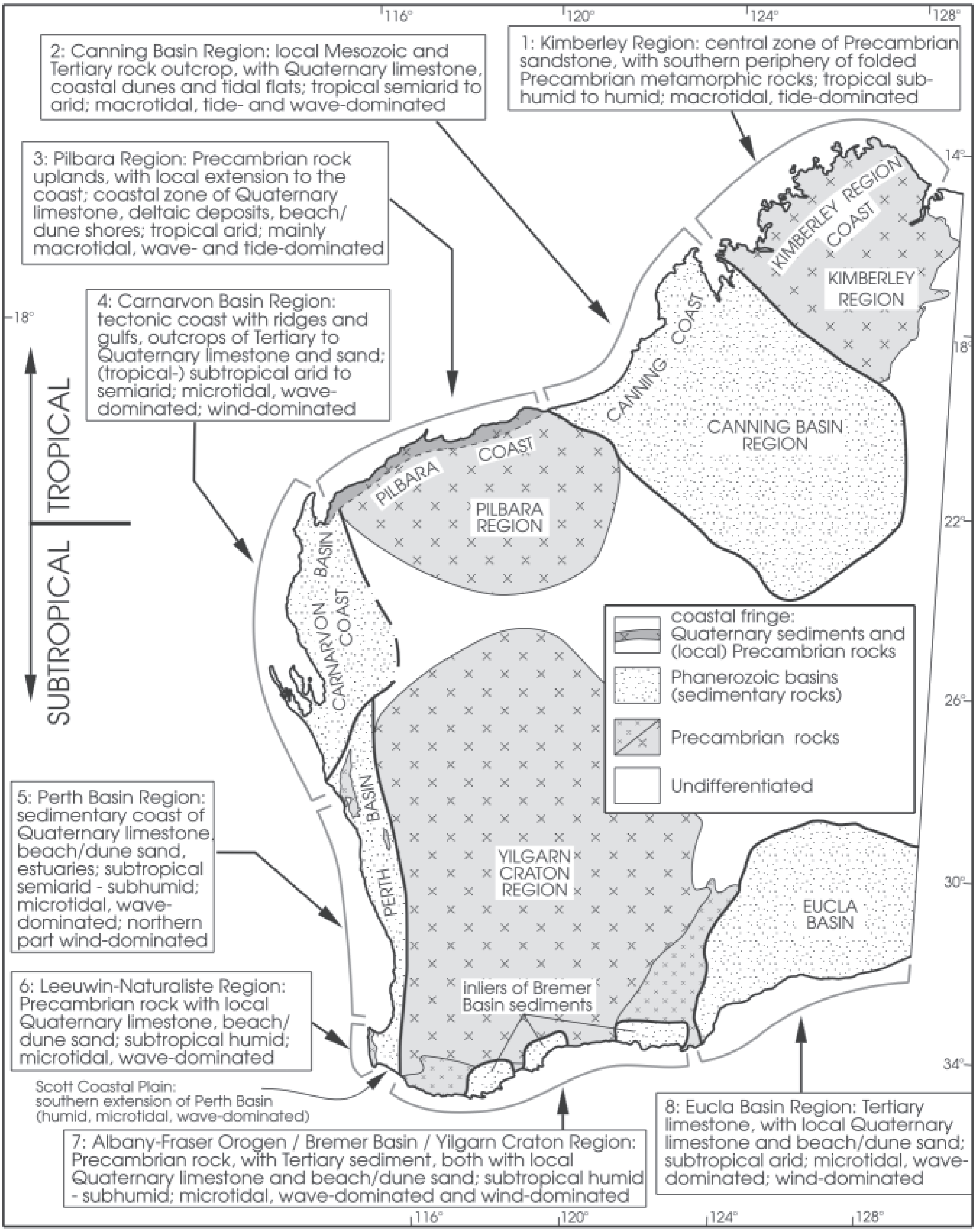


Figure 3. Simplified regional geological and environmental patterns of coastal Western Australia: distribution/description of geological regions, climate and oceanography patterns, and regional coastal sectors. Information from Gentilli (1972), Geological Survey of Western Australia (1975, 1990), Playford *et al*. (1976); Davies (1980), and Semeniuk (1993, 1995, 1996a). Note that the coast in the Scott Coastal Plain area is not another geological region but the southern extension of the Perth Basin.

the Pilbara Coast, and macrotidal beaches along the Canning Coast), but rather on the pre-Holocene geological character that will determine small-scale lithologic and geomorphic expression along wave-washed cliffs.

Coastal form can be determined by oceanography. Coasts may be extreme macrotidal, macrotidal, mesotidal, or microtidal (Davies 1980; Semeniuk 2005), and wave-dominated or tide-dominated, or protected (Figure 3). Northern Western Australia is extreme macrotidal and macrotidal, and semidiurnal, and to some extent wave dominated, with a maximum tidal range at King Sound, decreasing northwards and southwards to macrotidal between Port Hedland and the northern Kimberly area. Tidal range decreases to mesotidal and microtidal and semidiurnal towards south, until along the southern coast it is microtidal and diurnal. Oceanography determines the variation in extent that wave or tidal action develops coastal forms such as cliffs, or beach ridges, tidal creeks, rips, ridges-and-runnels, and cusps, amongst other products, and the extent that shore platforms and benches along rocky shores are formed at various tidal levels.

Additionally, coasts are influenced by the climate in which they reside (Figure 3). Northern parts of Western Australia are tropical and subhumid, with high evaporation, and enough rainfall to affect coastal margins *via* freshwater seepage and run-off. Climate changes southwards to tropical and subtropical arid, with high evaporation rates and minimal rainfall, to subtropical (near temperate) with moderate evaporation and high rainfall, and to subtropical arid along the south coast. Climate affects sea temperatures, with consequences on the production and solubility of carbonate grains, and carbonate precipitation (*viz*. skeletal production, limestone solubility, and diagenesis). The rainfall/evaporation ratio determines the amount of evaporation in the coastal zone, especially on macrotidal flats, and the amount of freshwater that is delivered to the coast in humid climates. Climate also determines whether the coast is wind-dominated, and the wind patterns, directions, and strength, with its attendant effects on coastal dunes, wind waves, and evaporation, the extent that dunes are mobilised, and that rips and cusps are developed. In this context, the southern and central western coasts of Western Australia are wind-dominated.

The oceanographic and wind climate regions in Western Australia are as follows (Figure 3): the north-west coast of the Kimberley region, the Canning Coast and Pilbara Coast, the Carnarvon Basin Coast[2] and northern Perth Basin Coast, the southern Perth Basin Coast, and the south coast

Table 2

Summary of the geology/lithology of the geological regions along the coast

Region	Diagnostic pre-Holocene geological features at the coast
Kimberley	central region (Kimberley Basin) of Proterozoic sandstone, basalt, siltstone, and basic intrusive rock, and a tectonic periphery (King Leopold Mobile Zone) of deformed igneous, metamorphic and sedimentary rock including greywacke, basalt, siltstone, acid volcanic rock, basic intrusive rock and granite
Canning Basin	Mesozoic sandstone with an abundance of diverse sedimentary structures; locally, Tertiary sediments, Pleistocene calcarenites, and Pleistocene red sand
Pilbara	Precambrian granites, and folded to layered greenstones, cherts, and ironstones, and dolerites, volcanic rocks; coastal fringe of Pleistocene limestone, red sand, and conglomerate
Carnarvon Basin	largely horizontally layered Tertiary marine limestones, locally Silurian sandstone (with an abundance of diverse sedimentary structures), red to yellow quartz sand; Pleistocene limestone (seagrass facies, beach/dune facies, coral reefs, pedogenic materials, and rocky shore sequences)
Perth Basin	Pleistocene limestone (calcarenites) composed of seagrass facies, beach and dune sediments, rocky shore sequences, and coral reefs
Leeuwin Complex	granite, anorthosite gneiss and amphibolite strongly deformed (folded, faulted, and sheared) and recrystallised to granulite facies
Albany-Fraser Orogen / Bremer Basin / Yilgarn Craton	Yilgarn Craton in its southern region: granite and gneiss Albany-Fraser Orogen: amphibolite to greenschist facies sedimentary protolith gneisses, migmatites and granites, with tectonic structures related to subduction processes and prolonged strike-slip tectonism (folded, faulted, and sheared); Bremer Basin: largely horizontally layered sandstone, siltstone, spongolite
Eucla Basin	horizontally layered bryozoan calcarenite, and locally developed shore-parallel coastal and aeolian deposits

From Geological Survey of Western Australia (1975, 1990), Playford *et al*. (1976) and Myers (1994).

[2] Traditionally, geographically, various tracts along the mid Western Australia coast encompassing Geraldton, Kalbarri, Zuytdorp Cliffs, Shark Bay, and extending to the Ashburton River have been variably known as the “Batavia Coast”, the “Coral Coast”, and the “Gascoyne Coast”, with formalisation of the latter as the “Gascoyne Bioregion”. The term Carnarvon Basin Coast is used here for the tract between Kalbarri and North West Cape (in lieu of “Gascoyne Coast”), corresponding to the location of the Carnarvon Basin and in keeping with a nomenclature reflecting that geological region controls coastal form (Semeniuk 1993). Linking the coast nomenclature to the Carnarvon Basin (with its tectonic control of coastal form) better reflects regional structure of this coastal sector.

Level 2 – category-oriented classification of coastal types developed by the five coast-forming processes

The category-oriented classification of coastal types has been designed to classify a wide variety of settings. It has involved identifying the range of coastal forms (*i.e.*, types of coasts, formed as products of the main end-member processes), capturing all forms of coasts at a high order level of classification, and provides a framework within which sites of geoheritage significance can be consistently compared and assessed. To relate the coastal features to a scalar frame we use scale descriptors, thus ensuring that not only are coastal types and coastal features captured at all scales, but that similar coastal forms expressed at different scales also are captured.

Types of coastal forms and/or geological features developed at the coast

Given the main formative processes and their combinations outlined above, we recognise nine types of coastal forms and/or geological features developed in the coastal zone; these are:

Type 1: landforms developed by the post-glacial marine inundation of pre-existing landforms (the primary pre-inundated landscape is still evident);

Type 2: landforms developed by marine inundation of pre-existing landforms *and* coastal erosion of the bedrock geology, or hinterland landforms;

Type 3: landforms wholly developed by coastal erosion, or where erosion has totally or nearly totally overprinted primary (pre-transgression) hinterland landforms;

Type 4: coasts developed by the exhumation or isolation of older landforms and their geological features;

Type 5: coastal landforms developed by marine inundation *and* sedimentary infilling;

Type 6: landforms wholly constructed by coastal sedimentary processes that have been active during the Holocene;

Type 7: landforms constructed by Holocene coastal sedimentary processes that have superimposed erosional features;

Type 8: biogenic coasts; and

Type 9: coasts with dominant or conspicuous diagenetic features.

Furthermore, in order to recognise geohistory that may be manifest either within Holocene coastal features, or within pre-Holocene sequences, a further three types are required for identifying sites of geoheritage significance and for geoconservation.

Type 10: erosional coasts recording Holocene sea-level history;

Type 11: Holocene depositional coasts recording sedimentary history, ocean history, climate history and sea-level history; and

Type 12: sea cliffs exposing lithology, stratigraphic sequences and contacts, and structure.

While these classification categories were developed within Western Australia, Types 1–12 can be recognised worldwide. However, as noted earlier, there are two additional types occurring globally but not represented in Western Australia. They are added here as Types 13 and 14 for completeness. Type 13 is a volcanic coast, formed by Holocene volcanism. It is analogous to sedimentary coasts, but accretion, progradation, and coastal development is driven by volcanism not sedimentation. Type 14 is a glacial coast (an ice coast), where ice sheets and ice cliffs form coasts. Glacial coasts do not include glacigenic sedimentary coasts.

Coastal Types 1–7 and their inter-relationships are summarised diagrammatically in Figures 4 and 5, and placed in groups showing the intergradation between them (Figure 6). Types 1–7 are morphological stages with a trend towards increasing erosion on one hand, and a trend to increasing sedimentation on the other. Being intergradational, they are placed in a quasi-chronological order specifically to show their evolutionary stages following a marine transgression, and to show the sequence from erosion-dominant coasts to sedimentation-dominant coasts. Type 9 involves specific features developed by diagenesis. In all these coastal types that there will be variation in scale of the geological or geomorphological feature. Types 10, 11, 12, and in part Type 8 are special categories that manifest geological features useful to determining pre-Holocene Earth history, or sedimentary history, ocean history, climate history or sea-level history during the Holocene.

Types 1 and 2 overlap to some degree, but generally Type 1 is developed at the larger scale (*e.g.*, rias). Type 3, though expressed as large-scale features (such as sea cliffs along the edge of the Nullarbor Plain, or the Zuytdorp Cliffs), is best expressed at the fine to small scale (*e.g.*, benches along rocky shores). In many locations, Types 1, 2 and 3 are separated, because although often co-existing in the same region, they represent stages in coastal development from primary to fully eroded, and the types may be present at different scales within the same tract of coast. Types 1, 2 and 5 also are inter-related: marine inundation and erosion of bedrock along the coast can develop sedimentary accumulations that are linked to the pre-existing topography, and these sediments partly fill the embayments of Coastal Type 1 (*cf*. Semeniuk 1985a), or there may be development of cuspate forelands, and tombolos that capture eroding nearshore rocky islands. Types 5 and 6 overlap, reflecting increasing erosion of Holocene sedimentary materials.

As a product of the interaction of seawater, fresh water, evaporation and chemical reactions along the shore zone, Type 9, with fine- to small-scale diagenetic features, can occur in any of the other coastal types. On the other hand, it can also form a shore type in isolation (*e.g.*, beach-rock coasts where beach rock forms thick cemented deposits that dominate the shore).

There may be partitioning of some of the coastal types listed above across a shore. This is particularly the case for coasts with diagenetic features and biogenic features. That is, a given shore may have tidally-related zones of diagenesis or biogenic construction, *e.g.*, a sea cliff (Type 12), or a beach/dune system (Type 7), may have a coral reef along its low tidal zone, or a zone of distinct diagenesis, respectively.

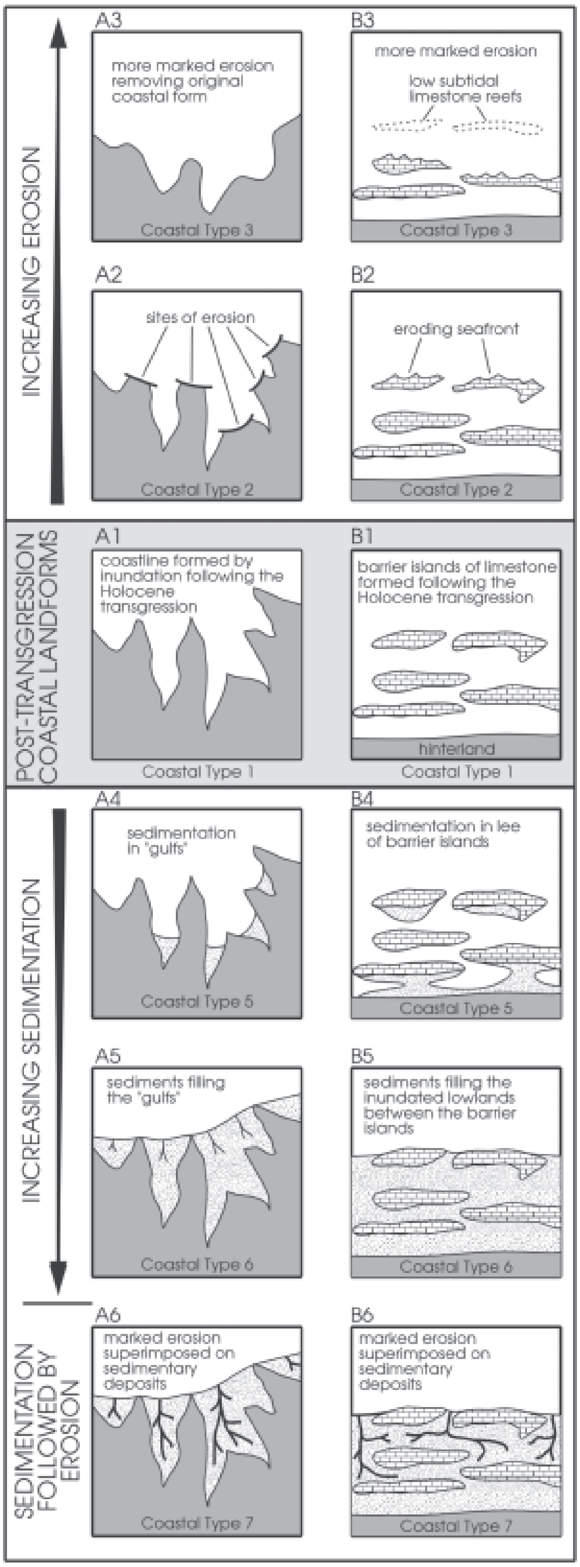


Figure 4. Coasts developed by marine inundation and other coastal processes on a fluvially-dissected landscape (sequence A) and on a terrain of Pleistocene limestone ridges (sequence B). Examples of these coastal types are shown in Figure 8. The central coastal types have been developed by simple marine inundation (A1 and B1). One trend shows results of increasing effects of erosion (A2–A3, and B2–B3), the other shows increasing effects of sedimentation (A4–A5 and B4–B5), with the final diagrams (A6 and B6) showing later erosion superimposed on coastal landscapes formed by sedimentation.

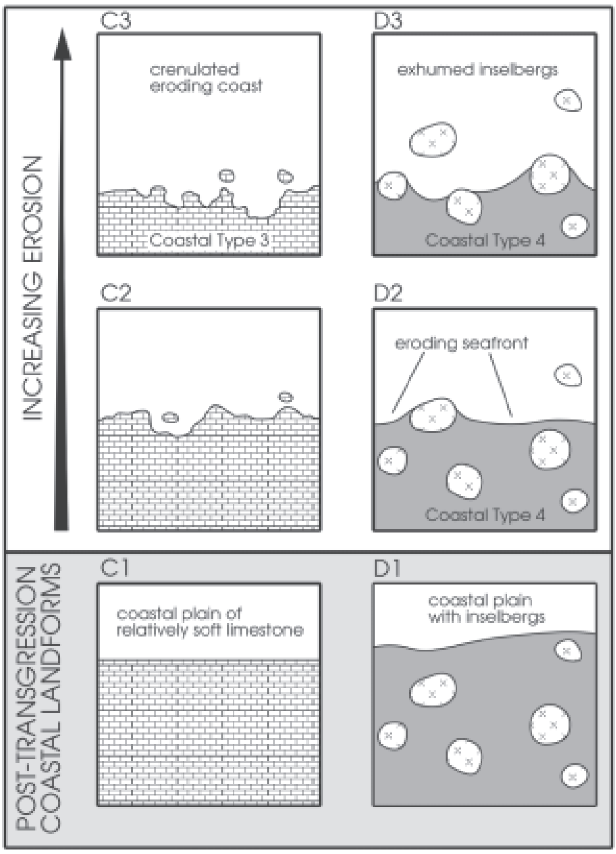


Figure 5. Coasts developed where erosion is dominant and has eliminated the pre-inundation morphology (gradation C1–C3), and where erosion has exhumed inselbergs (gradation D1–D3).

Type 12 is a special category of coast where erosion has particularly emphasised the lithological, structural and stratigraphic features of the local pre-Holocene geology. The rock types can range in age from Precambrian to Pleistocene.

In the above examples, there is emphasis on products, but there are extant processes that are still generating these products. What constitutes "dynamic processes" has been discussed earlier, encompassing those that are very active and conspicuously dynamic (such as ingressing mobile dunes, collapsing sea cliffs), to the slowly retreating cliffs, slowing advancing coasts, slow-acting chemical and bioerosion that nonetheless control and develop the small-scale and fine-scale geomorphic features at the coast. Regardless of rate and scale of process operating, it is the coastal process (or processes) *in action* that constitutes a dynamic environment.

The complex nature of coasts and the different geoheritage attributes of a coast mean that a tract of coast, from a geoheritage perspective, can be assigned to a number of categories of coastal type. Assignment to one category, however, does not mean exclusion from another. The Baxter Cliffs along the Nullarbor Plains can be assigned geomorphologically as an "eroding coast" *and* to the category of reference stratigraphic site or type section (Type 12) for the Toolinna Limestone at Toolinna Cove, as well as to the category that comprises fine- to

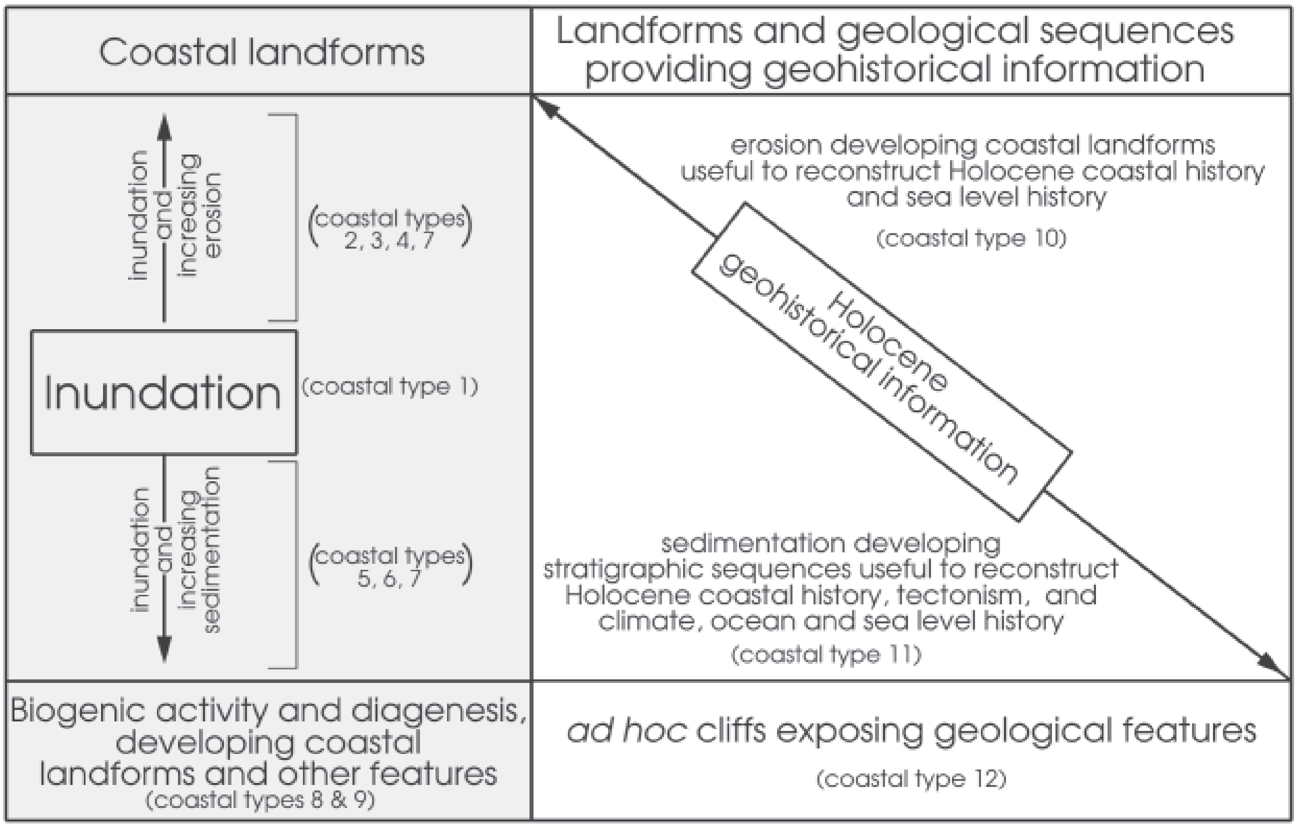


Figure 6. The groupings of the 12 Coastal Types occurring in Western Australia. The suite of coastal landforms developed by marine inundation, increasing erosion and/or sedimentation, and biogenic activities and diagenesis, is grouped in the grey box, a group focused solely on modern *coastal landforms*. Geological features and sequences, Holocene sedimentary sequences, and earlier Holocene landforms that provide Holocene and pre-Holocene geohistorical information are placed into the second group.

small-scale diagenetic features formed along the coastal zone (in the development of a cemented rocky shore platform in this particular climatic and hydrological setting). Similarly, the Point Becher area can be assigned to the category of "landforms constructed by Holocene sedimentary coastal processes" (*i.e.*, the accreting beach-ridge plains, the coastal chaots, and the local ingressing parabolic dune), as well as to that of "depositional coasts recording sedimentary history, ocean history, climate history and sea-level history" (*i.e.*, the stratigraphy under the beach-ridge plain records sea-level history, ocean history, and climate history).

As mentioned earlier, for many of the types of coast, a given coastal feature can occur at different scales. The classification of coastal types, therefore, has been presented as non-scalar, and the identification of a coastal type or coastal features is not fixed to a given scale. In this context, coastal features identified and classified as to type can be related to a scale by a (geomorphic) descriptor (*viz*., megascale, macroscale, mesoscale, microscale, leptoscale, or other size-equivalent term). Spits and rocky shores are used to illustrate coastal feature (or a coastal type) occurring at various scales (Figure 7).

Some coastal forms can be developed by erosion during a number of repetitive Quaternary transgressions, of which the current Holocene marine inundation (axiomatically) is the last in a series of such episodes. Hence, at the megascale and macroscale, coastal forms developed by erosion may be reflecting a number of Quaternary erosional episodes. This is most likely to develop where there has been marine inundation of dissected topography cut into hard rocks to develop ria shores, and hence the current ria form also is the Pleistocene form. Nonetheless, the Holocene transgression has inundated a Pleistocene topography, some of which may have been developed by Pleistocene coastal processes. With softer rocks, where erosion is rapid (*e.g*., eroding limestones to form the Twelve Apostles in Victoria, and the Baxter Cliffs in southern Western Australia, and coastal Pleistocene limestone in southwestern Australia), this is not an issue because Holocene erosion actually is the determining factor in developing the coastal form.

Descriptions of these Coastal Types are provided below, largely drawn from Western Australian examples, but supplemented by other Australian and by international examples. Some of these Coastal Types are illustrated in Figures 8–10. In the descriptions that follow, the relationship of the types to the four categories of geoheritage of Brocx & Semeniuk (2007) is provided. Examples of coastal forms that are present within the twelve coastal types in Western Australia are provided in the description of each of the Coastal Types.

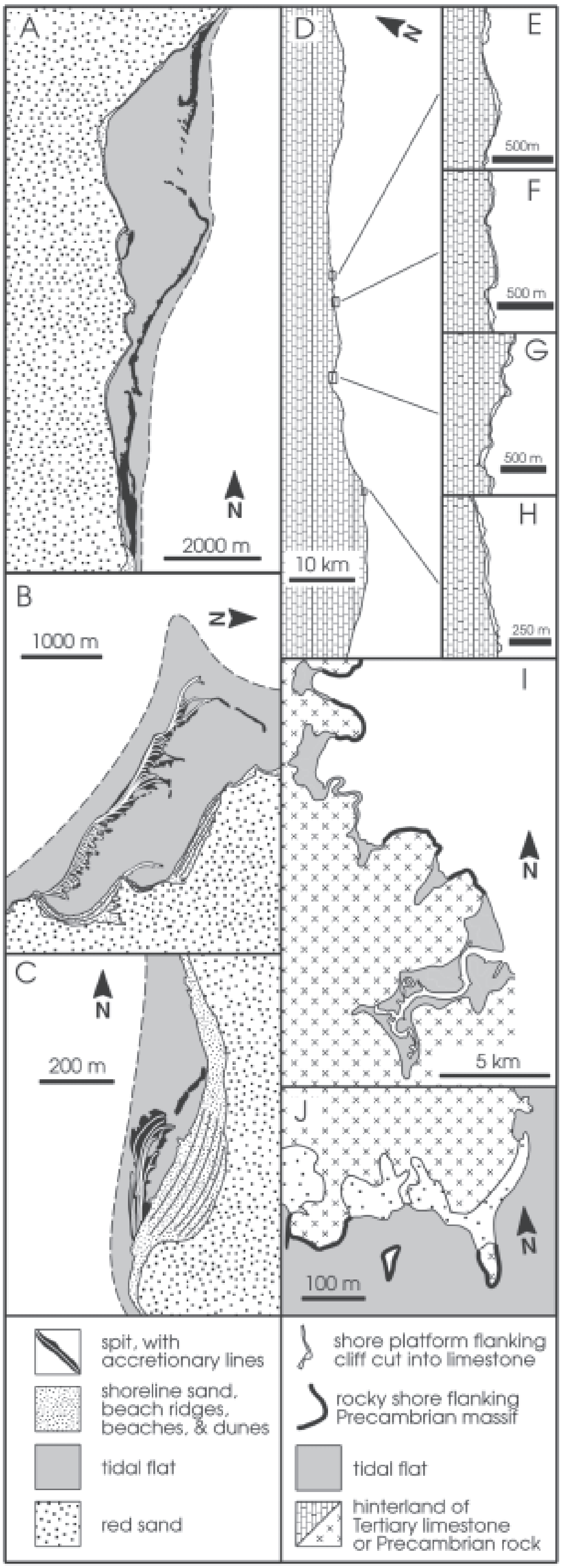


Figure 7. A–C. Various sizes of spits in Shark Bay (east shore of L'Haridon Bight; northern Faure Island; and south of Eagle Buff). D–I. Various sizes and extent of rocky shores in Western Australia. D–G: The Baxter Cliffs, Eucla Basin. H: Port Warrander, Kimberley Coast. I: King Bay, Pilbara Coast. These examples illustrate coastal forms can have expression at various scales, from megascale to mesoscale.

Type 1: coastal landforms formed by marine inundation

Coastal landforms developed by the post-glacial marine inundation of pre-existing terrestrial landforms, including those of Pleistocene age, vary from large-scale features to smaller-scale morphologic features. Examples from Western Australia of large-scale coastal landforms are the ria shores of the Kimberley Coast (which formed by the marine inundation of a fluvially-dissected terrain), the limestone barrier island complexes along the Pilbara Coast (Semeniuk 1996a), the complex coast of the Dampier Archipelago, and the gulf-and-peninsula morphology of Shark Bay. Examples of fine- to small-scale morphologic features are the inundated boulder slopes of the rocky islands of the Dampier Archipelago (Semeniuk *et al.* 1982), and some of the limestone barrier islands along the Pilbara Coast (Semeniuk 1996a), amongst others.

Coastal Type 1 can be assigned to the geoheritage category of *modern, active landscapes* in that coastal landforms developed by the post-glacial marine inundation of the landscape are extant.

Type 2: coastal landforms developed by marine inundation *and* coastal erosion

These are coastal landforms developed by the result of marine inundation of pre-existing landforms *and* coastal erosion of the bedrock geology, or hinterland landforms. Marine inundation develops the primary coastal type, and erosion develops finer-scale features therein. The erosional products vary in size from large-scale (such as marine cliffs) to small-scale features such as shore platforms and benches, or micro-morphologic features (such as micro-pinnacles and tafoni). Variation in style and form of coasts result from differing bedrock materials such as granite, shale, folded metamorphic rock, or limestone (*e.g.*, rounded shores, plunging cliffs, stepped platforms and benches, serrated platforms, or high tidal pavements cut into limestone by salt weathering), and the various coastal landforms developed by marine inundation of the pre-existing terrestrial landforms, examples at the fine- to small-scale features are platforms, benches, notches and micro-pinnacles cut into calcarenites exposed along the shores of Rottnest Island and the Perth region (Semeniuk & Johnson 1985; Playford 1988), and the extensive high-tidal limestone pavements formed by salt weathering of Pleistocene limestone barriers in the Pilbara region (Semeniuk 1996a). The emphasis here is that coastal erosion has modified the morphology of the coast after the post-glacial marine inundation, resulting in varying coastal forms from medium scale to small and fine scale. Some of the complexity of products of erosion are the result of marine erosion acting on lithologically-layered or heterogeneous rocks (*e.g.*, structural benches controlled by lithology such as horizontal shale beds, or horizontal, hard, sandstone beds), and some are due to the effect of marine planation and erosion, producing benches that are related to present and former Holocene sea-level positions, and modern climate setting and oceanographic setting.

Coastal Type 2 mostly can be assigned to the geoheritage category of *modern, active landscapes* in that coastal landforms developed by the post-glacial marine inundation of the landscape, and their erosion, are extant.


A
Coastal Type 1
5 km
B
Coastal Type 2
1 km
C
Coastal Type 5
1 km
D
Coastal Type 5
1 km
E
Coastal Type 3
F
Coastal Type 4
G
Coastal Type 4
exhumed Bunbury Basalt
H
Coastal Type 7
prograded depositional coast
superimposed tidal creek erosion

Type 3: landforms wholly developed by coastal erosion

These coastal landforms are wholly developed by erosion, or where erosion has totally or nearly totally overprinted primary (pre-transgression) hinterland forms. Sea cliffs are a common product of this type of coastal development, and these can vary from large scale, such as extensive and high sea cliffs, to smaller-scale cliffs, platforms and benches. At smaller scales along all scales of sea cliffs, there may be lithologically-determined structural benches and platforms, and benches, and platforms, smaller cliffs, and a variety of other fine-scale features (Semeniuk & Johnson 1985) determined by height of the shore relative to sea level in a given climatic/oceanographic setting.

Examples of this coastal landform are the modern crenulate cliffed coast cut into Tertiary limestone along the edge of the Nullarbor Plain in Western Australia (*e.g.*, the Baxter Cliffs), the modern retreating, crenulate, cliffed coast cut into Tertiary limestone in Victoria ("The Twelve Apostles"), and the smaller-scale cliffs, platforms and benches, along the seaward edge of limestone barriers of the Pilbara Coast (Semeniuk 1996a).

Coastal Type 3 can be assigned generally to the geoheritage category of *modern, active landscapes.*

Type 4: coasts formed by the exhuming or isolation of older landforms

These landforms have been developed by coastal erosion, exhuming or isolating formerly buried landforms and other geological features. The coastal landform usually is derived by the exhuming of a relatively large geological feature, and should dominate the coast, not merely be part of a hard band or other more resistant layer or band within a sedimentary, metamorphic or igneous system. Examples are inselbergs, or volcanic plugs that are embedded in less durable materials and that through coastal erosion, have been exhumed or isolated. Such landforms can vary from large scale (such as granitic or gneissic headlands) to smaller scale, such as resistant basaltic bodies (*e.g.*, dykes, or valley fills). The emphasis here is that, following the post-glacial transgression, coastal erosion has removed more easily eroded material that formerly had enveloped a geological feature (or landform) on the hinterland, and has isolated that feature now making it a prominent *coastal* landform. The landform and its coastal morphology has not formed primarily as a result of marine inundation, as is the case for a ria coast, or formed as a result of erosion of a geologically relatively uniform system, as is the case of the sea cliff along the edge of the Nullarbor Plain, but is the result of the exposure by coastal erosion of a geologically harder "node". In Western Australia, examples of coasts formed by exhuming or isolation of older landforms are: 1. rounded coastal granitic headlands (formerly inselbergs, or monadnocks that were scattered and partly to fully buried by Tertiary sediments inland of the Esperance coast) now exposed by the erosion of the surrounding Tertiary sediments; and 2. the outcrop of Bunbury Basalt, south of Bunbury, with outcrop of basalt-filled valley tract now exposed by the erosion of the enclosing Cainozoic sediments.

Coastal Type 4 can be assigned to the following two geoheritage categories: *modern, active landscapes* in that they have been formed by the post-glacial marine inundation of the pre-transgression landscape and its subsequent erosion. Where such coastal landforms have been in existence since the early to middle Holocene, and are now largely relict from earlier Holocene time, they represent a coastal type that can be assigned to the geoheritage category of *geohistorical sites* where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed. However, more generally, though mostly an exhumed feature, these coastal types carry a degree of on-going processes such as erosion.

Type 5: coasts developed by marine inundation *and* sedimentary infilling

Coastal landforms developed by marine inundation of the bedrock geology, or hinterland landforms *and* sedimentary infilling of the inundated bays, gulfs, or lagoons may vary in size from large-scale (such as sediment-filled gulfs) to medium-scale features such as sediment-filled swales in Holocene-inundated Pleistocene limestone-barrier complexes. Coastal sediments filling inundated regions/areas can wholly fill the marine embayments, or only partially fill them. Examples include the seagrass bank sediment-filled linear embayments that have shoaled to tidal levels in the Edel Land system of Shark Bay (*e.g.*, Useless Inlet, Boat Haven Inlet, Depuch Inlet), the tidal-sediment, partial fill fringing the gulf of King Sound, and the tidal-sediment fill between the barrier-island complex of Pleistocene limestone at Salmon Inlet (west of Port Hedland). The emphasis here is that coastal sedimentation has modified the morphology of the coast after the initial post-glacial marine inundation by sedimentary infill or partial infill, resulting in varying coastal forms from large scale to medium scale.

Some of the sedimentation in this type of coast is the result of marine erosion acting on the inundated coast. The Peron Peninsula at Shark Bay is an example: marine transgression after the last glacial period has inundated the ancestral "gulfs" of Shark Bay, leaving the ridge of red sand as a peninsula, and coastal erosion has developed sandy shorelines, recurved spits, sand platforms, and (calcrete) breccia ribbons.

◀ **Figure 8.** Coastal forms in Western Australia. A. Ria coast in the Kimberley Region (Coastal Type 1). B. Partly sediment-infilled ria coast in the Kimberley Region (Coastal Type 2). C. Partly sediment-infilled limestone barrier coast in the Pilbara Coast (Coastal Type 5). D. Limestone barrier coast in the Pilbara Coast with sediment infilling the inter-ridge swales (Coastal Type 5). E. Wholly erosional coast, the Baxter Cliffs along the edge of the Nullarbor Plains (Coastal Type 3). F. Coast formed by exhuming of inselbergs in the Esperance region (Coastal Type 4). Inselbergs on the coastal plain, still partly buried by Tertiary sediments, are visible in the background. G. Coast formed by exhuming of a valley-fill of Mesozoic basalt (the Bunbury Basalt) south of Bunbury (Coastal Type 4). H. Coast comprised of sedimentary deposits (shoaled tidal-flat sediments), with superimposed erosional features, *viz.*, tidal creeks (Coastal Type 7).


A
1 km
Coastal Type 6
B
Coastal Type 6
Coastal Type 11
C
Coastal Type 6
Coastal Type 11
D
Coastal Type 6
100 m
E
100 m
Coastal Type 6
F
100 m
Coastal Type 6
G
Coastal Type 11
Horsewater Soak Calcarenite
stratigraphic interface between
beach and dune deposits located
2 m above its modern position
Kennedys Cottage Limestone
H
Coastal Type 12
I
Coastal Type 12
1 m

Coastal Type 5 can be assigned to the following two geoheritage categories of *modern, active landscapes* in that coastal landforms developed by the post-glacial marine inundation of the landscape, and their sedimentary infilling, if still on-going, is extant. Where Holocene sedimentation is now inactive, the coastal type can be assigned to the geoheritage category of *geohistorical sites* where the history of the Earth can be reconstructed, or the processes within the Earth in the past (in the Holocene) can be reconstructed.

Type 6: landforms wholly constructed by Holocene coastal processes

This type of coast comprises landforms wholly constructed by sedimentary coastal processes that have been active during the Holocene. This Coastal Type focuses on coastal landforms, not on sedimentary sequence. Examples at the large and medium scale include dune barriers, beach-ridge systems, beach/dune systems, estuarine sedimentary accumulations, and deltas, amongst others. These tend to be relatively permanent coastal landform features. Examples at the small scale include sand spits, coquina (shell) spits, emergent tidal deltas, ridge-and-runnel complexes, and beach cusps, amongst others. Some of the smaller-scale rhythmic coastal features tend to be relatively short term features (*e.g.*, ridge-and-runnel complexes, and beach cusps), although for some coasts, because of local coastal morphology such as headlands flanking curved beaches, combined with prevailing wave and wind patterns, there may be a tendency for some rhythmic coastal forms to be recurring on a regular basis. Examples of significant large- and medium-scale coastal landforms in Western Australia wholly constructed by coastal processes include the coastal carbonate mud flats, sandy barriers, and earlier Holocene barriers of the Canning Coast (Semeniuk 2008), the deltas and barriers of the Pilbara Coast (Semeniuk 1996a), the delta of the Gascoyne River (Johnson 1982), the twin cuspate foreland of the Rockingham-Becher area (Searle *et al*. 1988), and the Leschenault Peninsula Barrier Dune system (Semeniuk 1985b).

Coastal Type 6 can be assigned to the geoheritage category of *modern, active landscapes* in that coastal landform development is extant.

Type 7: landforms constructed by Holocene coastal sedimentary processes that have superimposed erosional features

This type of coast comprises landforms constructed by Holocene sedimentary coastal processes but where there has been later erosion. Thus it comprises depositional forms, with superimposed erosional landforms. This Coastal Type also focuses on coastal landforms, not on sedimentary sequences. Examples at the large and medium scale include tidal flats with tidal-creek erosion, dune barriers with an eroding seaward margin, and beach-ridge systems with an eroding seaward edge, amongst others. Examples in Western Australia of such coastal landforms initially constructed by Holocene coastal processes but with subsequent superimposed erosion include tidal creeks cut into tidal flats in King Sound, Roebuck Plains, and Port Hedland (Semeniuk 1981a, Semeniuk 2008), the eroding seaward edge of some deltas of the Pilbara Coast (Semeniuk 1996a), and the eroding tip of Point Becher of the Rockingham-Becher area (Semeniuk 1995).

Coastal Type 7 can be assigned to the geoheritage category of *modern, active landscapes* in that coastal landform development is extant.

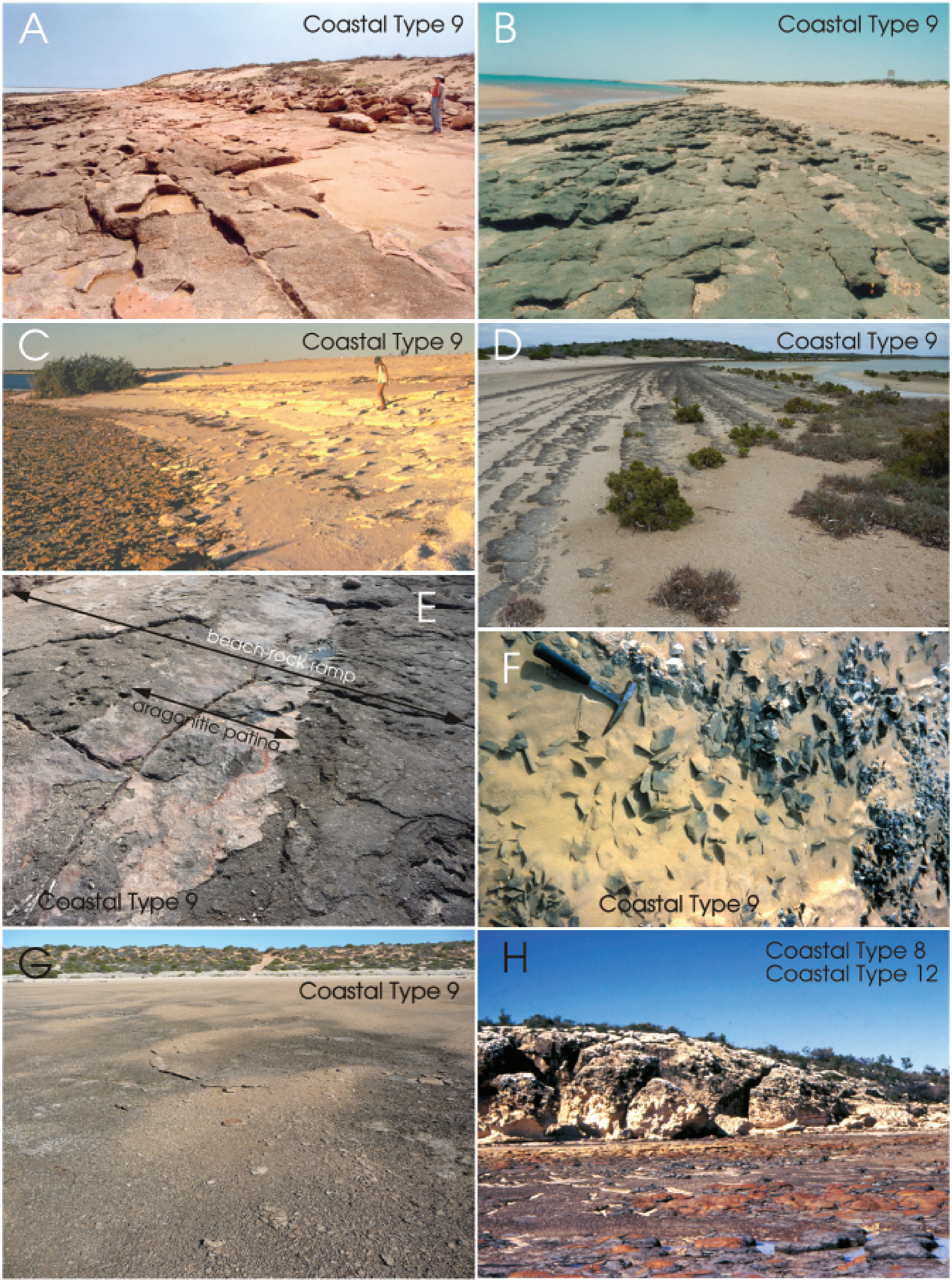
Type 8: biogenic coasts

Coasts can be built by biogenic processes. This refers to coasts that have developed hard-surface reefs (coral reefs, serpulid reefs, oyster reefs, stromatolitic reefs) which are not due to sedimentary deposits that merely have a skeletal component. Skeletons of organisms behave as sediment particles under action of waves, tides, currents and wind: they are transported, sorted, built accumulations, and develop sedimentary structures. As such, though biogenic in origin, skeletal accumulations are treated as sediments in this paper.

Biogenic coasts tend to range from microscale to the mesoscale. They are locally developed in Western Australia, *e.g.*, where oysters form thick crusts or reef-like accumulations on cliff shores (as in the Dampier Archipelago), or where coral reefs fringe shallow subtidal to low tidal rocks and rock platforms (*e.g.*, Port Hedland tidal platforms). In Shark Bay, stromatolitic reefs form in the tidal zone (Logan *et al*. 1974), developing resistant structures fronting Hamelin Pool and prograding seawards (Figure 10H). Biogenic coasts most commonly occur in combination with other coastal forms (Figure 10H), *i.e.*, as zones or patches or short sectors within erosional or sedimentary coasts, and only infrequently in Western Australia dominate the coast.

Coastal Type 8 can be assigned to the geoheritage categories: *modern, active landscapes* in that the processes and products are extant and (if stranded and fossil) as *geohistorical sites* where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed because there is an emphasis on the record of sedimentary history, ocean history, climate history and sea-level history. The elevated stromatolitic reefs of Shark Bay illustrate the use of these structures to infer former higher Holocene sea levels.

◀ **Figure 9.** Coastal forms in Western Australia. A. Coast formed wholly by sedimentation – a large delta, *viz.*, the Ashburton River delta, Pilbara Coast (Coastal Type 6). B. Coast formed wholly by sedimentation – a barrier dune system, *viz.*, the Leschenault Peninsula (Coastal Types 6 and 11). C. Coast formed wholly by sedimentation – a cuspate foreland, *viz.*, Point Becher cuspate foreland (Coastal Types 6 and 11). D. Coastal form developed by modern processes, *viz.*, ridge-and-runnel complex east of Esperance (Coastal Type 6). E. Coastal form developed by modern processes, *viz.*, rips and their feeder channels in the Esperance area (Coastal Type 6). F. Coastal form developed by modern processes, *viz.*, beach cusps in the Esperance area (Coastal Type 6). G. Cliff cut into Holocene limestone at Port Smith (Canning Coast) showing stratigraphic interface between the beach facies and dune facies located some 2 m above their modern position (Coastal Type 11). H. Cliff cut into the Broome Sandstone in the Entrance Point area (Broome) showing well-exposed stratigraphy, structures and lithology (Coastal Type 12); person for scale. I. Close-up of cliff shown in (H) showing details of sedimentary structures, cut-and-fill structure, sedimentary sequence, and well-exposed lithologies (Coastal Type 12). Tafoni are also evident in the lower part of the photograph.


A
Coastal Type 9
B
Coastal Type 9
C
Coastal Type 9
D
Coastal Type 9
E
beach-rock ramp
aragonitic patina
Coastal Type 9
F
Coastal Type 9
G
Coastal Type 9
H
Coastal Type 8
Coastal Type 12

Type 9: coasts with dominant or conspicuous diagenetic features

Diagenesis involves precipitation, solution, or chemical/mineral reactions. Diagenetic features can be formed along the coastal zone by hydrochemical, biological, and physical processes, acting alone or in combination in response to the interactions of seawater, fresh water, and evaporation and transpiration gradients across the tidal zone. The products may be fine-scale and small-scale and isolated, but conspicuous, overprinting existing sediments and rocks and superimposed on any of the Coastal Types described above, or can come to dominate the coast as medium-scale products, and locally, diagenites, as in massive beach-rock occurrences that form "rocky shores" (Figure 8 of Semeniuk 2008) and in extensive cemented pavements and breccia pavements. Examples of diagenetic coasts include beach rock (Ginsburg 1953) and gypsum precipitates such as nodules, crystal rosettes, crusts, and crystals forming an interlocking resistant meshwork, under hypersaline flats (*cf*. Logan 1974; Shinn 1983).

Diagenetic features and sequences of significance in Western Australia include those recorded by Logan (1974) in Shark Bay (*viz*., carbonate-cemented crusts, gypsum precipitates, beach rock), those of the Pilbara Coast (Semeniuk 1996a), and beach rock of the Canning Coast (Semeniuk 2008). Figures 10A–10G illustrate beach-rock ramps forming seafronts along the Canning Coast and Pilbara Coast, a cemented upper beach surface, carbonate pavements, cemented carbonate layers, and a meshwork of gypsum rosettes from a supratidal flat all in Shark Bay, and an aragonitic patina (crust) formed on beach rock along the Canning Coast.

Coastal Type 9 can be assigned to the geoheritage category of *modern, active landscapes* in that the processes and products are extant.

The importance and implications of coasts formed by diagenesis or strongly overprinted by diagenesis will be explored in more detail in the Discussion.

Type 10: erosional coasts recording sea-level history

This is a type of coast where erosion manifests specific detailed Holocene Earth-history information through the expression of geomorphic features preserved along the shore. Contrasting with accretionary coasts where sea-level history can be preserved (see below), erosional coasts, where there has been cutting of platforms or pavements in the intertidal zone, can record coastal history, and in particular sea-level history (again, with relative sea-level history being eustatic, or the result of tectonism). Rocky shore sedimentary deposits and biogenic imprints also may be preserved. In this type of coast, there is focus on environmentally-specific erosional features (that can be related to mean sea level, or a tidal level). This is exemplified by various platforms, benches, and pavements cut into calcarenite exposed at the coast along south-western Australia, along the Pilbara Coast, and along the Canning Coast. Examples of erosional coasts that have been used to construct (eustatic or tectonic) sea-level history include rocky shores cut into calcarenite at Point Peron (Fairbridge 1950) and Rottnest Island (Playford 1988).

Coastal Type 10 can be assigned to the geoheritage category of *geohistorical sites* where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed because there is an emphasis on the record of sea-level history.

Type 11: depositional coasts recording tectonic history, sedimentary history, ocean history, climate history and sea-level history

This is a type of coast where sedimentation has stratigraphically recorded specific Earth-history information. Sedimentary sequences can record sedimentary history, oceanic history, climate history and sea-level history (a geohistorical record). This Coastal Type thus focuses on stratigraphy and the fine- to small-scale sedimentary sequences for reconstructing geohistory in the Holocene. Examples in Western Australia of coastal sedimentary packages that record sedimentary history, climate, sea-level history (with relative sea-level history being eustatic, or the result of tectonism), and ocean history are provided by the Leschenault Peninsula Barrier Dunes (Semeniuk 1985b), the cuspate forelands of the Rockingham-Becher to Whitfords area (Semeniuk & Searle 1986; Searle *et al*. 1988), the Preston Beach area (Semeniuk 1996b), and the Canning Coast (Semeniuk 2008; and Figure 9G). The sedimentary sequences containing the geohistorical records may not necessarily be large to the extent that they dominate the landform, as are the examples cited above, nonetheless they can still contain valuable information.

Coastal Type 11 can be assigned to the geoheritage category of *geohistorical sites* where the history of the Earth or its past processes can be reconstructed, because there is an emphasis on the record of sedimentary history, ocean history, climate history and sea-level history.

Type 12: sea cliffs exposing lithology, stratigraphy, contacts, and structures

Sea cliffs are recognised as special sites of potential geoheritage significance, providing exposure of stratigraphic sequences, igneous and metamorphic sequences and contacts and structures; types sections,

◀ **Figure 10.** Coastal forms developed by diagenesis and biogenesis in Western Australia. A. Tidal beach-rock ramp in northern Canning Coast (Coastal Type 9). B. Tidal beach-rock ramp in the Dampier area, Pilbara Coast (Coastal Type 9). C. High tidal cementation indurating the upper surface of shell beach in Shark Bay, with break-up of cemented crusts to form rock slabs (Coastal Type 9). D. High-tidal surface of truncated seaward-dipping sediment layers that have been cemented in bands, resulting in a coast in Shark Bay with exposure of alternating indurated and semi-indurated layers (Coastal Type 9). E. Patina of a thin aragonite crust on a beach-rock ramp at Broome (Coastal Type 9). F. Rosettes of gypsum blades, in an interlocking resistant meshwork, forming a sheet on and under the supratidal flat, Shark Bay (Coastal Type 9). G. Cemented pavement in the high-tidal zone in eastern L'Haridon Bight, Shark Bay (Coastal Type 9). H. Stromatolitic reef in middle ground and foreground, comprised of stromatolite heads and indurated sheets (Coastal Type 8); in background, cliff cut into Pleistocene Carbla Oolite (Coastal Type 12) at its type section at Goat Point.

reference sections, or culturally significant sites, *i.e.*, significant features of bedrock are made more evident by coastal erosion and provide the opportunity to study Earth history in detail. With such diverse reasons for their geoheritage significance, cliffs do not fall into the gradation of natural groups as do the other coasts, and is essentially an *ad hoc* allocation with an emphasis on geological content, not coastal geomorphology. While this coastal form is described as "sea cliff" it must be stressed that this landform can vary from vertical cliffs to steeply plunging shores. The main feature is that marine erosion exposes critical geological content, which may be manifest in vertical cliffs or in steeply plunging coastlines.

While similar geological features may be exposed in inland cliff faces, river banks, soil-covered hill sides, or local outcrops, commonly there are better and more extensively wave-washed natural exposures along the coast as a result of cliff erosion, washing by wave action, erosion by wave action, and salt weathering (Brocx & Semeniuk 2009). This also is evident in the literature because some of the best and classic stratigraphic locations and geological features are manifest in sea cliffs: the Devonian sequences around the coast of Devonshire in south-western England (Rudwick 1985), the chalk cliffs of Beachy Head, Seaford Head and the Seven Sisters along southern England (Gallois 1965; Melville & Freshney 1982), the Old Red Sandstone along the Orkney Islands in Scotland, the unconformity at Siccar Point in Scotland (Barclay *et al*. 2005; Brocx & Semeniuk 2007), the wave-cut platform developed on steeply-dipping layered limestone along the Bay of St. Jean-de-Luz, France (Machatschek 1969), the unconformable contact between Precambrian rocks and Permian glacigene sediments at Hallett Cove in South Australia (Parkin 1969; Dexel & Preiss 1995), and the Miocene limestone in the Port Campbell area ("The Twelve Apostles") in Victoria (Birch 2003). A review of texts dealing with Nature Reserves and coasts also shows that exposures of stratigraphic sequences and geological features are best manifest in sea cliffs (Bennett 1989; Blandin 1992; Goudie & Gardner 1985; Holmes 1966; Michel 1991; Sale *et al*. 1989; Snead 1982; Soper 1984).

Often sea-cliff exposures may expose extensive bedding-plane features, and lithologically-determined structural benches not as well evident in inland outcrops. For instance, shales that are recessively weathering in inland outcrops and cliffs, may exhibit sedimentary and palaeontological features on the bedding plane as a result of marine erosion, thus exposing important aspects of lithology, sedimentary structures, and palaeontology.

Examples of cliffs of significance in Western Australia include: exposures of Precambrian igneous rock in the Dampier Archipelago (Figure 13 in Semeniuk 1986), the granitoid/gabbro contact at Hearsons Cove (Figure 6.4 in Brocx 2008), Precambrian exposures at Sugarloaf Rock, Skippy Rock, Barge Bay and Ringbolt Bay along the Leeuwin-Naturaliste Ridge (Myers 1994), Precambrian gneiss, granite, and migmatite at The Gap, near Albany, Precambrian granite with xenoliths of earlier granite, west of Esperance (Figure 18 in Myers 1997), the Silurian Tumblagooda Sandstone at Red Bluff, Kalbarri (Figure 1C in Brocx & Semeniuk 2009); the Mesozoic Broome Sandstone at Gantheaume Point and Entrance Point at Broome (Figure 9H and 9I); exposure of columnar-jointed Bunbury Basalt at Black Point (Figure 41 in Playford *et al*. 1976); the Tertiary Toolinna Limestone, Wilson Bluff Limestone, and Abrakurrie Limestone at the edge of the Nullarbor Plain (Figure 70 in Geological Survey of Western Australia 1975, and Figure 4–19B in Geological Survey of Western Australia 1990); the Quaternary Tamala Limestone of the Zuytdorp Cliffs (Figure 36 in Geological Survey of Western Australia 1975); Pleistocene aeolianite and soil sheets at Hamelin Bay; and Precambrian rock, an elevated Precambrian/Pleistocene unconformity, Pleistocene aeolianite, marine bands, shore platform, and exhumed karst at Bunker Bay (in Fairbridge & Teichert 1952).

Coastal Type 12 can be assigned to the following three geoheritage categories: *type locations for stratigraphy*, fossils, and mineral sites, including locations for teaching, research, and reference; *cultural sites* where classic locations have been described; and *geohistorical sites* where there are classic exposures in cliffs and outcrops where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed.

In Western Australia, stratigraphic type sections that are located and well exposed as sea cliffs at the coast are: the Broome Sandstone at Gantheaume Point (Brunnschweiler 1957), the Toolinna Limestone at Toolinna Cove (Lowry 1968), the Peron Sandstone, at Cape Peron, Shark Bay (Logan *et al*. 1970), the Tamala Limestone at Zuytdorp Cliffs (Geological Survey of Western Australia 1975, amended from Tamala Eolianite of Logan *et al*. 1970), the Pleistocene Carbla Oolite at Goat Point (Logan *et al*. 1970; and Figure 10H), and the Holocene Kennedy Cottage Limestone and Horsewater Soak Calcarenite along the shores of Willie Creek (Semeniuk 2008).

Level 3 – fine-scale refinement of Coastal Types and coastal products

Environment-specific features mentioned earlier in the review of other coastal classifications can be identified, described and comparatively assessed within the setting of the twelve coastal categories. For instance, an erosional coast may be assigned geoheritage significance based on its local geology or bedrock exposure, its representativeness, or on some local feature not found elsewhere, *e.g.*, the Tertiary limestone along the Baxter Cliffs in Western Australia stands separate to the unconformity exposed at Hallet Cove in South Australia to the Permo-Triassic sequences along the southern and central cliff coast of New South Wales, and to the Cretaceous chalk cliffs in Sussex, England. While all these sites illustrate examples of sea cliffs, each provides its own level of international and national significance based on geological (and tectonic) setting, age of sequence, stratigraphic sequence, and specific local (unique) feature.

The full extent of further subdivision of Coastal Types for assessing geoheritage significance, in developing an inventory of coastal features particular to geological and environmental setting, will be dependent on the variability in geology (including tectonism), geomorphology, diagenesis, climate and oceanography that is manifest locally, and is outside the scope of this paper. It is not possible in this paper to identify every nuance of coastal variation in Western Australia (or globally) for purposes of assessing geoheritage significance comparatively, rather, we illustrate the approach to fine-scale subdivision of the main Coastal Types. Table 3 lists some examples of the finer-scale features for selected coastal regions in Western Australia.

An inventory of the key geological features for eleven coastal sites in Western Australia is presented in Table 4. The sites are selected to illustrate coasts in various geological, climatic and oceanographic settings, to illustrate a contrast in detail and significance of cliff types cut into Silurian, Mesozoic, or Quaternary rocks, and to contrast the detail between some sedimentary coasts. Information from such an inventory provides a basis for inter-regional to international comparison of coastal types for determining their representativeness or unique nature for purposes of assessing geoheritage significance and for geoconservation. For instance, although the Point Becher cuspate foreland and the Leschenault Peninsula barrier dunes, both in the Perth Basin region, are Coastal Type 6, they represent different styles of sedimentary accumulations, with a different set of finer-scale coastal landforms and sedimentary structures. Again, for other coasts developed by modern sedimentation (Type 6 coasts), but from different coastal regions, Table 4 contrasts a wave-dominated delta in the Pilbara region (the Maitland River delta) and another in the Carnarvon Basin region (the Gascoyne River delta). Though wave dominated, one is macrotidal and the other microtidal, and there is a difference in finer-scale geomorphic and sedimentary features within each in terms of specific landforms developed, and smaller-scale sedimentary structures, which render them different. Thus, regional geological, climate and oceanographic settings of a coast will result in site-specific expressions of climate history (*e.g.*, expressed in sediments through fauna, microbiota such as foraminifera, and diagenesis), history of storminess (*e.g.*, expressed in cheniers and tempestites), and MSL history (expressed in heights of stratigraphic interfaces, or sea-level specific landforms), amongst others. Table 4 also specifically contrasts coastal products at the fine scale of the sea cliffs using one cut into Silurian sandstone at Red Bluff and another cut into Mesozoic sandstone at Gantheaume Point.

This approach to identifying finer-scale coastal features for determining geoheritage significance, as outlined in Tables 3 and 4, can be systematically applied to other coasts elsewhere State-wide, Nationally and

Table 3

Examples in Western Australia of finer-scale features occurring within Level 2 Coastal Types

Level 2 Coastal Type	Potential finer-scale features for a given Coastal Type, and next stage of coastal division
Type 1: landforms developed by inundation	coasts such as ria, dendritic embayed forms, ridges-and-gulfs, or limestone barrier islands (all based on the inundated ancestral hinterland morphology)
Type 2: coast developed by inundation *and* erosion	coasts as for Type 1, as to form, with erosion features such as cliffs, talus, shore platforms and benches, notches, micro-pinnacles and tafoni, and lithology-related variation in style of erosion (*viz.*, rounded shores, plunging cliffs, stepped platforms and benches, serrated platforms, high-tidal pavements) linked to oceanographic and climate setting
Type 3: coast developed wholly by erosion	cliffs, shore platforms and benches, notches, micro-pinnacles and tafoni, lithology-related variation in style of erosion (rounded shores, plunging cliffs, stepped platforms and benches, serrated platforms, high-tidal pavements) linked to oceanographic and climate setting
Type 4: coasts developed by exhumation of older landforms	isolated headlands, coastal knolls, cove-and-headland morphology, and the erosional products peripheral to the resistant landforms
Type 5: coast developed by inundation *and* sedimentation	ria, dendritic embayed coasts, ridges-and-gulfs, or limestone barrier islands with associated depositional forms such as barriers, spits, tidal flats, beach-ridges, bay-head deltas, linked to oceanographic and climate setting
Type 6: coast constructed by sedimentation	barrier dunes, cuspate forelands, beach-ridge plains, beach/dune coasts, deltas, prograded tidal flats
Type 7: coast constructed by sedimentation; superimposed erosion	tidal creek, or seafront erosion of deltas and prograded tidal flats; and eroding (cliffed) seafront of barrier dunes, cuspate forelands, and beach-ridges, with style of erosion linked to oceanographic and climate setting
Type 8: biogenic coasts	bioherms or biostromes constructed by corals, oysters, mussels, stromatolites, serpulid worms, mainly in relationship to climate
Type 9; diagenetic coast	coasts are comprised of beach-rock, cemented pavements, gypsum pavement, linked to oceanographic and climate setting
Type 10: erosional coasts recording Holocene history	identifying sea-level related erosional features, or elevated diagenetic and biogenetic features on the rocky shore
Type 11: depositional coasts recording Holocene history	identifying type of stratigraphy and biostratigraphy, and identification of sea-level, climate, and ocean-history features related stratigraphy
Type 12: sea cliffs exhibiting lithology and history	identifying geological Formation, and rock sequences and rock features exposed by cliffs; details deriving from, and dependant on Level 1 setting

Table 4

Some finer-scale features occurring along selected sites of coastal geoheritage significance in Western Australia

Location	Geological, climatic, oceanographic setting	Coastal Type	Key smaller-scale features at the site of geoheritage significance
Willie Creek, north of Broome	northern Canning Basin Coast: Tropical semiarid climate; wave- and tide-dominated macrotidal regime	Type 7 and Type 11	cliff cut into Holocene shoaling tidal sand flat, beach, and dune deposits now lithified to limestone (Willie Creek Calcarenite, Kennedy Cottage Limestone, Horsewater Soak Calcarenite; Semeniuk 2008); type location for the Willie Creek Calcarenite, Kennedy Cottage Limestone, and Horsewater Soak Calcarenite; oolitic limestone; earlier Holocene bouldery tempestite deposits in the limestone; earlier Holocene bubble and other beach sedimentary structures; sea-level history; rocky shore cut into Holocene limestone; beach rock exposures; erosion by tidal creeks; ridge-and-runnel coastal forms (Semeniuk 2008)
Gantheaume Point, Broome	northern Canning Basin Coast: Tropical semiarid climate; wave- and tide-dominated macrotidal regime	Type 10 and Type 12	Mesozoic sandstone (Broome Sandstone) exposed in high cliffs in a wave-dominated and macrotidal setting; exposure of platforms, tessellated pavements, ramps, notches, benches, boulder talus, tafoni; type location for the Broome Sandstone; exposure of details of sedimentary lithology and structures, such as cut-and-fill and channel forms, cross-bedding in sandstone, conglomerate, mud layers, mud cracks, burrows, and mud flake breccia, unconformably overlain by Mowanjum Sand (Semeniuk 2008) with fissures filled with red muddy sand; breccia and soil developed between Broome Sandstone and Mowanjum Sand; decimetre-sized polygonal cracking and fissure-fills on the surface of the Mowanjum Sand
Finucane Island, Port Hedland	Pilbara Coast: this area consists of local outcrops of Precambrian rocks (islands), and coastal fringing Quaternary sedimentary deposits; Tropical arid climate; wave- and tide-dominated macrotidal regime	Type 5 and Type 10	Pleistocene oolitic limestone forming a shore-parallel barrier (Semeniuk 1996a); limestone exposed in moderately high cliffs in a wave-dominated and macrotidal oceanographic setting; exposure of platforms, benches, tafoni; exposure of details of sedimentary lithology and structures in the limestone, including a Pleistocene unconformity and Pleistocene shoreline boulder deposit, unconformably overlain by Holocene shell gravel and dune sand with fissures filled with shell and sand (Semeniuk 1996a); sea-level history
Hearson Cove, Dampier Archipelago	Pilbara Coast: this area consists of outcrops of Precambrian rocks (islands) sheltering Quaternary sediment-filled embayments; Tropical arid climate; wave- and tide-dominated macrotidal regime	Type 5 and Type 12	Precambrian igneous rock contact between intrusive gabbro/dolerite sill and country rock granite; lithological and grain-size layering in the gabbro/dolerite; lithological variation in the gabbro/dolerite; extremely coarse pyroxene crystals in the gabbro towards its base; granophyre textures in the granitoid as a result of the gabbro/dolerite intrusion; inundated (formerly terrestrial, hill-flanking) boulder deposits now forming a bouldery shore; Hearson Cove is the seaward edge of a prograded, sediment-filled former strait; high-level, mid-Holocene cementation of the boulder deposit (essentially a bouldery "beach-rock"); modern beach rock locally occurring along the Hearson Cove beach; extremes of facies variation within Hearson Cove (gravel grading to fine sand to muddy sand in response to graded wave energy); geomorphic sedimentologic nature of the shore; reflective beach and dissipative sand flats, and recurring beach cusps formed in shell gravel and in various grades of sand
Maitland River delta, Dampier Archipelago region	Pilbara Coast: this area consists of outcrops of Precambrian rocks (islands) sheltering Quaternary sediment-filled embayments; Tropical arid climate; wave- and tide-dominated macrotidal regime	Type 6 and Type 11	wave-dominated macrotidal delta, comprised of prograded (seaward) sand ridges, mud- and sand-floored inter-ridge lagoons, sandy cheniers, and mud-floored tidal flats, with the mid- to high-tidal, mud-and-sand sequence shoaling from sandy and shelly sand low-tidal flat sediments (Semeniuk 1996a); mangrove facies in mid- to high-tidal zone; muddy sediments, mangrove facies; and low-tidal sandy sediments are mostly bioturbated; surface structures at fine scale comprised of sand ripples, mud cracks, mud flakes, and burrow punctures

Goat Point, Shark Bay	Carnarvon Basin coast: this location is within the ridge-and-gulf complex of Shark Bay; Subtropical arid climate, wave-dominated microtidal regime	Type 8 and Type 12	sea cliff cut into an aeolian mound of Pleistocene oolitic limestone (Carbla Oolite); type location for the Carbla Oolite (Logan *et al*. 1970); cliff shows aeolian cross-layering, and a Pleistocene shoreline breccia; the coast is also biogenic in the tidal zone, and comprised of stromatolitic reefs
Gascoyne River delta	Carnarvon Basin coast: this location is to the north of the ridge- and-gulf complex of Shark Bay; Subtropical arid climate, wave-dominated in a microtidal regime	Type 6 and Type 11	wave-dominated microtidal delta, asymmetric because of strong southerly winds, comprised of prograded repetitive sand ridges, mud- and sand-floored inter-ridge lagoons, with mangrove facies in the mud-floored lagoons, shoaling from a sandy mid- to low-tidal flat beach and bar (Johnson 1982); the wave-dominated, low-tidal sandy beach and bar sediments are laminated and cross-laminated, wind-dominated supratidal dune (sand ridge) sediments are large-scale cross-laminated; protected and biogenically-altered mid- to high-tidal sediments are mostly bioturbated; surface structures at fine scale comprised of sand megaripples, sand ripples, shell pavements, mud cracks, mud flakes, and burrow punctures
Red Bluff, Kalbarri	Carnarvon Basin Coast: here consisting of local outcrops of Silurian sandstone, Pleistocene limestone amid Holocene deposits; Subtropical semiarid climate; wave-dominated microtidal regime	Type 2 and Type 12	Silurian sandstone exposed in high cliff in wave-dominated and microtidal oceanographic setting; rocky shore of platforms, benches, notches, ramos, boulder talus, tafoni; cliff exposures of sedimentary lithology and structures, such as cut-and-fill and channel forms, cross-bedding, cross-bedding in sandstone, conglomerate, mud layers, mud cracks, vertical burrows, animal tracks, mud-flake conglomerate and breccia, slump structures and other deformation structures (convolute bedding); unconformably overlain by Quaternary deposits such as yellow sand and aeolian calcarenite
Muderup Rocks, Cottesloe	Perth Basin Coast: here consisting of local outcrops of Pleistocene limestone and Holocene deposits; Subtropical semiarid climate; wave-dominated microtidal regime	Type 3 and Type 12	rocky shore cut into Pleistocene limestone showing former Pleistocene rocky shore unconformably overlain by a Pleistocene beach-to-dune sequence (Semeniuk & Johnson 1985); modern rocky shore showing classic geomorphic sequence of rim, platform, overhangs, cliff and notch, benches, pools, lapiés, talus breccia, and gravelly deposits; earlier Pleistocene rocky shore features of potholes, overhangs, shell gravel, lithophagic borings, echinoid excavations, bouldery deposits; one bench is an exhumed Pleistocene rocky platform; Pleistocene beach/dune stratigraphy shows shoaling-upward sedimentary sequence, with beach to dune sedimentary structures, bubble sand, and *Sepia* and *Spirula* fossils; sequence is punctured by vertical pipes filled with yellow sand, and riddled with rhizocretions; unconformably overlain by yellow sand
Point Becher, cuspate foreland, Rockingham	Perth Basin Coast: here consisting of local outcrops of Pleistocene limestone and Holocene deposits; Subtropical subhumid climate; wave-dominated microtidal regime	Type 7 and Type 11	Holocene prograded coastal plain comprised of low beach ridges (Searle *et al.* 1988; C A Semeniuk 2007), and a variety of coastal dune forms (Semeniuk *et al*. 1989); underlain by a shoaling sequence of seagrass facies sediments, beach and dune sediments; two orders of beach ridges reflecting Double Hale Cycle influence on Indian Ocean climate, and the 250-year climatic cycle (Semeniuk 1995); Point Becher preserves a history of beach ridge accretion and erosion reflecting the 250-year climatic cycle (Semeniuk 1995); Holocene sea-level history preserved in the stratigraphic sequence (Semeniuk & Searle 1986)
Leschenault Peninsula barrier dune	Perth Basin Coast: here consisting of shore-extensive Holocene deposits; Subtropical subhumid climate; wave-dominated microtidal regime	Type 7 and Type 11	Holocene retrograding barrier dune system (Semeniuk & Meagher 1981; Semeniuk 1985b) underlain by dune sand (Safety Bay Sand) and estuarine sediments (Leschenault Formation); modern barrier illustrating staggered parabolic dune development, and its geomorphic evolution to soil-covered plain; complex Holocene sea level history preserved in the stratigraphic sequence (Semeniuk 1985b, 1986b; Semeniuk & Searle 1986)

Internationally. Information to construct such inventories can be obtained from numerous texts and specialised papers that deal with the smaller-scale features of igneous, metamorphic, structural, and sedimentary geology, and geomorphology (as exemplified by the illustrations of small-scale geological and geomorphic features in Davis & Reynolds 1996; Emery & Kuhn 1982; Ginsburg 1953, 1975; Guilcher 1953; Hills 1949; Kelletat 1995; Pettijohn & Potter 1964; Reineck & Singh 1980; Wilson 1982). Recently, in developing a comprehensive classification of coasts, Finkl (2004) provided an exhaustive list of features that are present along coasts that can be applied to this level of categorisation.

Discussion

The categorisation of coastal types at the three levels presented in this paper can be applied to develop an inventory of coastal features, and lead to an assessment of geological and (hence) geoheritage values. Level 1 provides a context and framework for subdivision and interpretation of the significance of coasts of different geological, climate and oceanographic regions. In Western Australia, using Precambrian rock coasts as an example, the range of geological features in the folded Precambrian system of the King Leopold Mobile Zone of the south-western Kimberley region will be different to those of the Precambrian igneous complexes of the Pilbara region and those of the Albany-Fraser Orogen along southern Western Australia. Similarly, Quaternary limestone-dominated rocky shores set in a tropical arid, macrotidal and wave-dominated setting in the Pilbara Region will exhibit different geologic and geomorphic features to rocky shores cut into Quaternary limestones of the central Perth Basin.

The classification at Level 2 is based on identifying coasts developed by processes of marine inundation, erosion, sedimentation, biological activity, and diagenesis. It identifies those coastal types that have specific geoheritage value, and can be applied at the largest scale and the finer scales of coastal expression. The classification at Level 2 is designed for use in geoheritage and geoconservation: firstly, it identifies the fundamentally *different types of coasts* that form the framework for more detailed studies; secondly, it identifies those that have specific geoheritage significance or value; and thirdly, it can be used for comparative assessment, *e.g.*, coasts of inundation forms can be compared to other inundation forms, and erosional coasts can be compared to other erosional forms, and those that illustrate Holocene history or earlier geological history can be compared to a similar category of coast elsewhere. In this context, use of the coastal categories provides a consistent approach for comparative assessments in geoconservation and geoheritage, and a systematic approach for classifying, cataloguing, and assessing sites for geoheritage purposes.

Level 2 classification deals with the intergradation between coasts by recognising the intermediate forms (*e.g.*, eroded coasts with sediment accumulations) as separate Coastal Types. The classification at Level 2 also addresses the fact that different categories of coastal features (and therefore different categories of coastal features of geoheritage significance) can occur at different scales. In application, the classification is non-scalar (the Coastal Types transcend scale). Hence there is a focus on form and type, regardless of scale and, once identified and classified, coastal features can be related to a scale by descriptors. This is not to say that particular coastal features are not related to a given scale, or do not have a tendency to occur within a specified scale range (Figure 1). Some coastal types, such as rias of the Kimberley region, and the limestone barriers of the Pilbara region, are expressed more consistently at a regional scale, while others, such as beach-rock ramps along tropical Western Australia, are expressed more consistently at local scales, but many other coastal types can be recognised within varying frames of reference. Level 2 classification also provides a context for describing, comparing and assessing sites of geoheritage significance at the finer scale within a consistent framework – thus, fine-scale coastal features are compared only within similar coastal types.

Because the classification at Level 2 is designed for geoheritage purposes, some of the categories do not correlate with existing classifications (though this is not strictly necessary). Coastal Types 1–7 form a natural gradational series (starting with a Holocene marine-inundated landscape), with a trend resulting from increasing erosion on one hand *versus* a trend resulting from increasing sedimentation on the other, and are conceptually parallel, in part, to some existing classifications (*e.g.*, Valentin 1952 and Bloom 1965). However, Coastal Types 10, 11 and 12, identified as types because they record Holocene history of sea-level changes, tectonism, oceanography, climate, or record pre-Holocene geology, are not addressed in existing coastal classifications. In summary, Coastal Types 1, 2, 3, 5, 6 and 8 are, in part, covered by some existing coastal classifications, or conceptual classification schema, but Coastal Types 4, 9, 10, 11, and 12 are not recognised in existing classifications. The reason for this, as noted earlier, is that geoheritage and geoconservation have not been the basis for developing previous coastal classifications.

Using the proposed classification, a given Coastal Type can be classified from a number of different perspectives, and therefore have different geoheritage values. Eroding rocky shores exemplify this. An eroding coast can be classified as Coastal Type 3, illustrating modern coastal forms developed in response to marine erosion, with formation of vertical cliffs, wave-cut benches, lithologically-determined benches, cementation-determined benches, talus, and various microtopography. The same sea cliff, if exhibiting geomorphic features and cementation features developed during a former higher sea level can also be categorised as Coastal Type 10. If there is significant stratigraphy, or other geological content, exposed in the wave-washed cliff, the coast may also be categorised as Coastal Type 12.

The different geomorphic aspects of the coast, and different geologic components of the coast, as well as features at different scales along a given tract of coast, may have different geoheritage significance. These matters have to be addressed in identifying sites of geoheritage significance. In Shark Bay, for example, there are numerous small-scale coastal features of geoheritage significance that are embedded in larger-scale coastal systems that, in their own right, are of geoheritage significance. Small-scale features of geoheritage significance in Shark Bay include breccia pavements, or gypsum rosettes. Large-scale features of geoheritage significance include the marine-inundated ancestral topography of ridges-and-gulfs that is a feature reflecting the tectonically-active western margin of the Carnarvon Basin. Siccar Point in Scotland provides another example: the unconformity at Siccar Point has global (cultural) geoheritage significance, but at the geological and geomorphological small scale, as a rugged coast of rocky shores cut into Silurian and Devonian rocks, with cliffs and platforms, it is a site of geoheritage regional significance occurring at the geomorphic medium scale. To be useful for studies in geoheritage, and for geoconservation, the various scales at which natural features express themselves need to be considered and noted by using a scale descriptor and assessed independently.

Classification of the coastal zone and its smaller-scale products have been reported from a number of disciplines and perspectives with the result that there is a variety of systems, and a wide range of detailed studies that categorise the large-scale and finer-scale products along the coast. Coastal geomorphologists and sedimentologists have classified/ categorised the coast globally, regionally, and locally, providing over-arching and/or theoretical schemes at one extreme, and identifying smaller-scale features of the coastal zone at the other. The over-arching classification systems and other existing coastal classifications have not been used in this paper for a number of reasons. Firstly, in a context of geoheritage and geoconservation, the conceptual models, while useful for understanding the development of coastal forms, do not provide categories of coast for empirical and comparative purposes. Secondly, coastal scientists have had different objectives, and their classifications and categories have not always been applicable across disciplines, and specifically have not been directly applicable to geoheritage and geoconservation. The approaches adopted by geomorphologists, for instance, have not always been applicable to sedimentology, and *vice versa*, and that of identifying diagenetic products has not been applicable to geomorphology, sedimentation, or to erosional coasts. From the variety of studies cited above, information useful to geoheritage and geoconservation are the categories of coastal types that have been identified to date (*e.g.*, rocky shores, delta types, barriers dunes, cuspate forelands, beach cusps), and smaller-scale products such as bedforms, sedimentary structures, and fine-scale rocky-shore features, amongst others (and these are mainly applicable at Level 3). Thus, the approaches in coastal geomorphology, sedimentology, and diagenesis have not been directly applicable to the issues of geoheritage *except at the lowest level of classification of categories* that may be used in comparative inventories, or in compiling assemblages of smaller-scale features at a given site.

Diagenesis provides a good example to illustrate the lack of communication between the various disciplines in coastal science, and how scientific categorisation of products has not been directly useful to the issues of geoheritage and geoconservation, or even coastal classification.

Researchers of modern diagenesis have categorised coastal diagenetic features, but have tended to concentrate on its specific interesting effects and have therefore focused on smaller-scale products, documenting site-specific products, and providing information useful for interpreting ancient sequences, with an emphasis on diagenetically susceptible materials, such as carbonate sediments in arid and hypersaline environments. Generally, the approaches have not presented diagenesis as a unified discipline for coastal science, and the results have not always been transferable to the other areas of coastal science. As such, information on diagenesis, scattered in the literature, does not provide a framework for coastal classifications based on diagenetic products. Coasts, in fact, generally are not classified on their diagenetic products, and those formed by diagenesis are not generally recognised as a coastal type. Rocky shores well illustrate this: diagenesis is an important process-and-product component along rocky shores, especially those cut into porous Quaternary limestone, but its role in shore development and its control of microscale and leptoscale features has not been fully explored. So while there is mention of some of the products of diagenesis, the role of diagenesis in coastal development generally is seldom considered by coastal scientists. A perusal of a range of texts dealing with coastal science sometimes will find beach rock (a product of diagenesis) listed in the index, but not diagenesis itself. The corollary is that the results of most studies on diagenesis (diagenetic processes, or products), cannot be imported into geoheritage and geoconservation. We use diagenesis in Shark Bay to further illustrate this principle.

Shark Bay is designated a World Heritage area (inscribed in 1991) and, as such, it has global, national and State-wide importance. Amongst other aspects of its natural history, Shark Bay is comparatively well researched in terms of Holocene diagenesis (Logan 1974). Paradoxically, however, diagenesis is not emphasised as a natural process that has any international or national significance, and there is a general lack of application of diagenesis to coastal geomorphology, coastal evolution and, of course, to geoheritage and geoconservation.

While diagenetic processes and products were systematically described by Logan (1974) in a stratigraphic/hydrochemical framework, and the study was relatively exhaustive, some of the globally significant and unique diagenesis in the Shark Bay area was not highlighted. The study by Logan (1974) provided neither a framework, nor results, nor global comparison which could be used for developing an understanding of coastal evolution, or for geoheritage and geoconservation. That is, the results of studying diagenesis in Shark Bay were not applied to matters of coastal geomorphology, coastal erosion, coastal evolution, or many other of the aspects of coastal sedimentation. Even comparing the results from Shark Bay to other areas globally could have formed the basis of geoheritage comparisons and assessment. These outcomes are not surprising, as the objective of the study by Logan (1974) was an inventory of Holocene diagenesis within Shark Bay *per se*, not a catalogue of diagenetic products for the purposes of comparative geoheritage and geoconservation. However, the matter of diagenesis in Shark Bay does illustrate the point that one of the most comprehensive studies undertaken of diagenesis globally cannot be readily compared with other sites elsewhere, nor can it be easily transferred to matters of geoheritage and geoconservation, except on an inventory basis, to catalogue diagenetic features that may be of geoheritage significance. This example from Shark Bay underscores that diagenesis, as a process resulting in various coastal types, and controlling and modifying coastal form, largely has been overlooked by coastal scientists.

Coasts present many products of geoheritage significance, from varying expression of landforms, to products uniquely developed in the coastal zone from the interaction of coastal processes, to sea cliffs that reveal Earth history, however coastal deposits and coasts also can uniquely record a Quaternary history of sea level, climate, and oceanic processes because they interface with oceans. Such stratigraphic and biostratigraphic sequences in Western Australia have been used to document relative sea-level changes (Semeniuk 1985b, 1996b, Semeniuk & Searle 1986, Playford 1988, Searle *et al.* 1988, Semeniuk 2008), as represented by Coastal Types 10 and 11. Encoding of climate patterns is discussed further below.

The oceans dominate the Earth's surface and act as large receptors for solar radiation, encoding climate changes in a number of ways. Though not strictly globally homogeneous (in terms of salinity, temperatures, and circulation), oceans are much less heterogenous than landmasses that can express variable geology, landscape, soils, and vegetation at regional to small scales. Consequently, terrestrial environments respond to climate changes in more complex ways than oceans. It was partly for this reason, to study Quaternary climate changes, that stratigraphers and palaeoclimatologists concentrated on cores and biostratigraphy of deep ocean basins where there was/is a degree of environmental spatial consistency. In essence, therefore, the oceans can more consistently register the effects of short-term to long-term climate changes but, with oceans being fluid and circulating, the effects of climate can be relatively rapidly dispersed and not necessarily preserved. However, the coast, being the edge of an ocean, regardless of whether it is erosional or depositional, is an important zone where oceanic patterns reflecting climate and sea-level history *can* be recorded in landforms, sediments, biota, and isotopes, and can be read, if the alphabet of the encoding is manifest as landform, stratigraphic, biostratigraphic, and isotopic signatures. In Western Australia, the Holocene sequence of the Rockingham-Becher Plain in its regularly-spaced, low-relief beach ridges (Searle *et al*. 1988) records cyclic climate changes responding to the solar Double-Hale Cycle (Semeniuk 1995). Regular beach-ridge patterns recording the solar Double-Hale Cycle also have been documented in Hudson Bay by Fairbridge & Hillaire-Marcel (1977). In effect, the coast can be the permanent receiving interface (or the register) of oceanic patterns which are driven by climate changes and sea-level changes (Semeniuk 1995). In this context, the modern coastal zone can be an important site of geoheritage significance, recording the history of the Earth in the Holocene. Sequences and landforms that record this ocean history are represented by Coastal Types 10 and 11.

While most of the Coastal Types identified in this paper form part of an inter-gradational natural group, or continuum, or are products of interacting processes, *i.e.*, Coastal Types 1–9, reflecting the balance of the five marine and coastal processes, or form another natural group recording Holocene history, *i.e.*, Coastal Types 10 and 11, sea cliffs provide an anomalous category. As an *ad hoc* category with an emphasis on geological content, not coastal geomorphology or Holocene history, they are not part of a natural continuum in Coastal Types shown in Figures 4 and 5.

Sea cliffs provide an interesting example of how a coastal feature can be viewed from different geoheritage perspectives. Viewed strictly as sea cliffs, *i.e.*, geomorphologically, such coastal features would be captured as various categories in the classification presented in this paper, *viz*., where erosion has partly modified the coast (Coastal Type 2), or has fully modified the coast (Coastal Types 3 and 4), and in this context, the emphasis on these types of coasts is geomorphological. Different sea cliffs, composed of diverse materials, would respond variably to coastal processes, and would provide geomorphologically, geologically, and processes-oriented information useful to science and to coastal managers. Sea cliffs can also preserve ocean history and sea-level history in benches and platforms (Coastal Type 10). As mentioned earlier, Coastal Type 12, sea cliffs, emphasise geological content, not geomorphic features.

Brocx & Semeniuk (2009) pointed out that sea cliffs generally provide excellent locations for studying rock sequences (sedimentary, igneous, or metamorphic), and provide some of the best exposures of geological features of geoheritage significance. Indeed, there are numerous such examples that already have been afforded global and national recognition because of their geological or cultural importance – these include the chalk cliffs along the Sussex coast in England, the unconformity first described by Hutton exposed at Siccar Point in Scotland, cliffs along the coast of Victoria (White *et al* 2003), and at Hallett Cove in South Australia (Parkin 1969; Dexel & Preiss 1995). Fine- to small-scale rock structural features, intra-lithologic features, and various lithologic types are best brought out by coastal erosion effected by wave washing, (sand-charged) wave erosion, wind erosion, and salt weathering. A range of textbooks on sedimentary structures and other geological features from the realm of sedimentary, igneous, metamorphic rocks, and structural geology reveal that a large number of well-exposed outcrops occur in the coastal zone (*e.g.*, Pettijohn & Potter 1964). In contrast to outcrops inland or along river courses (apart from regularly river-washed steep gorges), coastal outcrops not only present wave-washed and salt-weathered exposures, but also a generally better continuity of outcrop (Brocx & Semeniuk 2009). A corollary is that coastal rock exposures are often also the best outcrops for type sections and reference locations. In Western Australia, the Broome Sandstone at Gantheaume Point, the Toolinna Limestone along the edge of the Nullarbor Plains, and the Carbla Oolite at Goat Point, Shark Bay exemplify this.

While type sections, reference sections, teaching sections, culturally important geological sites, and sites that exhibit geohistorical information are variably captured in the twelve Coastal Types, it needs to be stressed that if they are to function as important geological sites, generally they should be relatively fixed (*e.g.*, cliffs) and able to be examined and revisited as knowledge expands and new research directions are developed. Along the same lines, some of the active, dynamic coastal terrains should be relatively long term features, acting as standards and reference locations that can be examined and revisited, *e.g.*, the mobile parabolic dunes of the Leschenault Peninsula, (Semeniuk & Meagher 1981), or those of the Yeagarup Dunes along the southern coast of Western Australia. Other active coastal forms appear to be relatively temporary or ephemeral, *e.g.*, ridge-and-runnels, and beach cusps, and might not be viewed as qualifying to be assigned geoheritage significance. However, we present the argument that where rips, ridge-and-runnels, and beach cusps are regularly developed at some locations (because of the configuration and orientation of the shore, the occurrence of headlands framing a curved beach or cove, and the prevailing wave climate), they stand as important teaching and research laboratories. While they may not be strictly permanent systems, rips, ridge-and-runnels, and beach cusps may be quasi-prevailing or regularly occurring for the reasons outlined above. Hence, there are locations where they can be predicted to more regularly occur. Also, as particular types of rhythmic coastal features, they can develop coastal formations and stratigraphic sequences indicative of specific coastal conditions (*e.g.*, cut-and-fill structures, lenses of trough-bedded sand, lenses of upward-shoaling sedimentary packages, shell and coarse sand lenses, and shell-lag deposits, amongst others). As natural reference sites, classrooms, and research sites, locations with quasi-prevailing or regularly occurring rips, ridge-and-runnels and beach cusps should be considered sites of geoheritage significance within the category of sites of active coastal geological processes.

This paper does not rank the coastal features as to their significance. The recognition of the twelve types of coast with different geomorphology and geological features, and the reasons for their differentiation, provide the template for identifying geodiversity and importance of the geology of the coast, and forms the first step to identifying sites of coastal geoheritage significance. The various coastal forms and coastal features can be readily assigned to the four categories of geoheritage sites as described by Brocx & Semeniuk (2007).

The Coastal Types described in this paper can be placed into a larger context, within a national or international framework, using information on geological setting (including tectonic setting) and hinterland geomorphology, as well as climate setting and oceanographic setting. The context of the coast would influence its detailed geomorphic, sedimentological, erosional and diagenetic responses. Tectonic setting, for instance, would control the developing shore morphology, the types of hinterland geomorphology that are presented at the shore, the erosion and sedimentation rates, and the types of sediment delivered to the shore. Geological setting would determine the coastal bedrock geology, which would control the "grain of the coast", the configuration of the coast, the structural and lithological controls on coastal form, the erodability of the shore, and the types of rock sequence that might be exposed. Hinterland geomorphology, once inundated by the Holocene transgression, would determine coastal forms in terms of shapes, steepness of shore, and riverine and marine interactions. Climate setting would determine water temperatures, and coastal processes in terms of tropical humid or tropical arid conditions at one extreme, to Boreal and Arctic conditions at the other (with ice interacting with coastal deposits, or annual freezing of coastal deposits), or would influence wind direction and intensities, rainfall, run-off volumes, evaporation, style of diagenesis, and effect of biodiversity, amongst others. Oceanographic setting would determine whether the coast is swell-, wind-wave-, or tide-dominated, and the prevailing direction of wave impingement. These higher-order settings provide a framework for national and international comparisons of Coastal Types presented in this paper so that features of geoheritage significance can be systematically compared and ranked in context, but not for comparing coasts with geoheritage values at smaller scales.

The hierarchical approach to classifying coasts proposed in this paper requires all three levels to be applied to be able to fully categorise a coast for assessing geoheritage values and for geoconservation (Figure 11). Applying only Level 1, *i.e.*, placing the coast in a geological, oceanographic and climatic context, clearly does not provide enough detail for delineating coastal forms for geoheritage purposes – it would just locate the coast geologically, climatically, and oceanographically without providing critical coastal product(s) information. However, the context provided by Level 1 classification is critical to the application of Level 3.

The core of the classification is at Level 2. While the benefits of Level 2 classification include categorisation of Coastal Types and, in the context of Coastal Types 10, 11 and 12, identification of different coastal forms with geoheritage significance, on its own it does not allow for detailed comparison of coastal types. For instance, for Coastal Type 3, the different types of eroded coasts occurring along the Baxter Cliffs, the limestone rocky shores in the Carnarvon Basin, or the cliffed, igneous rocky shores in the Pilbara would not be separated. For Coastal Type 6, the different types of accretionary coasts such as cuspate forelands, beach-ridge plains, barrier dunes and deltas, similarly would not be separated. However, Level 2 classification does provide a context for the subdivision that would follow, with the application of Level 3 classification, and used in conjunction with regional setting at Level 1, it provides a solid foundation to separating coastal types and provides a basis for assessing geoheritage values.

Applying Level 3 classification in isolation, *i.e.*, documenting a given coastal site in detail, will result merely in an inventory of geomorphic and geological features. However, the importance of information at Level 3 is that it separates the various coastal types on their finer structure, characteristics, and components, and can be used comparatively in an assessment capacity for determining geoheritage values. While Level 3 involves the smallest scale of information applied, its content will depend on the larger-scale geological, oceanographic, and climate setting, and the finer-scale information will have geoheritage relevance when used in conjunction with both the regional-setting context and with Level 2 classification of the coasts.

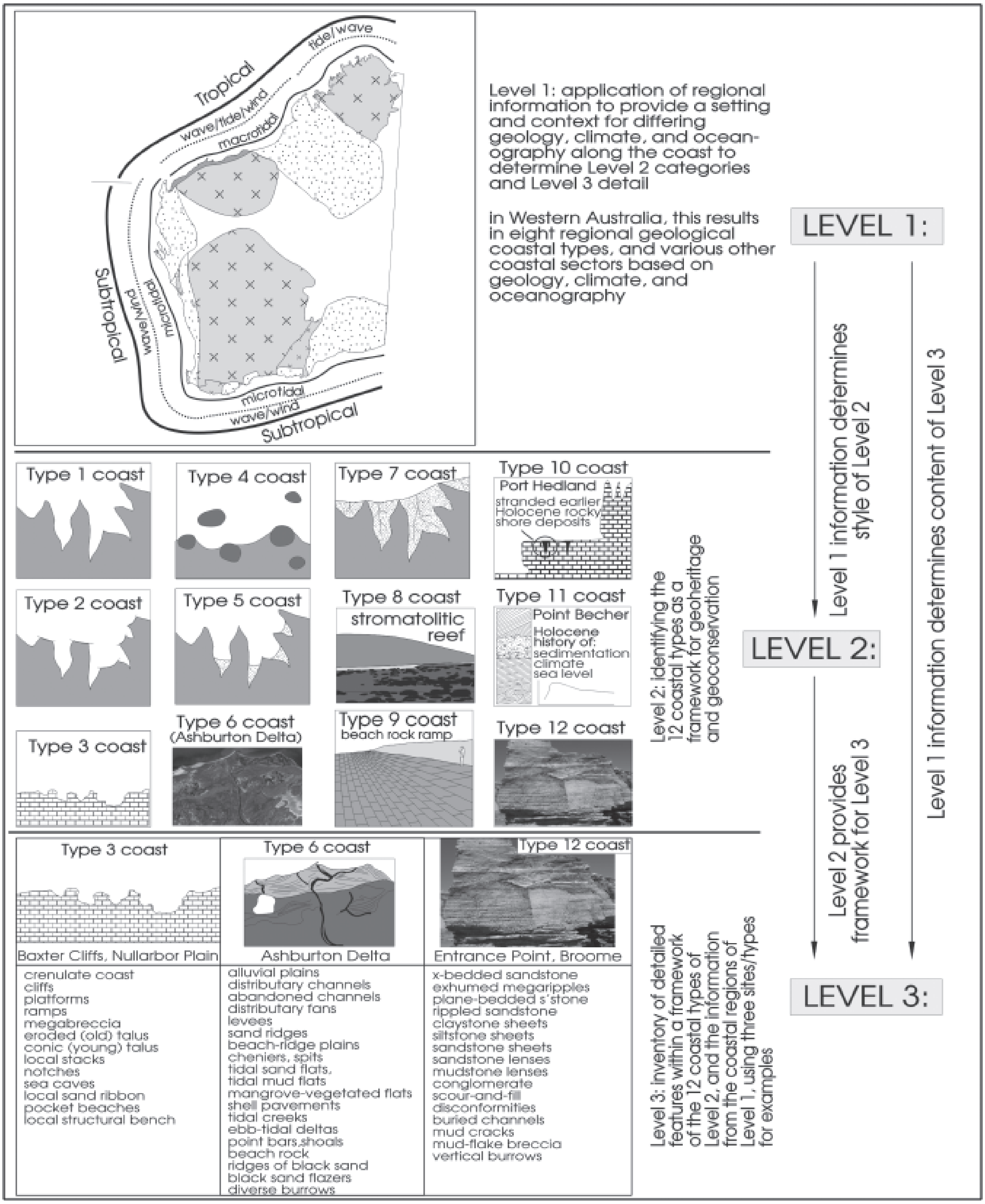


Figure 11. Application of Level 1 to Level 3 categorisation of Western Australian coasts. The three concentric lines of varying widths and styles circumferential to the coast represent, in generalised form, the extent of the tropical and subtropical coastline, the extent that a coastal sector is wave-dominated, tide-dominated, or wind-dominated, or mixed (the centrally-placed line) and, finally, the extent of macrotidal *versus* microtidal shores. Nomenclature and symbols for the cratons, orogens and basins in Western Australia are shown in Figure 3. Coastal types in Level 2 are drawn from Figures 4, 5, 9A, 9H, 10A and 10H. Coastal Type 10 at Level 2 derives from a limestone rocky shore at Port Hedland. Coastal Type 11 at Level 2 derives from the stratigraphic sequence preserved at Point Becher.

In essence, for geoconservation and assessment of geoheritage significance, all three levels of coastal classification have to be applied.

As noted earlier, classifying coastal sites for the purposes of geoheritage and geoconservation is not an easy task. In recognition of the complexity, intergradation, and variety of scales of coastal features, we have attempted to design a category-oriented (or product-oriented) classification to deal with types of coasts that can be applied to a wide variety of settings. By addressing the products developed by the five fundamental processes we believe the proposed classification at Level 2 captures the main coastal categories for purposes of assessing geoheritage significance and, as such, forms a basis for comparative assessment of sites, and a framework for a more detailed inventory as a basis for the selection of sites for geoconservation. By identifying the main coastal settings and the main processes and their combinations that develop the coastal forms and coastal products, it is possible to capture in this classification the higher-order levels of coastal categories. The classification presented herein addresses the types of coasts that are developed geomorphologically, the stratigraphic sequences that may be developed, the geohistorical record within coastal forms and coastal sequences, and the products of hydrochemical interactions – all aspects of the coast that can have geoheritage significance. Within this context, smaller-scale geological and geomorphic features can be identified for comparative purposes. But, conversely, any fine-scale features along the coast can be placed into the framework of category-oriented coastal types for inventory-based comparison and assessment to determine potential geoheritage significance.

While the approach presented in this paper is largely based on Western Australian examples, a review of the literature and site visits to locations elsewhere in Australia and overseas, show that it has potential for global applicability. Identifying geological region and climate and oceanographic setting clearly provides important information for understanding coasts, and is applicable globally. The literature already shows these underlying factors to have major influence on geological content for geoheritage purposes, as well as on coastal processes and coastal form (Davies 1980; Woodroffe 2002). At the next level, by addressing the products developed by the five fundamental processes we believe the proposed classification of twelve Coastal Types captures the main coastal categories and, as such, forms a basis for comparative assessment of sites of geoheritage significance and the selection of sites for geoconservation.

Many of the studies in coastal geomorphology, erosion, sedimentation and diagenesis have only been applicable to the issues of geoheritage and geoconservation at the specific product level (such as delta types, barrier islands, coastal dunes, as large-scale features, or ripple forms, beach cusps, flazer bedding, as small- to fine-scale features). Such coastal categories can only be applied as comparative inventories. The classification presented herein seeks to be more comprehensive and inclusive, addressing the types of coasts that are developed geomorphologically, the stratigraphic sequences that may be developed, the geohistorical record within coastal forms and coastal sequences, and the products of hydrochemical interactions – all aspects of coasts that can have geoheritage significance. In contrast to other coastal studies which describe, categorise, and classify coasts and coastal products, the classification presented here provides the basis for a systematic inventory-based assessment of coastal types and products for geoheritage and geoconservation.

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