GEOLOGICAL AND GEOMORPHIC FEATURES AND EVOLUTION OF THE LAKE MACLEOD – NINGALOO - CAPE RANGE - EXMOUTH GULF AREA, WESTERN AUSTRALIA

INCLUDING AN ASSESSMENT OF VALUES AGAINST WORLD HERITAGE LIST CRITERIA

A report prepared for the Department of Conservation and Land Management, Western Australia

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Cover image: ***Pseudo-colour gravity anomaly map of the western portion of Australia. The image shows Bouguer anomalies onshore and free-air anomalies offshore. The data are contrast enhanced and range from blue (low) to red (high), with sun-angle illumination from the northwest*** (from Milligan, P. R., Petkovic, P. et al. 2003 p.133).

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1 Executive Summary

The Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area is proposed for inclusion on the World Heritage List. The area is arid, located on the mid-west coast of Western Australia at latitude *c.* 22°S, in the climatic transitional zone between the temperate, winter-dominated rainfall zone to the south and the tropical, summer-dominated rainfall to the north. The main physiographic features are anticlinal limestone ranges, a living coralgal fringing reef, sand plains and dunes, a vast shallow coastal embayment and a large saline lake.

This reports describes the geological evolution and geomorphic features of the area, in support of its nomination for inclusion on the World Heritage List for its outstanding universal value (OUV) in relation to natural criterion (i) in paragraph 44 (a) of the Operational Guidelines (WHC 2002). It also aims to fulfil the conditions of integrity prescribed in paragraph 44 (b), (i) and (vi). The proposed nomination area is shown in Figure 17. Whilst the area is subject to claims on its natural resources, namely high-grade limestone, hydrocarbons, water, native forage, scenery and wilderness, this synthesis of geological and related knowledge is done objectively, without favour or prejudice to the various resource-use proponents.

The Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area demonstrates very well, (1) a geologically condensed period (150 Ma) of successive tectonic and sedimentary processes, and (2) landscape and biological co-evolution, closely related to the break-up of the Gondwanan supercontinent. This process commenced well to the northwest on the Argo Abyssal Plain at about mid-to late-Jurassic time, then progressively 'unzipped' our continent in an anticlockwise direction. For the Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area, the onset of rifting and generation of new seafloor on the Gascoyne and Cuvier Abyssal Plains occurred at the start of the Cretaceous Period (141 Ma). With the progressive separation of Greater India from Australia, mostly marine sedimentation occurred in various subsiding continental-margin basins, including the Exmouth and Gascoyne Sub-basins. These sub-basins, which contain the rocks now exposed in the area, are part of the much larger Carnarvon Basin. Climatic and depositional conditions changed at mid-Cretaceous time, resulting in the deposition of mainly pelagic biogenic carbonates, part of which are now exposed as the characteristic limestone karst in the ranges of the area. The ranges, of which Cape Range is the largest, were formed through tectonic compression in the Late Miocene or early Pliocene Epoch, in response to initial collision between the Australian and Asian plates. Following this uplift and later sea level fall, the area has been subject to various coastal marine and terrestrial geomorphic processes. These processes continue, and are essential for the maintenance of habitats and the various life forms they contain.

Embedded within this geological and geomorphological history are a number of outstanding natural features or aspects. Foremost, the Ningaloo Reef – Cape Range karst system, comprising Cape Range, the fringing Ningaloo Reef and coastal plains is a complex hydrogeological system supporting a distinctive cavernicolous biota. Geomorphically, it is an outstanding example of karstification initiated during a wet climatic phase but mostly developed under severe arid glacial or periglacial conditions. This landform has high natural beauty values, very high scientific values and very high conservation values.

The anticlinal ranges are outstanding examples of an unusual, well preserved tectonic style, involving transfer and tear faults, arising from a major shift in orientation and location of spreading centres from the Argo Abyssal Plain south to the Cuvier – Gascoyne Abyssal Plains. The atypical fault geometry maximised the uplift effect arising from the early Pliocene or Late Miocene compression, and co-beneficially, demonstrates very well, the tectonic transition from a passive divergent margin to an active convergent continental margin. Accordingly, the scientific values for research, educational and reference purposes are very high, as are the conservation values. When considered simply as landscape features, the natural beauty values are low.

As sea levels fell, wave-cut terraces reflecting highstand strandlines were formed on the flanks of the ranges. Four principal terraces are particularly well preserved on the western flank of Cape Range. They are incompletely studied but are of vital importance in improving the understanding of local and regional Pleistocene sea levels. Also important in Pleistocene studies are the dune deserts. Like the terraces, these sediments are incompletely studied but are providing valuable palaeoclimatic information for the Late Pleistocene Epoch. Overall however, the global scientific significance of the terraces and desert sediments is probably limited and accordingly, the World Heritage scientific values are moderate. The natural beauty values for both geomorphic features are low, but the conservation values are high, consistent with the very high conservation values of the Cape Range karst system and the anticlinal ranges.

The Giralia Range Cainozoic and Cretaceous fossils have very high scientific values because of their global contribution to understanding the biological transition from pandemism to endemism from the Mesozoic Era to the Cainozoic Era. Studies of certain microfossils are also contributing substantially to the global understanding of oceanic anoxic events (OAEs) during the Cretaceous floods. The natural beauty values are very low, whilst the conservation values, in order to conserve the very valuable field mapping and sampling sites, are high.

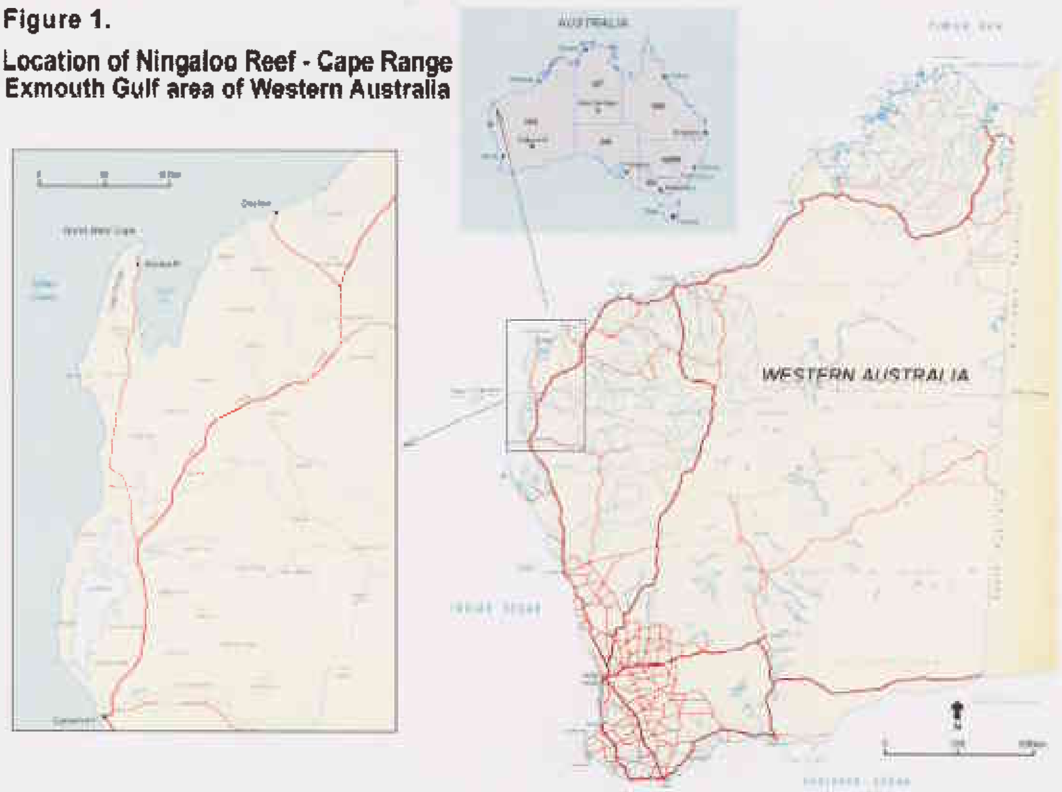
Lake MacLeod is a 'window' into a substantial and remarkable hydrogeological system, supporting an important and complex ecosystem. It has high World Heritage scientific values, very high conservation values and moderate natural beauty values. Although located up to 20 km inland, recharge is predominantly from the sea, via highly permeable subsurface limestone aquifers, in response to a 3 to 4m hydrostatic differential between ocean and basin maintained by high evaporation rates. This very unusual recharge mechanism has engendered several saline habitats, notably including mangrove stands, and provides an essential stopover location for large numbers of migratory shore birds. Lake MacLeod is an outstanding natural heritage feature of national and international importance.

In conclusion, the Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area is gaining national and international recognition as a place of considerable importance. It contributes an abundance of outstanding natural heritage features, each with multiple intrinsic values. Importantly, together, the geological and geomorphic features, as outlined above and in more detail elsewhere in this report, and the biological features described in the Draft Nomination for the Ningaloo - Cape Range World Heritage Property (GoWA in prep) present an intriguing story of geological and biological co-evolution. These features are very well preserved and accessible here. This area is pivotal to the complex story of Gondwanan fragmentation, both in the tectonic sense of transposed and rotated oceanic spreading centres, and in the biological sense of the change from pandemism to endemism. The proposed geological features (geo-evolutionary) nomination area (Fig. 17) also satisfies the important World Heritage integrity criterion.

Clearly, biological evolution cannot be 'divorced' from the geological 'substrate' on which it is fundamentally dependent. Here, one is able to retrace the history of evolution from entirely marine-based life to mixed marine and terrestrial life. Emergence of the Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area reflects sea level changes resulting from the interaction between tectonics and climate. Compressed into the geological record is evidence of continental rifting, new oceanic crust and new oceanic currents, melting and freezing of polar icecaps, uplift of new continental margin and changed sediment depositional regimes. The high concentration of diverse landforms and life forms here has arisen from the close juxtaposition of a number of globally and locally significant events through a relatively short (150 Ma) geological period. We must be very careful to not destroy this great natural richness and, applying the words of Ian McHarg (1996 p. 103) to this area, "it is a [very] special place - its geological history has made it so".

Figure 1.

Location of Ningaloo Reef - Cape Range Exmouth Gulf area of Western Australia



2 Introduction

The Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area of Western Australia (latitude approximately 22°S) is renowned for its striking scenery and abundant terrestrial and marine life. It is an arid bixeric coastal landscape of rugged limestone ranges, wave-cut terraces, extensive sandplains and dunes, samphire flats and a variety of marine environments. The area includes the fringing Ningaloo Reef, large and very shallow lagoons and seas, seagrass meadows and mangrove belts. Figure 1 (over page) shows the location of the study area.

These land and seascape features reflect an intensive geological and climatic history. The rocks, landforms, plants and animals 'record' this extraordinary history, our natural heritage, which includes super continent break-up and opening of the Indian and Southern Oceans, extinction events, refugia habitats of past climates, the modernisation of marine and terrestrial biota and the highest sea level of the Phanerozoic era (the Great Cretaceous Flood).

Parts of this area are included in Western Australia's conservation estate. The Cape Range National Park currently occupies an area of 50,581 Ha straddling the conspicuous Cape Range and abutting the Ningaloo Marine Park lying along the western side of Cape Range peninsula. The marine park extends from just north of the township of Exmouth, south to Amherst Point, a distance of approximately 260 km, covering an area of 508,000 Ha. Additions are currently being considered to the marine park at its southern end and over the Muiron Islands and Sunday Island at the northern end, and to the Cape Range National Park (CALM 2004).

There are multiple land uses in this area. Uses include the long established pastoral industry and the more recent but well-established tourism industry, commercial and recreational fishing, the hydrocarbon and limestone resource extraction industries and others. Thus multiple values are attached to specific parts of the environment, and not all are compatible. For example, in parts of the ranges, high-grade limestone occurs in very cavernous zones, now known to be specific habitat for highly endemic, in part relictual, cavernicolous fauna. Eco-tourism relies entirely on intact scenic, wilderness and biodiversity elements. Clearly, scientific and conservation values of this area need to be weighed against those uses which may cause long term devaluation or irreplaceable loss of these values.

3 Report Purpose & Outline

The purpose of this report is to provide geological and geomorphological context within which the significance of the natural features of the area can be assessed against certain natural heritage criteria for nomination to the World Heritage List.

Specifically, the report addresses the following two aspects to support nomination of the Lake MacLeod - Ningaloo - Cape Range - Exmouth Gulf area for inclusion in the World Heritage List, in accordance with Article 2 of the Convention:

(1) Description of the geological and geomorphic features of the study area in context;

(2) An evaluation of the identified values of the area against the World Heritage natural features criterion dealing with "...outstanding examples representing major stages of Earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features;" [paragraph 44 a. i] (WHC 2002).

Further, in regard to integrity sites described, "...should contain all or most of the key interrelated and interdependent elements in their natural relationships;" [paragraph 44 b. i] (WHC 2002).

Included in the report are diagrams and maps showing the location and extent of natural features or values referred to in the text, and a map (Fig. 17) showing this author's recommended World Heritage area boundary, taking in to account buffer and transition requirements for the conservation of substantially complete ecosystems and to meet World Heritage integrity criteria.

According to the two aspects (1) and (2) outlined above, the report is structured in two main parts. The first part (Section 5) provides the geological description, including sections on geological setting and the geological and geomorphic evolution of the area with inclusion of those palaeoclimatic and palaeobiological aspects, which have had a development influence on contemporary landforms and some life forms.

The second part (Section 6) is a critical assessment of the more significant or outstanding natural features previously described with respect to World Heritage Listing criterion. That is, their Outstanding Universal value (OUV) in terms of being globally <u>outstanding and complete examples</u>.

4 Sources of Information and Limitations

Most of the descriptive information in this report has been synthesised from numerous sources including published journal papers, books, conference proceedings, reports and maps, with only a minor amount sourced from unpublished documents or personal information. All sources are cited in the text where appropriate and are listed in Section 8 *(References)* at the end of the report.

Geological map coverage of the area is provided by the 1:250,000 scale map sheets **Yanrey-Ningaloo** (van de Graaff, W. J. E., Denman, P. D. et al. 1980), **Onslow** (van de Graaff, W. J. E., Denman, P. D. et al. 1982), **Quobba** (Denman, P. D. and van de Graaff, W. J. E. 1982), **Winning Pool-Minilya** (Hocking, R. M., Williams, S. J. et al. 1985) and **Kennedy Range** (Hocking, R. M., Williams, S. J. et al. 1985) published by the Geological Survey of Western Australia (GSWA). More detailed maps, as part of the GSWA state 100,000 scale mapping programme, are not yet available for this area.

The information in Section 6 (the assessment) is largely this author's own assessment, supplemented in parts by other opinions (cited where appropriate).

The report focuses on the geological and related aspects of the study area. It is a summary only and cannot be considered an exhaustive compilation or treatment of all available knowledge in this field, or of the related aspects of biodiversity and ecological processes. Aspects of indigenous culture are also not treated here.

In discussions of geological events, processes and evolution, it is frequently necessary to refer to their geological age or duration. The written convention for "millions of years" or "thousands of years" is Ma and Ka, respectively. For example, an event that took place 400 million years ago has its geological age written as "400 Ma", or a geologically young event that occurred say, 10,000 years ago, is written "10 Ka". In places, 'BP' is also used to denote "Before Present".

5 Geological & Geomorphological Aspects

5.1 Introduction

The earliest geological references to the Cape Range peninsula area are dated 1925, 1926, 1935, 1936 and 1947, and pertain to the Northwest Basin, now known as the Carnarvon Basin (van de Graaff, W. J. E., Denman, P. D. et al. 1980). However, the first systematic geological investigations of this area took place between 1948 and 1955 by the Bureau of Mineral Resources (BMR) now Geoscience Australia, and the Geological Survey of Western Australia (GSWA), as part of a larger survey of the on-shore Carnarvon Basin. Subsequent geological surveys have been undertaken, particularly during the period 1975-1985 and it is on this work that the current surface geological maps are based. Most of the subsurface geological information has been obtained through extensive company-sponsored hydrocarbon exploration since the early 1950s and extensive regional deep seismic surveys by Geoscience Australia in the 1990s.

Rough Range 1 well, drilled by West Australian Petroleum Pty Ltd (WAPET) in Rough Range, was both the first on-shore intersection of Jurassic aged sediments in Western Australia and, in November 1957, the first oil strike in Australia (Furnival, G. M. 1967). Although not commercial, this strike provided the exploration impetus, which led to the major discoveries of oil and gas in Queensland, Bass Strait in Victoria and in central Australia, and of course at Barrow Island (1967) and other parts of the Carnarvon Basin (Western Australia) in the 1970s and 1980s. Hydrocarbon exploration is still active in the region, particularly offshore from North West Cape and further to the northeast on the Northwest Shelf.

The area is also extensively covered by mineral exploration titles and includes a Ministerial Reserve for Limestone on Cape Range.

5.2 Regional Geological Setting

The Carnarvon Basin (Fig. 2) is a large geological province covering about 600,000km^2, stretching from near Geraldton in the south to just north of Karratha. The basin contains a large thickness of predominantly sedimentary rocks, maximum thickness about 15,000 metres, spanning geological age from Ordovician (base at ~480Ma) to Recent.

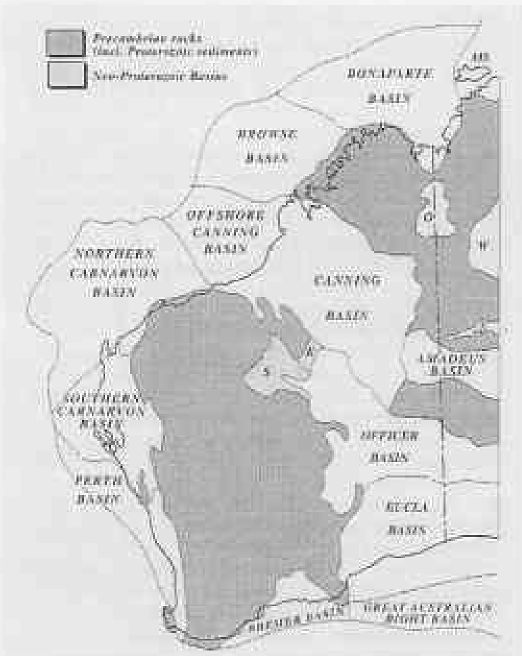


Figure 2. Location of the Northern and Southern Carnarvon Basins, and other geological provinces of Western Australia (from Purcell & Purcell, 1994)

Geologically, the basin extends westward from the Archaean-aged Yilgarn and Pilbara Cratons to the edge of the continental shelf (the continental-oceanic crust boundary) and comprises Palaeozoic to Cainozoic sedimentary depocentres which have been subject to multiple faulting and folding events, mainly in the Late Triassic/Jurassic and Cretaceous (Stagg, H. M. J. and Colwell, J. B. 1994). Interpretations of conventional, relatively shallow seismic data show 'classic' horst-graben rift geometry and syn- and post-rift sedimentary fill. However, at a broader scale, as shown by regional, deep seismic data, the basin still retains an intact layer-cake sedimentary sequence, little affected by crustal extension structures except along the landward margin of the basin.

The basin has been subdivided into two major parts (Fig. 2); the Northern Carnarvon Basin, which lies mostly offshore, and the Southern Carnarvon Basin, which lies approximately 60% onshore and 40% offshore. The Northern Carnarvon Basin has been subdivided into a number of sub-basins, dominated by southwest-northeast trending troughs. In the southern part of the basin, a series of echelon-arranged sub-basins lie along the southeast basin margin. These sub-basins include the Exmouth and Barrow sub-basins, and where they onlap the Precambrian Pilbara Craton basement, the Peedamullah Shelf. It is this shelf, the Exmouth Sub-basin and the northern extremity of the Southern Carnarvon Basin, the Gascoyne Sub-basin, that contain all the rocks that crop out in the Ningaloo - Cape Range –Exmouth Gulf area.

5.3 Local Geological Setting

The Peedamullah Shelf and Exmouth Sub-basin abut the northern extremity of the Southern Carnarvon Basin. The geological boundary between the two sub-basins is the Bullara Ridge (Condon, M. A. 1968), a prominent although buried basement ridge, trending north-northeast across the southern end of Cape Range peninsula from near Bruboodjoo Point (just north of Coral Bay) to Exmouth Gulf.

The rocks of the Ningaloo – Cape Range – Exmouth Gulf area comprise the southeastern margin of the Exmouth Sub-basin where the basin onlaps the basement along the Bullara Ridge and merge with rocks of the Southern Carnarvon Basin, in a sub-basin known as the Gascoyne Sub-basin, which includes the Lake MacLeod area. This geological transition zone, in which sedimentary and tectonic affinities with both the Northern and Southern Carnarvon Basins occur, especially from Cretaceous (post-rift, passive margin) time on, has been further subdivided into a series of fault bounded marginal terraces and a trough, namely, the Bundegi, Yardie, Learmonth and Ningaloo Terraces and Paterson Trough (Fig. 3). Thus the geological history of this area integrates the histories of the Exmouth and Gascoyne sub-basins, as parts of two important and much larger continental margin basins.

5.4 Geological Evolution

The geological evolution of the Carnarvon Basin is integrally tied to the break-up of super continents. During the Palaeozoic (to end of the Permian), this evolution is related to early but failed rift (break-up) events that are only briefly outlined below. In contrast, subsequent geological events in the Mesozoic (Triassic, Jurassic, Cretaceous) and Cainozoic (Palaeocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene) associated with rifting and eventual break-up of the super continents Pangea and Gondwana did play a major role. The Northern and Southern Carnarvon Basins and the Western Australian continental margin were shaped by these events, which in turn and in conjunction with climate, drove biological evolution to its present day forms and adaptations.

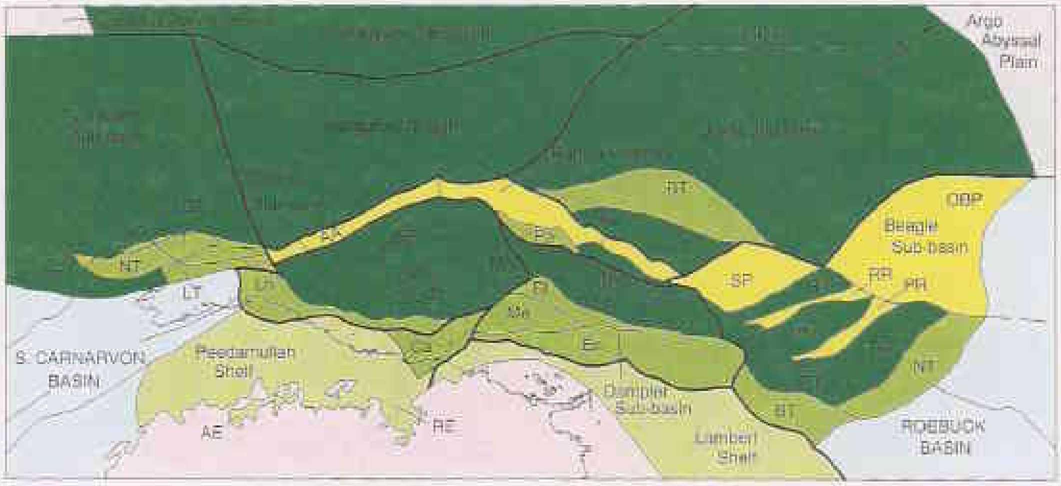


Figure 3. Subdivisions of the Northern Carnarvon Basin. Abbreviations: <u>Peedamullah Shelf</u>; Ca – Candace Terrace, AE – Ashburton Embayment, RE – Robe Embayment. <u>Exmouth Sub-basin</u>; PT – Paterson Trough, LT – Learmonth Terrace, NT – Ningaloo Terrace, BT – Bundegi Terrace, YT – Yardie Terrace. <u>Barrow Sub-basin</u>; Lo – Locker Terrace, WBS – West Barrow Syncline, BIT – Barrow Island Trend, LS – Lowendal Syncline, Mo – Montebello Trend. <u>Dampier Sub-basin</u>; En – Enderby Terrace, Me – Mermaid Terrace, El – Eliasson Terrace, LT – Lewis Trough, Le – Legendre Trend, Ma – Madeleine Trend. <u>Rankin Platform and Dixon Sub-basin</u>; AA – Alpha Arch, Pa – Parker Terrace, Ke – Kendrew Trough, VT – Victoria Trough, CT – Cossigny Trough, SP – Sable Platform, RT – Ronsard Trough, RR – Ronsard Ridge, PT – Picard Trough, PR – Picard Ridge, TG – Thouin Graben, NT – North Turtle Hinge Zone, OBP – Outer Beagle Platform. (from Hocking et al, 1994)

Basin evolution and continental margin development occurred in five (5) major depositional cycles (here called megasequences) and associated major tectonic events. These are described below and also shown as a stratigraphic chart (Fig. 4).

<u>Megasequence I</u> (Sag phase 1) From about the mid Carboniferous (325 Ma), the Carnarvon Basin probably began to develop (Yeates, A. N., Bradshaw, M. T. et al. 1987; Stagg, H. M. J. and Colwell, J. B. 1994) but evidence for actual basin initiation at this time is scant.

However, at this time the major continental masses of the World were beginning to amalgamate and by about 310 Ma, Western Australia was part of the super continent called Pangea [Pangea existed from about 310 to 150 Ma] and was migrating southwards from equatorial regions. The Western Australian part of Pangea remained at high southern latitudes for about 200 million years, until migrating northwards again, to our current position in the last 60 million years. For example, the Cape Range area was at approximately latitude 45°S at mid Carboniferous (325 Ma) times, about 58°S at Early Permian (280 Ma) times and, its highest latitude, 60°S at about 240 Ma (when eastern Australia was located over the South Pole) (Veevers, J. J. 1984). Severe glacial or periglacial conditions prevailed for much of this time with the formation of a continent-wide icesheet several kilometres thick, known as the Gondwanan Icesheet. Pangea eventually split into two smaller, although still very large super continents called Laurasia (comprising all the present day northern hemisphere continental masses) and Gondwana (comprising Africa, India, Australia, Antarctica and South America). This break-up had little or no direct effect on Carnarvon Basin evolution except that it then allowed Gondwana to eventually break-up, including the separation of Greater India and Australia along the developing Carnarvon Basin.

The Gondwanan Icesheet was a major geo-climatic event and is recognised by numerous occurrences of striated, polished pavements and other features formed by thick grinding ice, and a major stratigraphic unconformity (Namurian age) throughout Gondwana. The Cape Range area was near the northwestern limit of the icesheet, and in this area, the ice generally

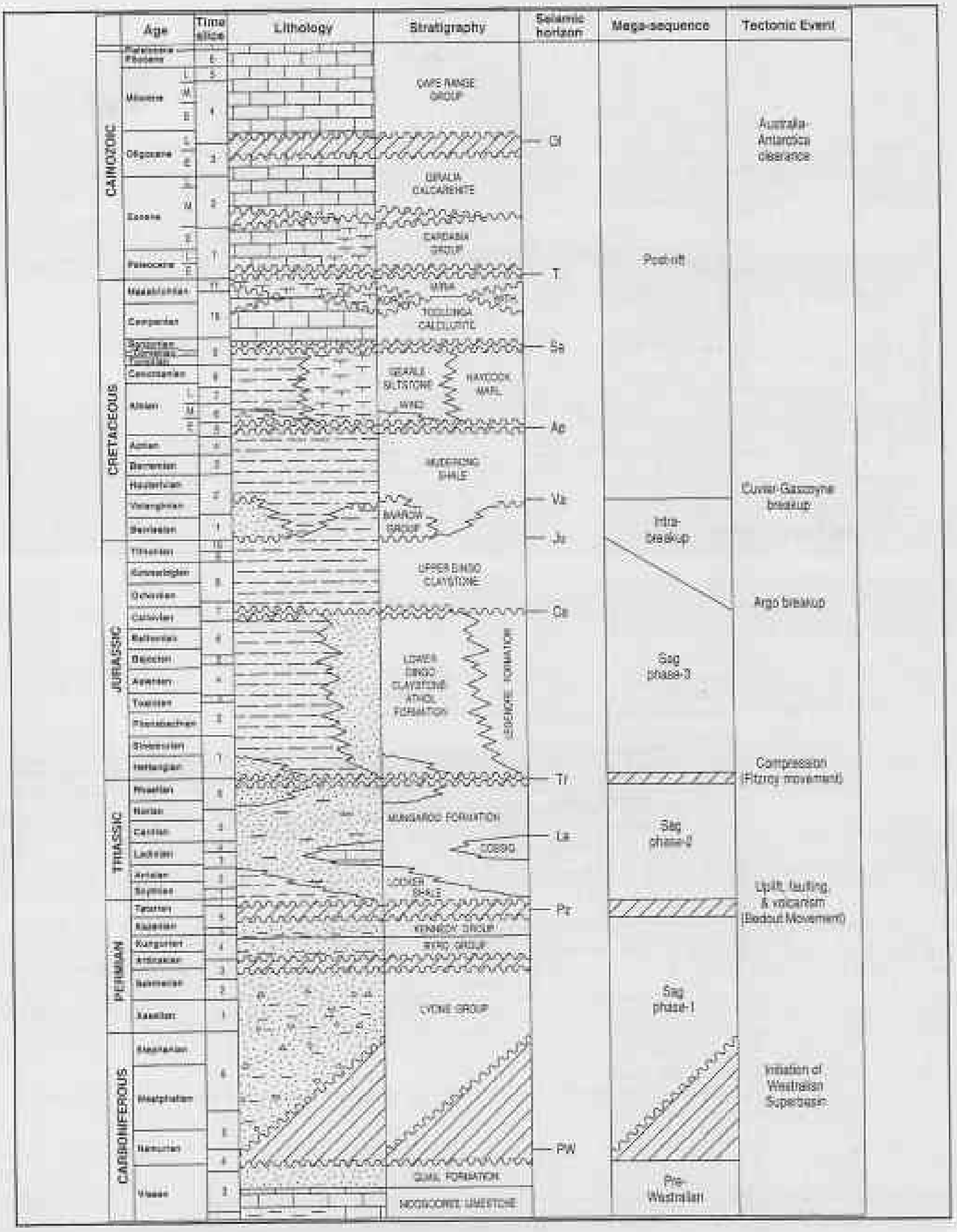


Figure 4. Stratigraphy of the offshore Carnarvon Basin, including megasequences and major tectonic events affecting the northwest Australian margin. (from Stagg and Colwell, 1994)

moved in a northwesterly direction. However, this event did not have a strong direct influence on the geomorphic development of this area; subsequent events have had a much greater influence.

After melting of the icesheet, as glacial conditions moderated, sedimentation resumed. Throughout the remainder of the Carboniferous and in to the Permian (to about 260 Ma), marine sediment, much of it glaciogenic, continued to be deposited in the gently developing sag basin, the proto-Carnarvon Basin. These sediments are now known as the Lyons, Byro and Kennedy Groups, and during this long period of over 70 million years, suffered little tectonic disturbance. The thickness of this sequence, although uncertain due to poor recognition of the base, is estimated to be 2 to 2.5 km.

Megasequence II (Sag phase 2) This long period of relatively uniform sedimentation was then interrupted by a short period of increased tectonic activity in the Late Permian (Tatarian, 252 Ma) characterised by uplift, block faulting and volcanism (known as the Bedout Movement) (Fig. 4).

Marine sedimentation resumed, and as the basin rapidly filled, extensive areas of thick, regressive, fluvio-deltaic sediments formed (Locker Shale and Mungaroo Formation) (Stagg, H. M. J. and Colwell, J. B. 1994) during the Triassic (251 – 205 Ma). The thickness of sediments is estimated at 5 to 6 km.

Megasequence III (Sag phase 3) Again, a period of tectonic activity in the Late Triassic or Early Jurassic (at about 205Ma), associated with the separation of continental slivers from northern Gondwana (Metcalfe, I. 1996), changed the depositional regime in the southern sub-basins. In the Exmouth Sub-basin, the main tectonic expressions are pronounced faults, open folds and an unconformity, but according to Stagg and Colwell (1994) this tectonism was not the onset of Greater India - Australia continental rifting, as had been earlier postulated (Fig.4).

Following this tectonic event, deposition of thick (3 – 4 km), restricted-basin marine shales (Dingo Claystone) continued in the Exmouth and other southern sub-basins, in response to rapid subsidence.

Megasequence IV (Intra-break-up phase) This phase of pre-rift (break-up) deposition continued through the Jurassic until about the start of the Cretaceous (141 Ma) when **seafloor spreading (break-up) commenced on the Gascoyne and Cuvier Abyssal Plains** and affected the southern parts of the basin. As shown in Figure 5, the resulting intra-break-up sedimentary sequence is very characteristic. It formed an extensive, northwards prograde sandy deltaic complex (Barrow Island Group and equivalents), which migrated towards the open ocean in the northern parts of the Northern Carnarvon Basin where break-up had commenced earlier, on the Argo Abyssal Plain. This is termed the intra-break-up sequence and its provenance was the continental margin, developing along the extensional transform fault zone of the Cape range Fracture Zone (CRFZ) but deposition was abruptly terminated in the Early Cretaceous (at about Valangian time, 134 Ma) in response to a second episode of seafloor spreading and removal of the major source of sediment to the south (Stagg, H. M. J. and Colwell, J. B. 1994), probably due to substantial sea level rise (D. Haig, *pers. comm.*, Aug. 2004).

The continental margin remained a topographically elevated area, that is, a sediment source, only while the CRFZ remained a continent-continent type transform fault (Veevers, J. J. 1984). With passage of Greater India past the Exmouth Plateau and the widening oceanic floor (the developing Indian Ocean), the continental margin began to subside, no longer providing a source of terrestrial sediment.

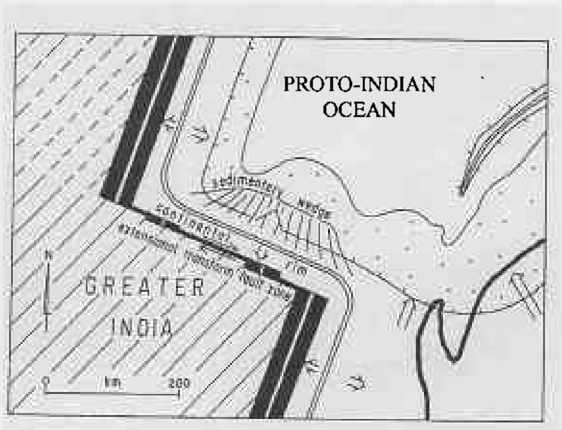


Figure 5. Cuvier – Gascoyne Abyssal Plains palaeogeographic reconstruction at 138 Ma, just after break-up, showing the Cape Range Fracture Zone (extensional fault zone). Stipple indicates fluvio-deltaic complex, beyond which is marine shelf environment of the proto-Indian Ocean, narrow double line is the elevated continental margin and broad arrows indicate sediment transport direction; present-day coastline (medium black line) shown for reference only (modified after Veevers, 1984).

Megasequence V (Post-rift phase) Subsequently, thick, restricted marine shales (Munderong Shale) were again deposited until the mid Cretaceous, in many of the southern sub-basins including the Gascoyne Sub-basin, but not in the Exmouth Sub-basin. Here, instead, major uplift, probably associated with emplacement of oceanic volcanic rocks in the Cuvier Abyssal Plain, caused erosion of several hundred metres of Early Cretaceous (Neocomian) strata.

Sedimentation then resumed in the mid Cretaceous (100 Ma) in the Exmouth Sub-basin (Fig. 6) in response to renewed basin subsidence. Initial sedimentation consisted of widespread, shallow marine-shelf radiolarian claystone and radiolarite (Windalia Radiolarite) followed by clastic, terrigenous material (Gearle Siltstone). But as basin margin areas became consistently starved of clastic sediment as the climate changed from humid to arid, and as sea

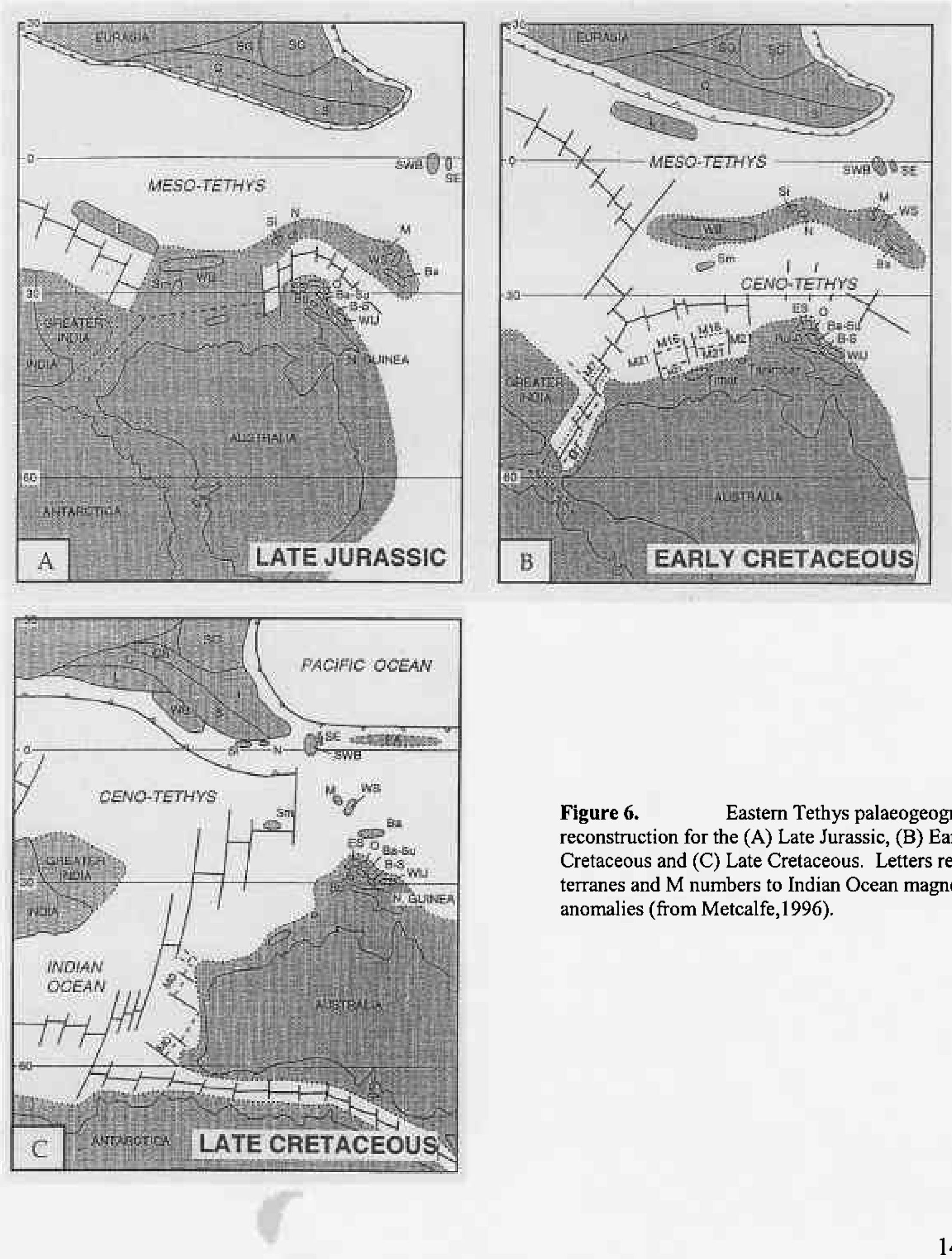


Figure 6. Eastern Tethys palaeogeographic reconstruction for the (A) Late Jurassic, (B) Early Cretaceous and (C) Late Cretaceous. Letters refer to terranes and M numbers to Indian Ocean magnetic anomalies (from Metcalfe,1996).

levels rose and sea surface temperatures warmed (but still cold), the deposited sediments became dominated by pelagic biogenic carbonate, almost devoid of terrigenous input (Henderson, R. A., Crampton, J. S. et al. 2000). This is an extremely important stage in the geological, geomorphological and biological evolution of this region and globally, and is further described in Section 5.5.

Carbonate-dominated deposition continued through the Cretaceous (Toolonga Calcilutite, Miria Marl), Palaeogene and Neogene (Cardabia Calcarenite, Giralia Calcarenite, Cape Range Group), Pleistocene (Exmouth Sandstone, Bundera Calcarenite) to the Present (surficial alluvial, colluvial and aeolian deposits), although punctuated several times by periods of non-deposition (unconformities) due to tectonic activity and eustatic adjustments. The Cretaceous and Cainozoic units are shown in Figure 7, below.

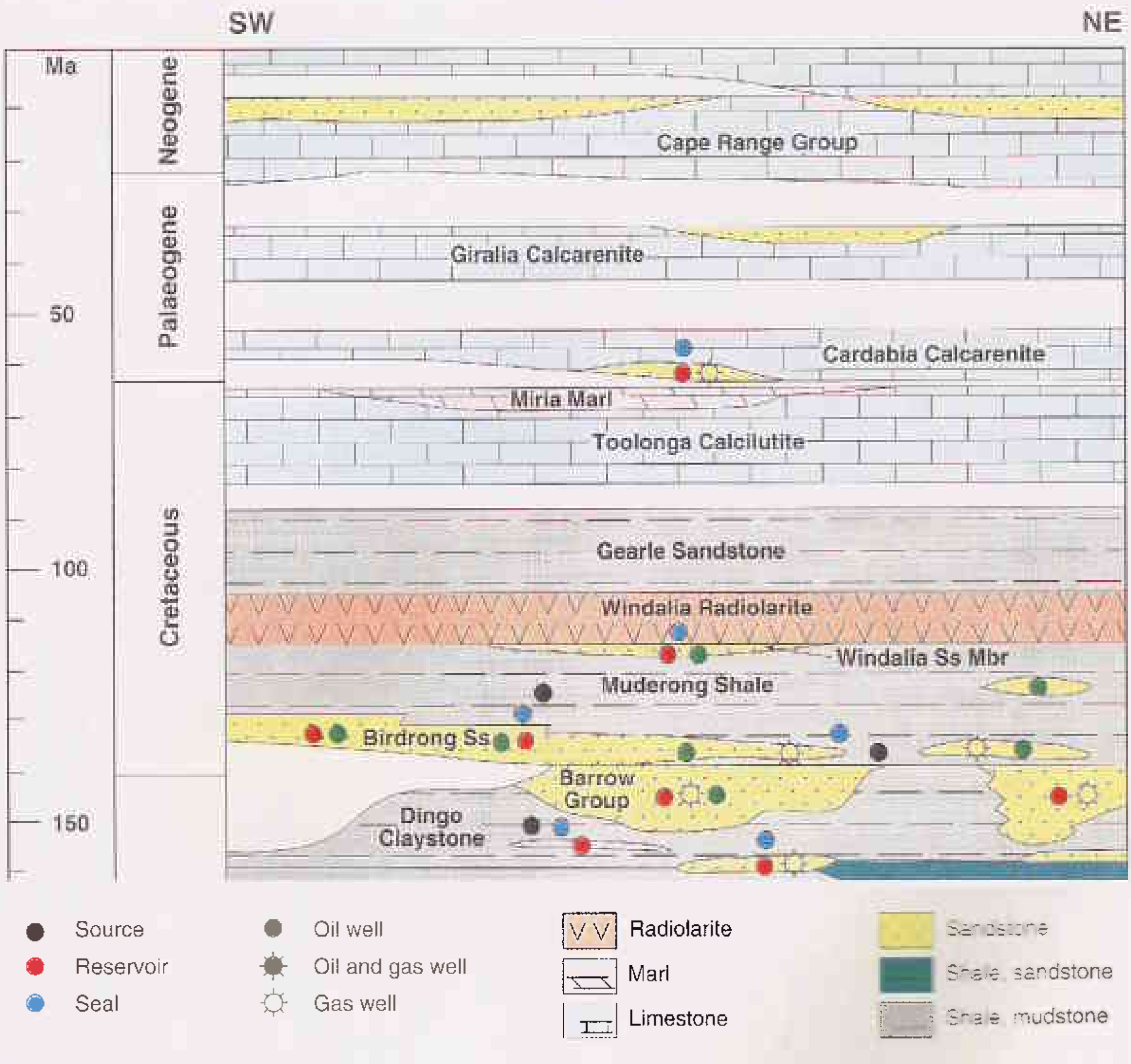


Figure 7. Post-Jurassic stratigraphy of the onshore Northern Carnarvon Basin (from GSWA, 2004)

Associated with the progressive opening of the new Indian Ocean from the Early to the Late Cretaceous (Figs. 5, 6 & 7), the Leeuwin Current developed, bringing warm tropical water southwards into colder, temperate zone waters. Although only narrow, usually 30 to 40 km wide, it is a seasonally strong current that continues to influence the southern Western Australian climate and, importantly, the marine biota. The extraordinary biota of the Ningaloo Reef is more comprehensively described in the Draft Nomination for the Ningaloo - Cape Range World Heritage Property (GoWA in prep).

The latest episode is post-Miocene, possibly initiated at late Pliocene or early Pleistocene time (approximately 1.8 Ma), and consisted of west-northwest – east-southeast directed compression causing reverse reactivation of older normal faults and the development of substantial folds in the Gascoyne, Exmouth and Barrow Sub-basins. In the Ningaloo – Cape Range – Exmouth Gulf area, these structures include the Cape Range, Paterson, Rough Range, Giralia, Yanrey and Wandagee Faults and the Cape Range, Rough Range, Giralia and Marrilla Anticlines (and associated synclines), all trending north-northeast (van de Graaff, W. J. E., Denman, P. D. et al. 1980) and further described in Sections 5.5.1 and 6.4.3. The Cape Range Anticline is the largest of these folds, being some 100 km long with structural relief of 450 m (Geological Survey of Western Australia 1975), and now forms the very conspicuous Cape Range. The Giralia Anticline, about 130 km long with structural relief of 200 m, forms the Giralia Range and the Rough Range Anticline forms the much smaller but rugged Rough Range between the two larger ranges.

Table 1 Summary geological evolution of the Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area*

TIMING	*EVENTS*
Holocene	Stable sea level, active coastal deposition of carbonate sands.
Pleistocene	Warping of older wave-cut terraces, overall sea level fall, formation of Tantabiddi Terrace, cessation of uplift, arid climate and dune desert formation, modern Ningaloo Reef started.
Pliocene	Uplift initiated by Australia – Asia collision, inversion movement on Learmonth Fault, emergence of Cape Range (island), humid climate, inception of karstification.
Miocene	Formation of MacLeod Graben. Deposition of Trealla Limestone (top of Cape Ra Grp).
Palaeocene-Eocene-Oligocene	Continuing carbonate deposition.
Mid - Late Cretaceous	Initiation of carbonate deposition, oceanic anoxic events, major marine transgressions.
Early Cretaceous	Commencement of seafloor spreading on Gascoyne and Cuvier Abyssal Plains (Greater India - Australia break-up), mainly siliciclastic deposition.
Mid Carboniferous – Early Cretaceous	Early Carnarvon Basin evolution, Gondwanan Icesheet, long periods of sedimentation interrupted by Late Permian, Late Triassic & Late Jurassic tectonic and volcanic events.

* Modified after Allen (1993), incorporating data from Malcolm et al (1991), Stagg & Colwell (1994) and Metcalfe (1996).

The formation of younger rocks and deposits, and the geomorphic evolution of the area are described in the following section (Section 5.5).

5.5 Local Physiographic Features and Development

The Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area can be subdivided into uplands, lowlands and the marine environment, and each of these can be further subdivided into a number of physiographic units based on their topographic expression in the landscape.

The major physiographic units are a direct expression of lithostructural geological processes of Late Cainozoic age, reflecting the regional tectonic instability of the time and in the words of Wyrwoll et al (1993) "Uplift has provoked a strong and distinctive erosional and depositional geomorphological response." The main physiographic units are shown in Figure 8 below.

These units are outlined below and several are discussed in more detail where they are good examples of, or relate to, the geological, geomorphological and/or biological evolution of the Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area.
The uplands consist of:

- Anticlinal ranges including wave-cut terraces,
- Elevated etch plains,
- Mesas, strike ridges and elevated duricrust remnants (breakaways).

The lowlands consist of:

- Coastal calcareous sand plains
- Flood plains, alluvial fans and river valleys, including valley calcrete,
- Sandplains and dunefields,
- Sand covered calcareous duricrust plains,
- Saline coastal lakes and associated sediments.

Units associated with the marine coastal environment include:

- Coral fringing reef system (Ningaloo Reef), located at the northern end and along the western seaboard of the peninsula,
- Tidal and supratidal mud and sand flats,
- Calcareous shoreline dunes and sands.

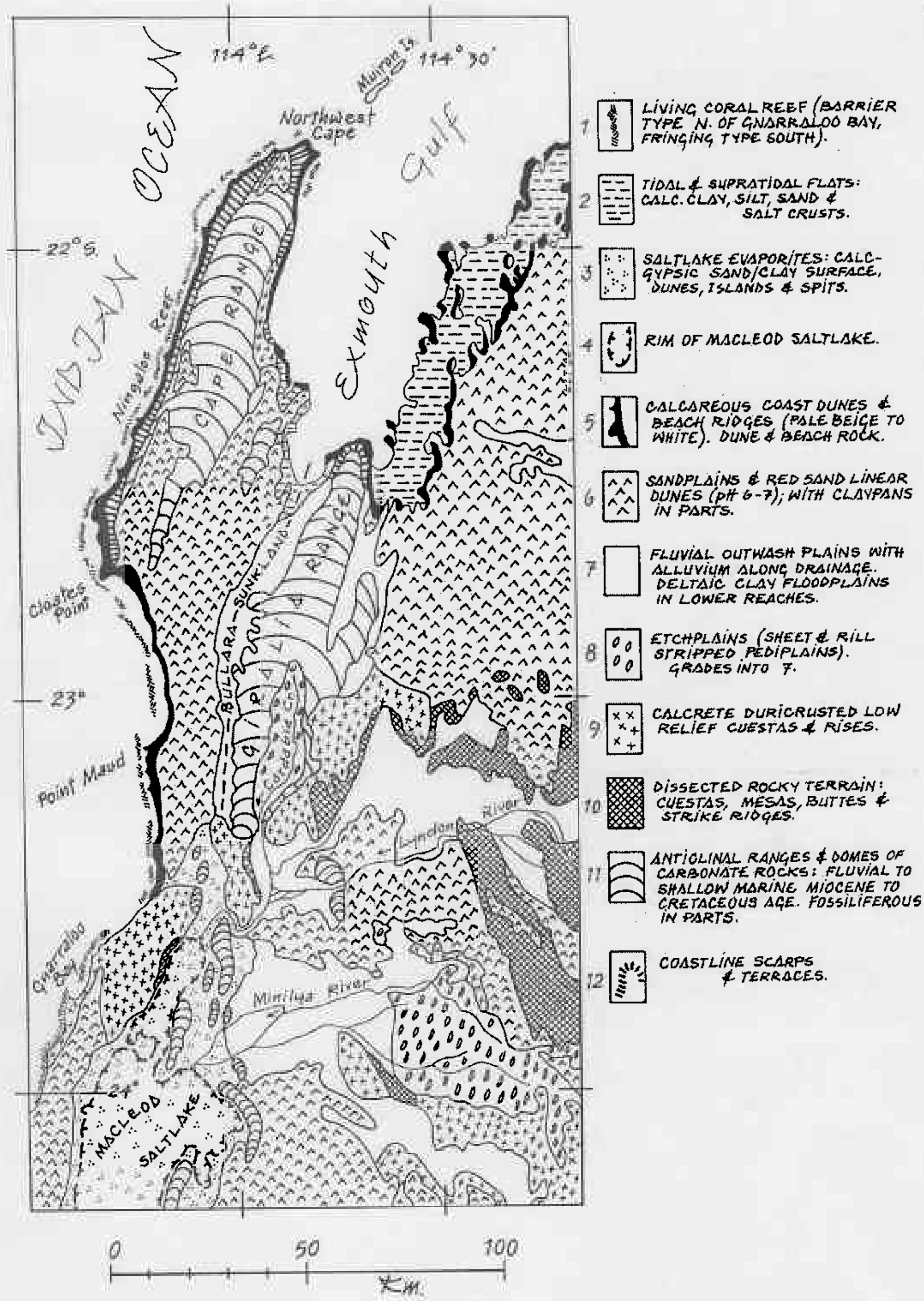


Figure 8. Generalised physiography of the Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area, compiled and adapted from physiographic mapping accompanying each of the relevant 1:250,000 Geological Series maps and memoirs.

5.5.1 *Anticlinal Ranges and Domes*

The peninsula landscape is dominated by a series of linear north-northeast trending ranges (Fig. 9), the surface expression of anticlines, synclines and associated faults resulting from west-northwest – east-southeast directed compression during the Late Cainozoic (Pliocene or Pleistocene).

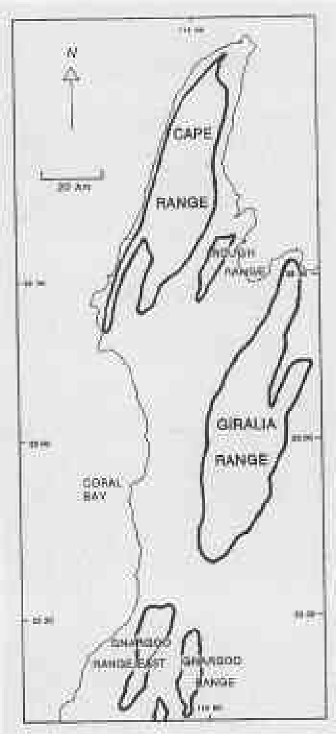


Figure 9. Location of the main anticlinal ranges in the Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area.

The anticlines are slightly asymmetric, with steeper eastern limbs, which has influenced the consequent drainage on opposite dip slopes. The ranges are Cape Range, Rough Range, Giralia Range and a group of small, low ranges and domes to the east and west of Lake MacLeod to the south of the peninsula. The highest point, Mt Hollister (311masl), is on Cape Range. Rough Range is the lowest of the peninsula ranges, only rising to about 75 metres above sea level.

The post-Cretaceous sequence forming much of the ranges is the Cape Range Group, comprising marine, mainly carbonate rocks, about 480 metres thick, which range in age from Late Oligocene at the base to Late Miocene at the top (Stagg, H. M. J. and Colwell, J. B. 1994). The group has been subdivided into mappable formations, namely, (from the base) the Mandu Limestone (280 m thick); Tulki Limestone (90 m); Trealla Limestone (20 m) and its upper lateral equivalent on the western and northern side of Cape Range, the Pilgramunna Formation (25 m), a quartzose calcarenite; and at the top, Vlaming Sandstone (65 m), an aeolian quartzose calcarenite.

Unconformably overlying the Cape Range Group rocks is the Exmouth Sandstone, a quartzose calcarenite of Pliocene age, comprising aeolian and shallow marine deposits. Stratigraphically (but not topographically) overlying this unit is the Bundera Calcarenite of Pleistocene to Holocene age. It is preserved as aeolian and shallow marine deposits on wave-cut terraces, mainly on the western, lower flanks of Cape Range. The wave-cut terraces are further described in Section 5.5.2 below.

The youngest deposits are of Holocene age and are currently active in a variety of environments including the Ningaloo Reef, coastal beaches and dunes, supratidal and intertidal flats, claypans, and sandplains and dune fields.

5.5.2 *Wave-cut Terraces*

Between Vlaming Head in the north and Wealjugo Hill in the south, a distance of about 90 km, a series of conspicuous wave-cut shoreline terraces or benches, forming giant steps, have been eroded into the lower flanks of Cape Range. There are four principal terraces, the lowest being the coastal plain from about 800 to 1,600 metres wide and 6 m above sea level, and the highest about 55 metres above sea level (van de Graaff, W. J. E., Denman, P. D. et al. 1975; Wyrwoll, K.-H., Kendrick, G. W. et al. 1993).

In order of increasing elevation above current sea level, the terraces are: Tantabiddi Terrace (the coastal plain from near the foot of the range), Jurabi Terrace, Milyering Terrace and Muiron Terrace (Fig. 10). The three upper terraces have been gently folded (warped) but not the lowest, indicative of geologically recent but now ceased deformation. Uplift and warping were essentially completed during the Quaternary (Wyrwoll, K.-H., Kendrick, G. W. et al. 1993).

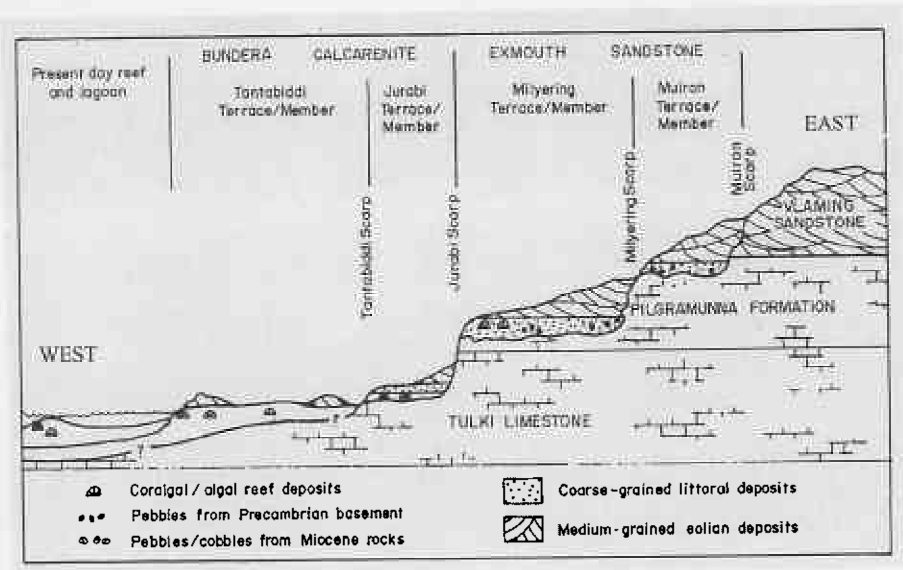


Figure 10. Cross-section of the western flank of Cape Range showing the main wave-cut terraces; note that the westerly dip of the Tulki Limestone and Pilgramunna Formation (being on the western limb of the Cape Range Anticline) is not shown here (from Wyrwoll et al, 1993).

These terraces record the uplift / sea level stillstand history of the Cape Range peninsula. They are cut into the Tulki Limestone and overlying Pilgramunna Formation, and on each are shallow inshore and near-shore clastic carbonate and minor siliciclastic deposits.

The ages of formation of the terraces are not well known. Sediment from the lowest terrace (Tantabiddi Terrace) has been dated by U-Th method at 132 – 127 Ka BP and corals from the same terrace gave a 123 Ka age (van de Graaff, W. J. E., Denman, P. D. et al. 1982; Wyrwoll, K.-H., Kendrick, G. W. et al. 1993). These dates are reasonably consistent, indicating that the terrace formed during the Late Pleistocene, Last Interglacial. The other terraces have not been dated, however, it is generally assumed that the three higher terraces are older than the Tantabiddi Terrace, indeed that terrace age increases with elevation. In other words, as sea level fell relative to the land, that is, as land uplift progressed, the shoreline retreated down the flanks of Cape Range. At each sea stillstand, wave-cut platforms or terraces were formed, thus the earliest formed is thought to be the uppermost, Muiron Terrace. The lower terraces formed at later stillstands.

However, there are complications, including evidence for multiple transgressive and regressive events (eg Tantabiddi Terrace), undoubtedly indicating a tectonic and geomorphic history somewhat more complex than is currently understood. This author agrees with Wyrwoll et al (1993) that knowing the age of each of the main terraces (and the minor terraces) is very important because "... of their direct bearing on the timing of uplift and hence on the geomorphological and biological (colonisation, speciation, endemism) processes that have generated the present Cape Range environment and biota."

5.5.3 The Ningaloo Reef - Cape Range Karst System

Another way to envisage or understand the area is to consider that several of its physiographic units can be included in a functioning karst system. This approach is advocated by Hamilton-Smith et al (1998) who suggest that the entire peninsula and associated near-shore marine environment, including the fringing reefs, constitutes a karst geomorphic province. This author agrees, because an ecosystems landscape approach allows better understanding of the functional relationships and dependencies between the various physiographic components and their contained life habitats.

The word 'karst' is derived from early descriptions of the extensive limestone plateaus located to the east of the Adriatic Sea in the present day Baltic republics. Karst is a term that encompasses a suite of landforms, sometimes spectacular, often intriguing, and largely dependent on high rock solubility (Twidale, C. R. and Campbell, E. M. 1993), characterised by internal and subterranean drainage, and other features. A karst province, such as the Ningaloo - Cape Range area, is a complex and dynamic system composed of highly interrelated landforms, various fluids, rocks, regolith and biological constituents, resulting from complex interaction between climatic, geologic, pedologic, hydrologic, physiographic and biological factors, collectively called environmental drivers. These drivers operate at a wide range of spatial and temporal scales.

The process drivers of karst systems can be grouped as follows:

- Geological processes and evolution (the setting), which influence:
  - Rock types (lithology),
  - Rock structure (bedding planes, joints, faults and folds).

- Climatic processes and evolution, which influence:
  - Available moisture,
  - Temperature.

Acting at large temporal and spatial scales, the geological and climatic drivers then drive a number of smaller scale drivers such as:

- Geomorphic and hydrological processes, which influence:
  - Topography,
  - Base levels and surface-subsurface hydrologic gradients,
  - Erosional and depositional processes.

The geomorphic and hydrological processes then drive a number of biophysical processes such as nutrient transfer, resulting in the mosaic of habitats (different regolith – plant – landform assemblages).

The drivers outlined above are described in more detail below, in the context of the Ningaloo-Cape Range-Exmouth Gulf Karst Province. More information on certain ecological implications of parts of this karst system and adjacent terrestrial systems is also provided below.

5.5.3.1 Geological Aspects

Lithological variation, in particular, chemical composition (purity), porosity and tensile (void-supporting) strength of carbonate rocks strongly influence the nature of karstification (Twidale, C. R. and Campbell, E. M. 1993; White, S. 1998).

A variety of carbonate rock types host the Ningaloo Reef - Cape Range karst system. They range in age from Palaeocene (65 – 54 Ma) to Holocene (10 Ka to Present) and range in composition from pure crystalline limestone to argillaceous (clay or silt bearing) limestone (marl). Most of the carbonates are shallow marine facies but some, such as the Bundera Calcarenite, consist of both aeolian and shallow marine facies.

Development of the older erosional (solution karst) features has been controlled by three main units (Fig. 11), namely, (in stratigraphic younging order) the Mandu Limestone, Tulki Limestone and Trealla Limestone (Allen, A. D. 1993). [note: the term "younging" or "facing" is the direction toward which a rock or layer youngs in geological age; in sedimentary sequences which have not been overturned or intensely folded, the younging direction is generally upwards] The most pronounced karstification occurs over a 100 metre (maximum) stratigraphic interval, comprising the recrystallised upper part of the Tulki Limestone and part of the overlying Trealla Limestone. The age of the carbonates hosting this pronounced karst zone is probably Early to Middle Miocene, and initiation of speleogenesis is thought to be Late Miocene to Pliocene (Allen, A. D. 1993). However,

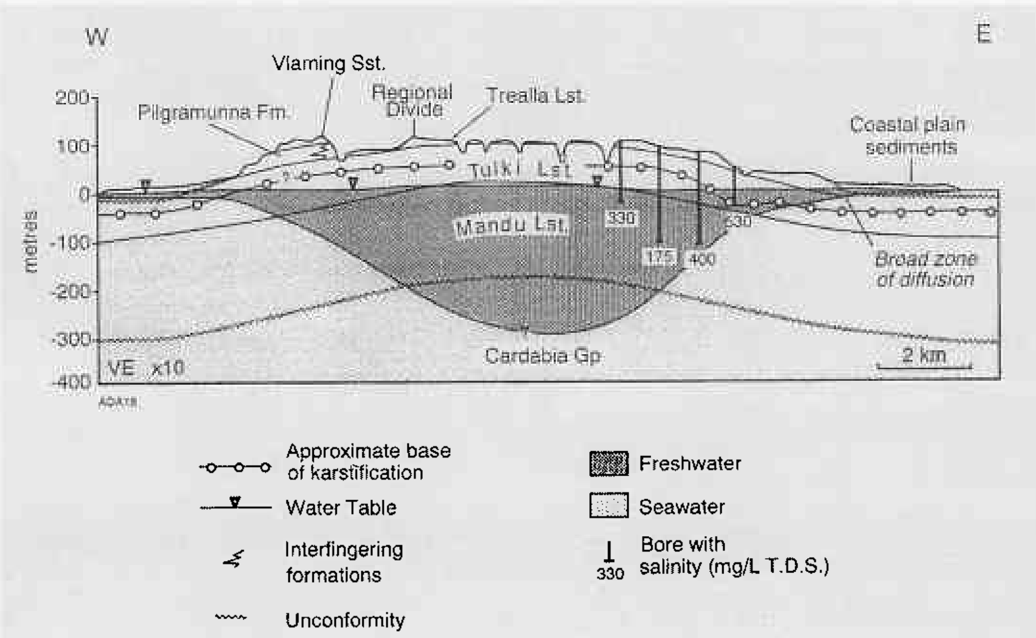


Figure 11. Cape Range hydrogeological cross-section (from Allen, 1993).

speleogenesis may have started earlier (see Section 5.5.3.4 on Geomorphic Aspects below). The Mandu Limestone is a relatively impermeable marl and has limited the depth extent of major solution features.

Rock structures such as bedding, joints, folds and faults strongly influence karst development and morphology by providing planes or zones along which vadose fluids migrate. Due to the sedimentological and tectonic history of this area, all of these features are present and provide numerous sites for piping and accelerated dissolution to occur.

Sinkholes and caves are developed along the drainage divide, the well jointed crest of the anticlinal ranges, and it is inferred that the most extensive cave systems are present beneath the essentially undissected etch plains where internal drainage is well developed (Allen, A. D. 1993). Most of the caves in the upland areas are 'dry' systems with poorly developed 'cave decoration'. The largest cave, "Wanderers Delight", flows weakly after heavy rainfall. In contrast, the cave systems along the coastal plain, from which the troglobitic fish have been recorded, are partially or totally filled with water; their depth below sea level and extent offshore are unknown (Allen, A. D. 1993).

5.5.3.2 Climatic Aspects

Climatic conditions play an important role in subaerial diagenesis and karstification of carbonate rocks. Only trace amounts of calcium carbonate are soluble in pure water, however, if carbon dioxide is present in solution, the water becomes weakly acid, allowing more carbonate to be carried in solution. Carbon dioxide is present in the atmosphere and, in greater amounts in the regolith, and at low temperatures, is readily absorbed by water. In addition, organic (humic) acids produced by plants assist in the acidification of water.

Karst can form in all climates, subject to available water, but in general, karstification rates are up to 4 times faster in humid tropical regions compared to humid cool regions. The rate differential is thought to be due to stronger fortification of vadose waters by humic acids (Twidale, C. R. and Campbell, E. M. 1993). Interestingly however, there is no readily apparent and consistent difference in karst morphology between cool and warm regions, and between wet and dry regions; the only significant difference is the rate at which the karst features form.

The present-day climate of the Lake MacLeod - Ningaloo - Cape Range - Exmouth Gulf area is tropical arid, subject to infrequent cyclonic and northwest cloud-band precipitation. Wyrwoll (1993) estimates that approximately 40% (110 mm) of the mean annual rainfall in the region is derived from tropical cyclones. The current rate of karst development is therefore likely to be slow due to the seasonal irregularity and usual paucity of water. Palaeoclimates of this area have however, included both more humid and more arid subtropical (not tropical) and cold periods. During the Late Miocene – Pliocene when karstification possibly commenced, the climate was much wetter than present but for most of the subsequent time, conditions were considerably drier than the present, as glacial or periglacial conditions prevailed.

5.5.3.3 Hydrological Aspects

Meteoric water, occurring in the vadose and phreatic zones, is the primary dissolution agent acting on emergent range and coastal carbonates. However, the base of karstification extends laterally offshore, beneath the seafloor, and here in the marine environment, seawater is the primary dissolution agent.

The contemporary local water table occurs within a heterogeneous karstic aquifer system (Allen, A. D. 1993), forming a broad freshwater lens or mound beneath each of the ranges; at Cape Range, the Cape Range Mound is thought to rise to about 10 metres above sea level with a radial flow pattern, probably discharging into the reef zone via sub-sea springs and into pools along the lower reaches of Yardie Creek and Qualing Pool (Allen, A. D. 1993). A large perennial freshwater spring at the contact of the Mandu and Tulki Limestones in a tributary of Shothole Canyon, in the Cape Range, has been reported by Forth (1973, cited by Allen, 1993). Importantly however, it is likely that the local groundwater mounds on the peninsula are separated from (not in hydrological connection with) the regional fresh groundwater system of the onshore Carnarvon Basin. The separation is caused by a large, shallow unconfined saline aquifer system to the south, of which Lake McLeod is a surface expression. This interesting feature is further described in Section 5.5.4 below.

Recharge to the karst province is by direct infiltration, albeit irregularly from the infrequent but intense or long-duration rainfall events. This has important implications for managing water extraction (for domestic and industrial use), groundwater pollution and maintenance of karst ecosystems.

5.5.3.4 Geomorphic Aspects

The Ningaloo Reef - Cape Range karst system comprises three main interconnected physiographic karst components (Fig. 12). The components are in hydrological connection and provide a range of habitats from elevated 'dry' openings to entirely aquatic environments.

1. Crest karst: best developed along the crest of Cape Range and less well developed on Rough Range. Here, relatively flat elevated remnants of a pre-existing plateau have pronounced rectilinear joint sets and well developed internal drainage beneath which, the subterranean karst system is better developed. On Cape Range, the best-preserved karst occurs at the southern end. There is no significant karst development on Giralia Range due to extensive dissection and removal of the Cape Range Group carbonates from the crest and upper flanks.

2. Flank karst: this karst component occurs on the flanks of Cape and Rough Ranges. Here, the karst terrain has been deeply incised, in many areas to such a depth as to expose Mandu Limestone and underlying Cretaceous units. Due to the increased slope, it is a higher energy fluvial environment, causing increased surface water runoff and less infiltration. Karstification is likely to be slower in this topographic setting and the lack of extensive cave systems on the range flanks supports this assertion. Some drainages, such as Yardie Creek, contain fault controlled linear reaches.

3. Coastal plain karst: the third physiographic component comprises the coastal plain karst that extends offshore some distance and includes the Ningaloo Reef system. Topographic slopes and hydrologic gradients are very low. In contrast to the crest and flank karst components where erosional processes predominate, both karst erosional and depositional processes operate on the coastal plain. Importantly, these processes are taking place in both the 'older', indurated Miocene-Pliocene limestones and in the 'younger', weakly indurated Pleistocene carbonate deposits.

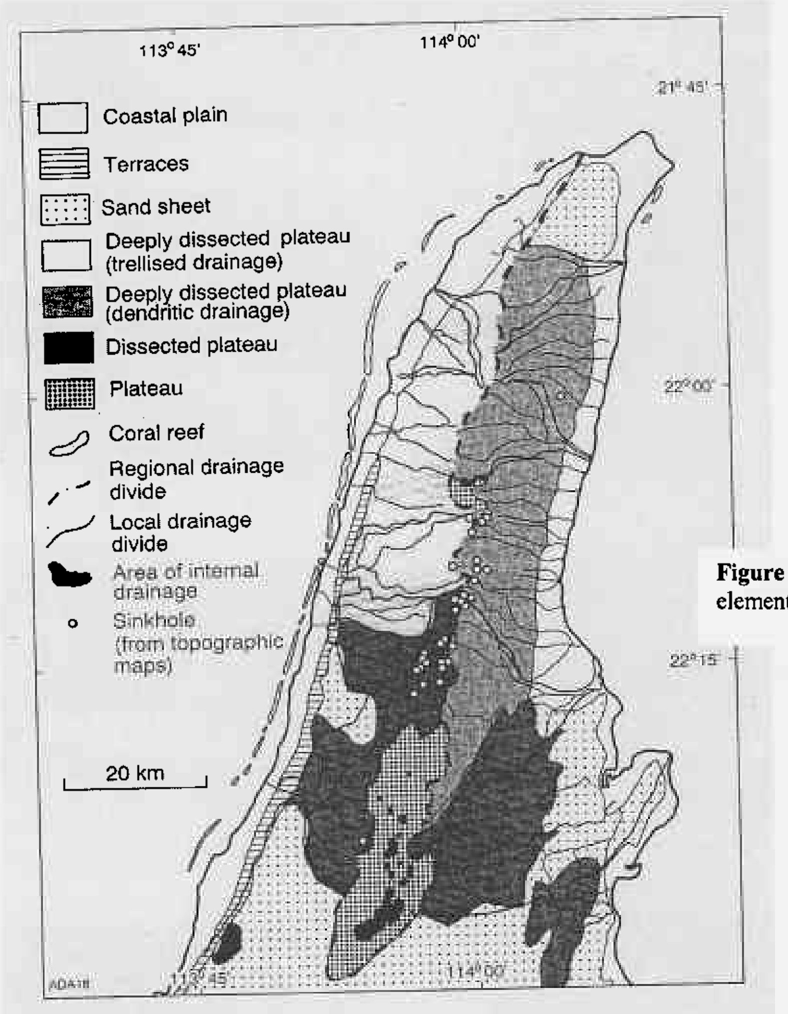


Figure 12. Cape Range physiographic elements and drainage (from Allen, 1993).

On the coastal plain, karstification of these poorly consolidated sediments has not yet been well studied. However, in other parts of Australia, more detailed studies of poorly consolidated sediments have been undertaken which do provide useful insights into the karstification process.

In mid-Pleistocene limestones of the Otway Basin, southwest Victoria, speleogenesis is currently occurring in calcarenite dunes that are only partly lithified or consolidated. Study of the rapid subaerial speleogenesis taking place here shows that, contrary to accepted karst theory, diagenesis (lithification) and solution (karstification) can and are occurring simultaneously (White, S. 1998). The key feature is the development of an indurated layer near the surface of the poorly consolidated carbonates, which then provides sufficient void-spanning strength for caves to form beneath (White, S. 1998).

Thus, simultaneous lithification of carbonate sands and formation of karst solution features is an important and contemporary speleogenetic evolutionary feature of the Ningaloo - Cape Range - Exmouth Gulf area. Given this, it is then possible that speleogenesis of the 'older' limestones, for example Trealla Limestone, commenced much earlier than has been postulated.

Table 2 Inferred speleogenesis history of the Cape Range area*

TIMING	*EVENTS*
Holocene (10 Ka – Present)	Rise of sea to present level; continued dissection of upper karst system; drowning of lower karst system; continued speleogenesis of coastal plain sediments.
late Pleistocene (800 – 10 Ka)	Maximum sea level fall to130m below present (glacial maxima conditions) & continued emergence of Cape Range area; accelerated deep erosion; possible lateral & depth extension of cave system (now offshore).
early Pleistocene (1.8 Ma – 800 Ka)	Continued emergence of Cape Range area; onset of arid conditions; limited speleogenesis.
L. Miocene – Pliocene (11 – 1.8 Ma)	Emergence of Cape Range as an island; development of groundwater system & initiation of speleogenesis under humid, near-tropical conditions.

* Modified after Allen (1993).

5.5.4 Lake MacLeod and Bullara Sunkland

Lake MacLeod is a large salt lake, some 110 km long by 40 km maximum width, inland from and paralleling the coastline (Fig. 13). The lake is the surface expression of a large shallow unconfined saline aquifer system, the Lake MacLeod basin, and includes saline alluvial plains with samphire and saltbush, and an inland mangrove assemblage confined to small patches around the lake. The riparian vegetation is, in general, in poor condition having been subject to very heavy grazing pressure (W & R C 1997). The wetlands are a major migration stopover and drought refuge for shorebirds (May, J. E. and McKenzie, N. L. 2003).

Lake MacLeod basin lies within the MacLeod graben, a fault-bounded north-trending structural depression forming part of Bullara Sunkland. The graben developed during the mid to late Miocene, initially forming an extensive marine embayment. Subsequently, basin morphology was modified by the accretion of Holocene dune ridges which terminated the ocean – basin surface connection. Accumulation of basin evaporites began about 5,800 years BP when Cygnet seepage face, the main portal for subsurface seawater inflow, began discharging seawater into the basin (Shepherd, M. J. 1990). The floor of the lake, now about 3.2 mbsl, consists of thin-bedded clays, silts and minor sand, and evaporitic minerals including halite (sodium chloride), potash (potassium carbonate), aragonite (calcium carbonate) and gypsum (calcium sulphate).

Small isolated pools of permanent water occur in parts. Apart from flood events following very heavy rainfall in the catchment, there is little direct overland or surface stream flow into the lake. Inflow or recharge is achieved indirectly by subsurface infiltration and lateral migration of water through Miocene limestones and Quaternary sediments surrounding and underlying the lake. Recharge is principally from the sea and very intermittently from inland drainages. The principal recharge to Lake MacLeod occurs through an extraordinary hydrological phenomenon, a natural pump. Hydrostatic pressure, generated by a 3 to 4m difference in level between ocean and basin, forces seawater laterally through the karstic Miocene limestones to eventually discharge as saltwater springs and seepages (the Cygnet seepage face) along the western margin of Lake MacLeod. This process constantly replenishes the brine in this vast evaporation basin. Discharge rates are controlled by the relationship between the rate of seawater transmission (relatively constant) and the evaporation rate (Shepherd, M. J. 1990). Discharge rates can be high enough to produce jetting where water is discharged in a continuous stream at high velocity through narrow vents, or so low as to be expressed only as subsurface seepage. This seawater feedstock is subsequently modified by evaporation, infiltration and runoff (Shepherd, M. J. 1990).

Secondary, ephemeral recharge occurs via inland drainage tracts, the main ones being: (1) the Bullara Sunkland, (2) Cardabia Creek, (3) Lyndon River and (4) the Minilya River. The Bullara Sunkland (Fig. 14) is a linear, topographically subdued unit, occupying the Bullara Syncline and trending north-northeast between the Rough and Giralia Ranges. It essentially provides a physiographic and hydrologic link between Exmouth Gulf and Lake MacLeod. Rainwater from the sandplain and Giralia Range catchments is directed via surficial sand and valley calcrete, and subsurface limestone aquifers either northwards to Exmouth Gulf or southwards to Lake MacLeod.

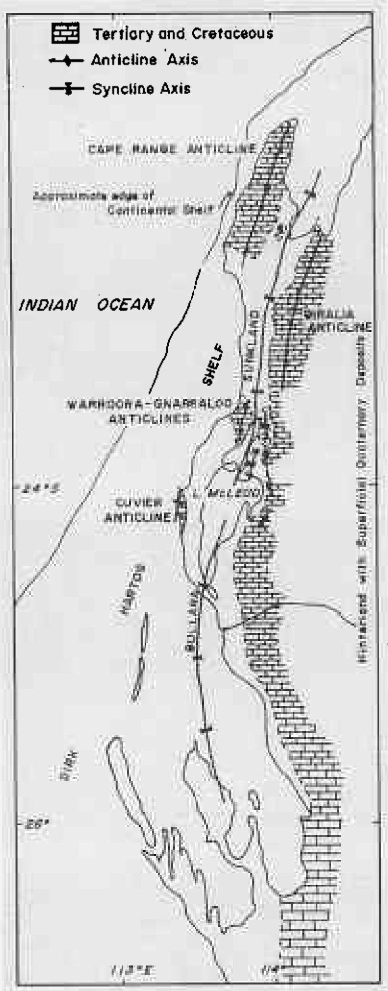


Figure 13. Map showing Lake MacLeod, Bullara Sunkland and main anticlinal structures, Shark Bay to North West Cape area (From Wyrwoll et al, 1993)

Cardabia Creek is an intermittent south-draining creek on the eastern side of Giralia Range. It consists of numerous tributaries incised into Cretaceous sediments in the upper reaches before infiltrating and disappearing into Quaternary sediments, eventually discharging into the far northern end, the 'panhandle', of Lake MacLeod on the west side of Ginargoo Range.

The Lyndon River is a short, generally westward flowing river arising about 200 km inland. It too has only intermittent surface water flow, most flow being in the subsurface through the bedload sands and gravels. Discharge into Lake MacLeod is not direct; it appears to form a subsurface confluence with Cardabia and Chinkia Creeks, approximately 15 km northeast of

Ginargoo Range, then together discharging into Lake MacLeod at its northern end. This confluence or intermittent floodout area also supports the southern-most extent of Mitchell grass (*Astrebla* sp.) in Western Australia, in turn supporting the southern-most extent of several species of migratory plains birds including brolgas and jabirus.

Minilya River is also a short river, generally westward flowing with intermittent surface flow. Like the Lyndon, this river also disappears into Quaternary sediments just southeast of Ginargoo Range before re-emerging as a series of small saline playas between the small low-relief anticlines and domes along the eastern margin of Lake MacLeod. These playa lakes are in hydrologic connection with, and form part of, the Lake MacLeod basin.

5.5.5 Pleistocene Dune Desert

Disjunct remnants of a once widespread Pleistocene desert, characterised by longitudinal (linear) dunes and sand plains, are found in the Lake MacLeod - Ningaloo - Cape Range - Exmouth Gulf area (Fig. 14). The main locations are (1) at the far northern end of Cape Range, (2) flanking the southern end of Cape Range and extending south between the coast and the Bullara Sunkland, almost to Lake MacLeod, and (3) east of Giralia Range and extending northwards into the southern and eastern parts of Exmouth Gulf, including locations such as Gales Bay and Yanrey Tidal Flats.

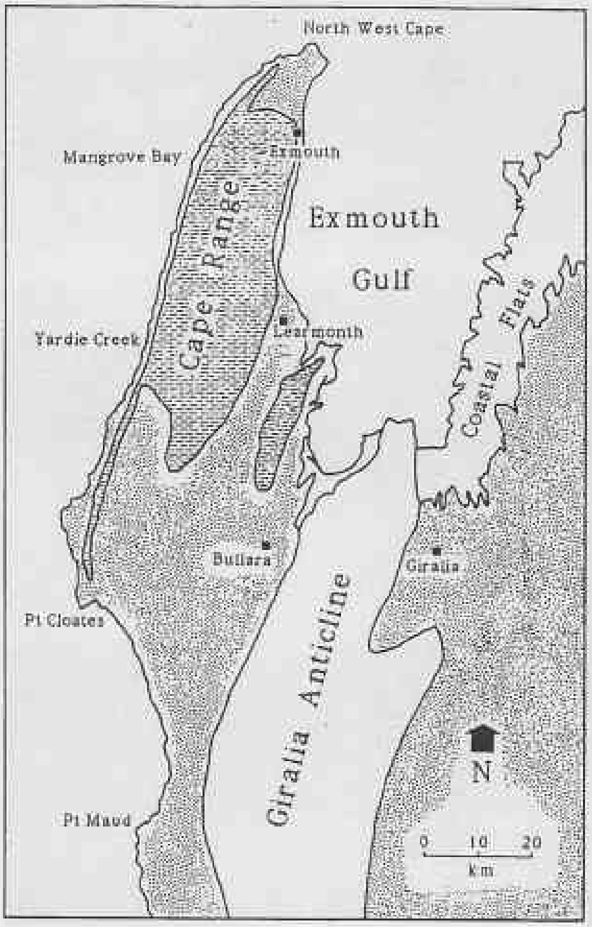


Figure 14. Generalised distribution of sandplains and dune fields (stippled) in the Ningaloo – Cape Range – Exmouth Gulf area (from Kendrick, 1993)

Regionally, the dunes trend predominantly north or north-northeast, and even in the offshore areas where the desert has been inundated by the sea, this trend is still evident from the dune remnants.

The following description is largely based on Wyrwoll et al (1993), which in turn is based on a review by Kendrick, Wyrwoll and Szabo published in 1991. This author is aware that further research on the dune sediments was planned but does not have the results of this work to hand.

At the northern Cape Range location, some reliable thermoluminescence dates have been obtained which yielded a Late Pleistocene Last Glacial Maximum age (23 and 16 Ka). Climatic conditions were very arid and cold. These sediments overlie Last Interglacial marine deposits and consist of red quartzose sand, with minimal profile differentiation. In contrast, the dune sands of the Gales Bay area contain more carbonate, probably through mixing with calcareous Holocene sediments, and have well developed profile differentiation.

5.6 CAINOZOIC and CRETACEOUS FOSSILS

5.6.1 Coral Fauna

Exposed in the Giralia Range, the Cretaceous marine fauna of the Miria Formation is dominated by molluscs but also includes the most diverse assemblage of Mesozoic corals in Australia (Jell, J. S. and Jell, P. A. 1998). One stylasterid, possibly the earliest known occurrence of this group, and ten species of ahermatypic scleractinian corals, representing very early occurrences, are recognised. The only other Cretaceous occurrences for some of these species are in Antarctica and southern India. A Maastrichtian age (71 – 65 Ma) for the fauna is indicated by associated foraminifers and ammonites (Jell, J. S. and Jell, P. A. 1998).

5.6.2 A Therapod Dinosaur

In late 1991, the Miria Formation, again in the Giralia Range, also yielded Western Australia's first fossil dinosaur bone. Found by Mr George Kendrick of the WA Museum, the weathered, partial humerus (upper arm) was from a meat-eating therapod dinosaur, but the species could not be determined (Long, J. 1993).

5.6.3 Cretaceous flood and anoxic events

The Cretaceous marine inundation was Australia's greatest flood (Fig. 15). It occurred at an important time in our geological evolution when the Australian continent was being shaped as a separate entity as the Indian and Southern Oceans progressively opened, along with global and local climate change and extinction events. These events are recorded in the Cretaceous rocks of the Ningaloo – Cape Range – Exmouth Gulf area.

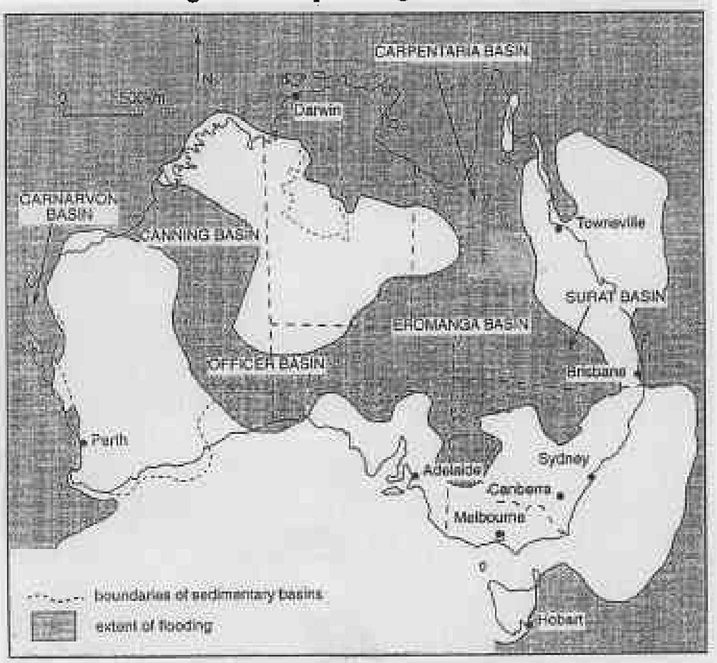


Figure 15. Extent of Cretaceous (Aptian) marine transgression (shaded) of Australia (from Campbell & Haig, 1999).

At the time of the great Cretaceous inundations, vast shallow seas formed along Australia's land margins including the onshore Carnarvon Basin (the marginal seas) and across the continental interior (the interior seas). The inundation occurred in two main cycles; the first transgression occurred during the Aptian – Albian (125 – 100 Ma), covering about 60% of the present-day land area (Campbell, R. J. and Haig, D. W. 1999) and the second peaked during the Turonian (92 Ma) at 250 m above present day sea level, the highest level of the entire Phanerozoic era . Associated with the shallow Cretaceous seas were major extinction events, induced by oceanic anoxic events (OAEs). However, in order to appreciate the scientific importance of the Cretaceous rocks in the Ningaloo – Cape Range – Exmouth Gulf area, it is necessary to understand certain differences between the marginal and the interior seas (Haig, D. W. 2004).

The marginal seas had the following characteristics:

- Vast shallow seas, mostly less than 100 m depth,
- Generally good hydraulic connection with the open ocean (for the Ningaloo – Cape Range – Exmouth Gulf area, this was the developing Indian Ocean),
- Entire water column reasonably well oxygenated,
- Mostly suitable habitat for open-marine types of zoo-and phytoplankton,
- Subject to tidal influence and storm surges,
- Moderate to high-energy shorelines.

In contrast, the interior seas had the following characteristics:

- Vast, very shallow seas, many areas less than 10 m depth,
- Very low gradient sea floor (no shelf or basin areas),
- Widespread restricted circulation and poor hydraulic connection with open ocean,
- Anoxic (O_2 depleted) bottom waters,
- Low energy shorelines,
- Suitable habitat for estuarine-types of zoo- and phytoplankton.

Modern analogues of these seas are the Gulf of Carpentaria and the Peel-Harvey Estuary, although these are much less extensive than the Cretaceous seas.

During the mid Cretaceous, the climate of Western Australia's coastal regions changed from humid to semi-arid. This caused much reduced stream inflow to the seas, inducing a change from predominantly very fine-grained, slow clastic sedimentation to predominantly pelagic biogenic carbonate deposition. In turn, these changes caused a number of sudden and widespread anoxic events where the entire water column became depleted in oxygen, resulting in the death of oxygen-dependent plankton and higher-order marine organisms. Extinction of existing species of plankton was not complete with the first anoxic event; instead, it occurred progressively in a stepwise manner, which allowed, in time, speciation or modernisation of benthic plankton to take place in the period 90 to 86 Ma (D. Haig, *pers. comm.,* Aug 2004).

Recognition of these anoxic events is not possible in the deposits of the interior seas because of their normal condition of anoxic bottom waters. However, in the marginal seas where anoxic conditions were not the norm, these extinction-inducing events can be recognised, as recent work in the Giralia Range at C-Y Creek shows. Here, the principal event occurred at the Cenomanian – Turonian boundary, dated at 93.5 Ma, just before maximum sea level (250 m above present level) at 92 Ma.

Much more detailed research is required here to fully unravel the extinction events and subsequent speciation of marine organisms.

5.6.4 *Pleistocene Dune Desert*

The Pleistocene desert sands (Fig. 14), apart from being an important indicator of extremely dry conditions during the Last Glacial Maximum, also have contemporary ecological importance. In the offshore extensions, remnant dunes provide a suitable substrate on which patch corals develop in the subtidal zone and in the supratidal zone, patches of coarser sediment accumulate. Hope Island is a good example of the latter. Both situations provide very distinct ecological zonation.

Further inland, a myriad of small swamps, lagoons and claypans are located in the dune swales, and these are probably subject to a tidal-controlled, local ?fresh or mixed groundwater table. This is a semi-submerged sand dune landscape.

6 Assessment Against World Heritage Criteria

6.1 INTRODUCTION

The Lake MacLeod - Ningaloo - Cape Range - Exmouth Gulf World Heritage study area lies within, and constitutes most of the Carnarvon 1 Bioregion (Cape Range subregion) and the northwest coastal portion of the Carnarvon 2 Bioregion (Wooramel subregion). Climate is arid, sub-tropical semi-desert with variable summer and winter rainfall, tending to bimodal pattern. The landscape consists of a mosaic of rugged Miocene limestone ranges supporting acacia shrubland over spinifex grassland, Pleistocene coastal sand plains and dunefields, tidal mud and sand flats, saline alluvial plains and playas supporting samphire and mangroves, and extensive red sand dunefields supporting sparse eucalypt and acacia shrub steppe over spinifex grassland (May, J. E. and McKenzie, N. L. 2003).

The above description, with mention of the geologically young epochs Miocene and Pleistocene, contrasts with the commonly held perception that Australia is only comprised of very old rocks and ancient, barely changed landforms. Indeed, the Lake MacLeod - Ningaloo - Cape Range - Exmouth Gulf area, whilst being the product of long geological evolution stretching back hundreds of millions of years, has also been geologically active in the recent past, creating a geomorphically young, rejuvenated and dynamic landscape. Deeply embedded in the geological evolution and geomorphic development (described previously in Section 5) is the co-evolution of living organisms, as they adapt to changing climatic conditions and habitats. As a result, this area is rich in relictual and endemic species, adding to the very high conservation and scientific values.

Before undertaking the values assessment, it is worth considering some basic concepts in geological heritage and the meaning of particular words.

6.2 SOME CONCEPTS IN GEOLOGICAL HERITAGE

Western Australia's rich natural heritage includes the diversity of geological materials such as minerals, rocks, regolith and fossils, and the landforms and other physiographic features with which they are expressed at the Earth's surface. Sometimes collectively referred to as geodiversity (cf. biodiversity), our geological heritage is the product of contemporary and past climates and geological processes. Conservation of significant geological and geomorphological sites and features is fundamental to the protection of our natural heritage, and to education and research in the earth and biological sciences.

The concept of significance is of basic importance in the assessment of geological and geomorphic features and sites (Joyce, E. B. and King, R. L. 1980). Joyce (1995) states that significance is a function of its value or use in research, including as a reference, in education, and for aesthetic or landscape qualities. The degree of significance is usually thought of as lying on a continuum between 'very high' and 'very low', or in a two-fold division, 'significant' or 'not significant'. Importantly, the basis on which significance is assessed is usually in one or two ways, namely, 'outstanding' or 'representative', and may be made at local, regional, state, national or international / World Heritage levels.

Joyce (1995) discusses the concepts of 'outstanding' and 'representative'. He finds, for example, that use of the word 'unique' frequently causes confusion by being made almost useless or meaningless, through overuse, for the simple fact that each and every geological feature or site is unique in the strict sense of the word. The term 'outstanding is much more useful, particularly if supported by discussion of the rarity of particular features or sites. An applicable dictionary definition of 'outstanding' is "*adj.* prominent; conspicuous; striking; that continues in existence; standing out; projecting; detached." (The Macquarie Dictionary, 1999).

The concept of 'representative', as clearly described by Joyce (1995), allows a degree of significance to be attached to one or more features which best represent a group of similar features. A representative feature need not be outstanding or striking, but need only be typical of the group it is to represent. A relevant dictionary definition of 'representative' is "*adj.* Serving to represent; representing; exemplifying a class; typical. *n.* an example or specimen; type; typical embodiment, as of some quality." (The Macquarie Dictionary, 1999).

For World Heritage nomination however, it is clear that a natural heritage property [or feature] must be of "outstanding universal value" (World Heritage Operational Guidelines (WHC 2002)), that is, assessment need only consider its value as an outstanding, but not necessarily representative, example. The level of assessment is at the international / World Heritage level, rather than at the lower national, state, regional or local levels. The World Heritage assessment criteria are outlined in Section 6.3 below.

6.3 NATURAL HERITAGE PROPERTIES WORLD HERITAGE LIST CRITERIA

The following information is taken directly from the Operational Guidelines for the Implementation of the World Heritage Convention (WHC 2002).

43. In accordance with Article 2 of the Convention, the following is considered as "natural heritage":

    "natural features consisting of physical and biological formations or groups of such formations, which are of outstanding universal value from the aesthetic or scientific point of view;

    geological and physiographical formations and precisely delineated areas which constitute the habitat of threatened species of animals and plants of outstanding universal value from the point of view of science or conservation;

    natural sites or precisely delineated natural areas of outstanding universal value from the point of view of science, conservation or natural beauty".

44. A natural heritage property – as defined above – which is submitted for inclusion in the World Heritage List will be considered to be of outstanding universal value for the purposes of the Convention when the Committee finds that it meets one or

more of the following criteria specified by the Operational Guidelines and fulfilling the conditions of integrity set out below.

Sites nominated should therefore:

a.

i. be outstanding examples representing major stages of Earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiographic features; or
ii. be outstanding examples representing significant ongoing geological or biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals; or
iii. contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance; or
iv. contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation;

and

b. also fulfil the following conditions of integrity:

i. The sites described in 44(a)(i) should contain all or most of the key interrelated and interdependent elements in their natural relationships; for example, and "ice age" area should include the snow field, the glacier itself and samples of cutting patterns, deposition and colonisation (e.g. striations, moraines, pioneer stages of plant successions, etc.); in the case of volcanoes, the magmatic series should be complete and all or most of the varieties of effusive rocks and types of eruptions be represented.

6.4 ASSESSMENT AND JUSTIFICATION

6.4.1 Introduction and Summary Table of Values

The following assessment and justification is based on Criterion 44 a i. This criterion focuses on geological and geomorphological history and processes including the fossil record of life. Although clearly related to and dependent on these processes, this assessment does not consider on-going or contemporary ecological and biological processes; these are comprehensively considered in the Draft Nomination for the Cape Range-Ningaloo World Heritage Property (GoWA in prep).

Being natural features or sites, each geological or geomorphic feature is assessed for its outstanding universal value (OUV) on the basis of aesthetic or natural beauty, scientific and conservation values. Where possible, the boundary of each feature, as shown in Figure 1, takes into account the spatial requirements of processes or phenomena so as to contain all or most of the key interrelated and interdependent elements and to protect the feature's heritage values from direct effects of human encroachment and impacts of resource use arising from outside of the nominated area. This aims to satisfy the World Heritage Listing conditions of integrity 44 b i and vi.

The following geological and geomorphological features are assessed:

1. Cape Range karst system including Ningaloo Reef (geomorphic feature),
2. Anticlinal ranges (geological feature),
3. Cape Range wave-cut terraces (geomorphic feature),
4. Pleistocene dune desert (geomorphic feature)
5. Cainozoic and Cretaceous sediments and fossils (geological features), and
6. Lake MacLeod aquifer system (geomorphic feature).

For each, the assessment and justification takes the form of three subsections comprising an *Introduction* which provides a succinct summary based on information more fully described in Section 5, a description or highlight of *Outstanding Aspects or Features,* and a comment on the *Aesthetic, Scientific and Conservation Values*. The values assessment has been summarised in Table 3 below and the recommended boundary to encompass the geological and geomorphic features for World Heritage Listing is shown in Figure 18.

Table 3 World Heritage natural heritage values and significance[1] matrix for **geological and geomorphic features**, Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area (World Heritage Criteria).

OUTSTANDING UNIVERSAL VALUE	CAPE RANGE KARST SYSTEM	ANTICLINAL RANGES	WAVE-CUT TERRACES	PLEISTOCENE DUNE DESERT	CAINOZOIC & CRETACEOUS SEDIMENTS & FOSSILS	LAKE MACLEOD
AESTHETIC / NATURAL BEAUTY	*High*	*Low*	*Low*	*Low*	*Very Low*	*Moderate*
SCIENTIFIC	*Very High*	*Very High*	*Moderate*	*Moderate*	*Very High*	*High*
CONSERVATION	*Very High*	*Very High*	*High*	*Moderate*	*High*	*Very High*

1. Rating Scale:
   Very High
   High
   Moderate
   Low
   Very Low

Explanation of the significance attached to the World Heritage Outstanding Universal Values for each of the features is given below. A five (5) level rating of significance from very low to very high is used here.

6.4.2 Ningaloo Reef - Cape Range Karst System

6.4.2.1 Introduction

The Ningaloo Reef - Cape Range karst system is a complex hydrogeological system composed of various landforms, fluids, rocks, regolith and biological elements. Landforms include Cape Range, coastal plains and Ningaloo Reef. The terrestrial elements include solution and collapse sinkholes, karst etch plateau, episodic exsurgent springs, caves of various types, alluvial fan deposits and the beach and dune deposits. Of the marine elements, Ningaloo Reef is clearly the most conspicuous element. It is a major biokarstic feature, classed as a fringing reef some 260 km long with the gaps or passages in the reef probably due to the discharge of freshwater from subsea karst springs.

Interactions between these elements support complex temporal-spatial habitat-forming patterns and processes, and various life-forms, the maintenance of which is driven by and highly dependent on the continued movement of air and water, both fresh and saline, through the physical spaces of the karst system. Meteoritic water, derived from ex-tropical cyclonic events (40%) and northwest cloud band disturbances (20%) comprise most of the freshwater recharge, albeit intermittently, to the groundwater system. Apart from its role in erosion and karst dissolution, this water is utilised by various organisms as it passes through the vadose and phreatic zones. Seawater has a similar role in the marine and near shore environments. In addition, the transition or mixing zone between the freshwater and saline water regimes and the closely related anchialine system are also important aquatic habitats. Air, comprising CO_2, O_2, N_2, other gases and water vapour, is also an important fluid in cave systems. Subterranean climates are generally more stable than at the surface (Hamilton-Smith, E., Kiernan, K. et al. 1998). Humidity and temperature remain fairly constant year-round apart from, presumably, perturbations caused by torrential rainfall events. The troglobitic fauna only occupies those caves or parts of caves where humidity is greater than 90% (White, M. E. 1994). Little is known of the subterranean atmospheres in the Cape Range karst system apart from the occurrence of high CO_2 levels in some caves at times – the periodicity and local controls of which are unknown, nor its significance for the cave fauna (Hamilton-Smith, E., Kiernan, K. et al. 1998).

6.4.2.2 Outstanding Aspects or Features

The Ningaloo Reef - Cape Range karst system hosts a rich subterranean or cavernicolous fauna comprising a high proportion of locally disjunct, endemic and relictual species. For example, the terrestrial invertebrate fauna of beetles, spiders, cockroaches, slaters, crickets, scorpions and millipedes, once part of a Miocene tropical rainforest leaf litter community, are now completely adapted to, and confined to their deep cave habitat (White, M. E. 1994). Similarly, in the anchialine habitat on the coastal plain flanking Cape Range, the entire Australian subterranean aquatic vertebrate troglobitic fauna is present, consisting of a gudgeon, an eel, two blind fish and crustaceans (White, M. E. 1994).

However, in regard to the biological elements of this karst system, as outstanding as they are, it is not the purpose of this report to review their intrinsic World Heritage values; a comprehensive assessment of biological values is provided in the Draft Nomination for the Ningaloo - Cape Range World Heritage Property (GoWA in prep). Instead, this report aims to highlight the point that the Cape Range karst system is a special place because its geological history has made it so. This place is the sum of natural, dynamic geological and related processes, both past and ongoing.

The Cape Range karst system has resulted from the deposition of sediments dominated by pelagic biogenic carbonate from the mid-Cretaceous, a profound change from earlier clastic-dominated sedimentation, followed by lithification (basin subsidence, compaction and diagenesis) and eventual Late Miocene - Pliocene folding and uplift, and post-Miocene exhumation (see Section 5.4 for details). All of these stages are directly related to the rifting and separation of Greater India from Australia, as part of Gondwanan break-up. The exhumation or emergence of Cape Range and associated anticlinal ranges, and the concomitant initiation of speleogenesis occurred during a wet climatic phase with subsequent karstification occurring mostly under arid periglacial conditions, but now continuing under warm arid conditions. This is important. The geological and climatic processes have driven biological evolution, the remarkable speciation and adaptation is wonderfully demonstrable here.

6.4.2.3 Aesthetic, Scientific and Conservation Values

The overall aesthetic or natural beauty value of the Ningaloo Reef - Cape Range karst system is considered to be high. From the crestal parts of Cape Range, the west-view panorama takes in the western flank of the range (foreground), the coastal plain and near-shore fringing Ningaloo Reef set in the clear lagoonal waters on the edge of the vast Indian Ocean. Panoramic views to the east take in the steeper eastern flank of Cape Range, the narrow coastal plain and the expansive shallow waters of Exmouth Gulf. Views along the crest of Cape Range, to the north and to the south, although less outstanding, nevertheless also capture the essential naturalness of the land and seascapes. The terrestrial karst landforms alone do not constitute outstanding aesthetic features, however, from within deeply dissected gorges, a strong feeling of isolation and wilderness is usually engendered within oneself. Ningaloo Reef is however, an outstanding feature at observational scales ranging from satellite images, to light aircraft flyovers and to an individual snorkelling on the reef.

The scientific value of the Ningaloo Reef - Cape Range karst system is considered to be very high. Whilst few of the geological processes or stages outlined above (and in more detail in Sections 5.4 and 6.4.3), when considered individually, constitute special or outstanding geological features (except for the Cretaceous carbonate deposition and associated extinction events; considered in Section 6.4.6 below, and the Miocene uplift event; considered in Section 6.4.3 below), when considered as a sequence, then this area is an outstanding example of geomorphic development of a coastal karst landscape under initially high then irregular, low rainfall (arid) conditions. There are no similar karst systems, located on a passive continental rift margin, in Australia or, as far as this author is aware, any other part of the former Gondwanan supercontinent. This is an extraordinary geological situation arising from the culmination of a series of (mostly) ordinary geological events.

Because the karst system is well exposed, the area also provides excellent opportunity to further knowledge of the geomorphic processes and history. Aspects that require specific study include cave and speleothem formation rates, the relationship of cave base-levels to sea levels, development morphology of the terrestrial karst types including the etch plateau, and development relationships between the terrestrial and marine (reef) karst elements.

The conservation value of the Ningaloo Reef - Cape Range karst system is considered to be very high. Clearly, it is absolutely necessary to maintain the integrity of the abiotic components of this complex hydrogeological system in order to maintain the habitats and dependent life forms. Critically, the compositional quality and flow regimes of all fluids must not be compromised; it is highly likely that the habitat requirements for the cavernicolous fauna, for example, are tightly constrained and thus any rapid deviation from usual conditions, arising from human activities, is likely to seriously threaten these communities.

In regard to the geological and geomorphological aspects, conservation of the abiotic components (the rocks and regolith) is also essential for the continued elucidation of karst landscape evolution during the Miocene – Pliocene, and contemporary karstification processes occurring in the Pleistocene sediments.

6.4.3 The Anticlinal Ranges

6.4.3.1 Introduction

The anticlinal ranges include the limestone ranges formed by the Cape Range, Rough Range, Giralia and Marrilla Anticlines (and associated synclines) and associated faults such as the Cape Range, Paterson, Rough Range, Giralia, Yanrey and Wandagee Faults occurring in the northern parts of the area and the smaller, less conspicuous anticlines delimiting the western and eastern margins of the Lake MacLeod panhandle. The largest anticline in this southern echelon group forms the Gnargoo Range and Cape Range is the largest of the peninsula ranges.

These structures resulted from Late Miocene or possibly early Pliocene, west-northwest – east-southeast directed compression along the margins of the Gascoyne and Exmouth Sub-basins (and the Barrow Sub-basin further to the northeast) and constitute the last major tectonic readjustment episode following the Australia – Greater India break-up, and the newly developing Australian – Asian plates collision (Bunda arc / Java Trench) along Australia's northwestern margin in the Timor area (Veevers, J. J. 1984; Malcolm, R. J., Pott, M. C. et al. 1991).

6.4.3.2 Outstanding Aspects or Features

There are two outstanding geological aspects.

The first aspect concerns transfer and tear faults. Southwesterly trending tear faults, which formed on the Bundegi and Ningaloo Terraces and Paterson Trough during the earliest Cretaceous as part of the last major syn-rift pulse (final break-up), curve westward to merge with older major transfer faults. Significant amounts of lateral and vertical movement occurred along the transfer faults (Malcolm, R. J., Pott, M. C. et al. 1991) and significant oblique-slip and block rotation occurred along the tear faults (Fig. 16).

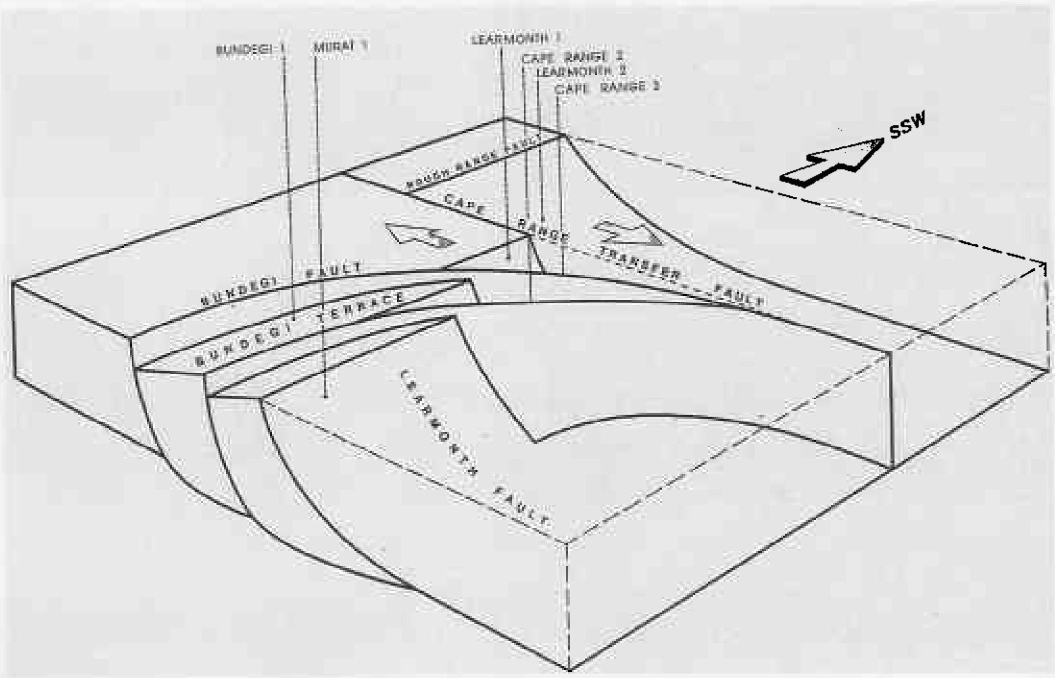


Figure 16. Schematic relationship between two tear faults, formed contemporaneously with rifting and merging with the Cape Range Transfer (transform) Fault, and the Rough Range and Learmonth (detachment) Faults (from Malcolm et al, 1991).

Apart from its role in the formation of hydrocarbon structural traps in this region, the structural architecture evident here provides an outstanding example of basin deformation mechanisms when there is a major shift in orientation and location of spreading centres. As described in Section 5.4, the Exmouth Sub-basin has been affected by two main tectonic break-up phases. The first in the Late Jurassic (Oxfordian) involved the creation of the Argo Abyssal Plain and the second at earliest Cretaceous time, involved the creation of the Gascoyne and Cuvier Abyssal Plains with the separation of Greater India from Australia. Magnetic anomaly trends show a 40° rotation between these two phases (Veevers, J. J. 1984 p.185; Malcolm, R. J., Pott, M. C. et al. 1991) and the tear faults described earlier, are a clear expression of this change. This change in orientation of spreading axes also explains the shape of the continental margin, broadly reflected by the present-day coastline, with the Cape Range area being the pivot about which the rotation occurred. This is an outstanding example of a particular structural regime in a divergent passive margin setting.

The second outstanding geological aspect is related to the Late Miocene – early Pliocene major compression event that affected the entire western margin of Australia. It is, however, best expressed in the Ningaloo - Cape Range region because of the atypical low-angle listric geometry of the older faults along the Exmouth Basin eastern margin. This unusual fault geometry maximised the uplift effect of the lateral reverse movement (thrust) on the reactivated faults (Malcolm, R. J., Pott, M. C. et al. 1991). In particular, the Cape Range and Rough Range Anticlines formed by thrust movement along low-angle listric detachment faults, the Learmonth and Rough Range Faults. Importantly however, "the southern extension of the Learmonth Fault, because of its basinward position, accommodated much of the Miocene – Pliocene compression, resulting in the northern end of the Rough Range Fault being sheltered from reverse movement" (Malcolm, R. J., Pott, M. C. et al. 1991 p.170). This aspect now provides an outstanding example for the study of the Miocene - Pliocene thrusting, from weakly affected to strongly affected parts along strike, as the northwest of Australia changes from a passive divergent margin to an active convergent margin. There are no other age-equivalent examples on the former Gondwanan continents.

6.4.3.3 Aesthetic, Scientific and Conservation Values

The overall aesthetic or natural beauty value of the anticlinal ranges is considered to be low. Although forming part of a landscape of overall high aesthetic value, the ranges themselves are not outstanding or striking topographic features. Cape Range, the largest and highest (311 m) of the anticlinal ranges, does dominate the peninsula area but when considered in the World context, is an insignificant feature.

The scientific value of the anticlinal ranges is considered to be very high. For the geological reasons described above, the anticlinal ranges and associated structures are outstanding examples highly suitable for further research and for educational and reference purposes.

The conservation value of the anticlinal ranges is considered to be very high. Given that the anticlinal ranges, as geological features, host the karst system (considered above), the Cretaceous sediments and fossils (considered below), the Lake MacLeod hydrogeological system and other geomorphic features (considered below), each of which has high or very high scientific and/or conservation values, then it is clear that the anticlinal ranges must have at least high conservation value. This recognises the World Heritage integrity criterion.

6.4.4 Cape Range Wave-cut Terraces

6.4.4.1 Introduction

A series of conspicuous, well-preserved wave-cut shoreline terraces or benches and associated seaward thinning sediment wedges and coralline deposits occur on the lower western flank of Cape Range. The terraces are a characteristic geomorphic feature of the area. As previously described in Section 5.5.2, these terraces provide a physical record of the Late Miocene to Pleistocene uplift history of the Cape Range area, the tectonic aspects of which are described in Sections 5.4 and 6.4.3.

Unfortunately, numerical dating of the terraces is still very incomplete and thus the detailed Pleistocene uplift, and geomorphic and biological chronologies are not yet comprehensively known. However, there are two regional aspects worth noting. The first concerns the lowest bench, the Tantabiddi. The age of the Tantabiddi Member has been established as Late Pleistocene (numerical dates in the range 132 – 127 Ka) but may range back to the Middle Pleistocene if suspected multiple marine transgressions prior to the highstand sea level of the Last Interglacial can be established (Wyrwoll, K.-H., Kendrick, G. W. et al. 1993). Temporal correlation between the Tantabiddi Member and the Bibra Formation of Shark Bay is now likely (Wyrwoll, K.-H., Kendrick, G. W. et al. 1993), providing support to the regional extent of the Last Interglacial sea levels.

The second concerns the palaeo-course of the Ashburton River. Near Vlaming Head, the pebble fraction in a basal conglomerate of the Milyering Member (on the Milyering Terrace) contains clasts of Archaean basement rocks. As Wyrwoll et al (1993) state, this assemblage resembles the present bedload of the Ashburton River near Onslow, some 50 km to the east, suggesting that during the Miocene-Pliocene deformation of the area, the lower reaches of the Ashburton (or other river) was located in the vicinity of Cape Range. The author is not aware of any studies being done, such as interpretation of night-time thermal infrared images, to establish palaeodrainage tracts.

6.4.4.2 Outstanding Aspects or Features

Coastal tectonics is focussed on the formation and deformation styles and rates of emergent marine strandlines, of which the Cape Range terraces are an example of one type. Marine strandlines are the most common tectonic markers in the Quaternary geomorphic record (Lajoie, K. R. 1986) and rapidly become less common in older sequences. Mapping and dating of strandlines aims to separate vertical crustal movements from past sea level changes. The most profound differences in geomorphic characteristics are found between the rugged erosional coastlines along active convergent plate boundaries and the subdued sediment-accretionary coastlines along passive continental margins (Lajoie, K. R. 1986). Examples of passive-margin coastlines are the southeast coast of North America and the shallow epicontinental seas in the Hudson Bay area, and the northeast coast of Australia. Examples of active margin coasts include the Huon Peninsula on the northern coast of Papua New Guinea, and the hilly to mountainous Pacific coastlines of North and South America.

An important point is that, according to Lajoie (1986), strandlines older than about 400 Ka are poorly preserved in areas of rapid uplift (> 4 m/Ka) owing to subaerial erosion and stream incision whereas strandlines up to 2.4 Ma may be preserved on stable or slowly rising coasts. The Cape Range terraces are outstanding examples formed in a passive divergent-margin coastal setting transitional to an active convergent margin (previously described in Section 6.4.3). The age of the lowest and youngest terrace is about 130 Ka; the age of the oldest terrace is unknown but could be earliest Pleistocene (1.8 Ma), and in regional aspects, complements and partially overlaps the Upper Quaternary changes recorded in the coral reef terraces at Huon Peninsula, Papua New Guinea (Chappell, J. 2003).

6.4.4.3 Aesthetic, Scientific and Conservation Values

<u>The overall aesthetic or natural beauty value of the Cape Range wave-cut terraces is considered to be low</u>. In comparison to the remarkable terraces at Huon Peninsula (Chappell, J. 2003), the massive steplike series of terraces on the Palos Verdes Peninsula of southern

California (Lajoie, K. R. 1986), the Thousand-tile Rock on the north coast of Ho-pin Island, Taiwan, and terrace complexes in other locations, the Cape Range terraces do not stand out.

The scientific value of the Cape Range wave-cut terraces is considered to be moderate. For the geological reasons described above, the terraces and associated sediments are outstanding, very well preserved examples, highly suitable for further research and for educational and reference purposes. These terraces will be essential for the detailed resolution of Late Miocene to Quaternary crustal uplift and glacio-eustatic sea level changes in the northwest region of Australia and across the continent. The global relevance is difficult to assess without the age of the oldest terrace being known; the older the age, the greater the global relevance.

The conservation value of the Cape Range terraces is considered to be high. In order to yield high quality scientific data, the terraces must be substantially conserved, so that critical exposures and locations, some probably not yet known, are not destroyed. It should also be highlighted that the lowest terrace (Tantabiddi) carries fossil reef fauna with strong species overlap with the adjacent living reef (Ningaloo Reef), thus enhancing the high natural integrity of the area. This author concurs with Hamilton-Smith et al (1998 p.33) when they point out that "the largely unstudied terraces…are a resource of enormous geomorphological importance that offer the prospect of dating cave development, valley incision and relief evolution, terrace formation, and the age and rates of coastal uplift."

6.4.5 Pleistocene Dune Desert

6.4.5.1 Introduction

The present-day Pleistocene dune fields, now disjunct remnants of a once very extensive desert, are located at the northern end of Cape Range, from the southern end of Cape Range south almost to Lake MacLeod, and east of Giralia Range extending northwards into Exmouth Gulf. Apart from coastal areas influenced by Holocene carbonate sands, the Pleistocene sands are reddish to brown and quartzose with some carbonate segregations.

The desert formed during the Last Glacial Maximum (between 16 and 23 Ka), reflecting very arid, windy and cold climatic conditions. It is likely that the dunes have been extensively reworked during the various arid phases of the Pleistocene. With the rise of sea level since that time, the dune field has been partly inundated by the waters of Exmouth Gulf. In the area known as Yanrey Tidal Flat, a Holocene tidal flat, longitudinal dune remnants provide suitable substrate for patch coral development (Wyrwoll, K.-H., Kendrick, G. W. et al. 1993) and further inland, a myriad of small brackish-water swamps and lagoons have formed in the dune swales.

6.4.5.2 Outstanding Aspects or Features

The most outstanding aspect of the Pleistocene dune desert is the important role that dune remnants have played in the development of supratidal accumulations, as islands within the tidal flats, allowing the development of very distinct ecological zonation (Wyrwoll, K.-H., Kendrick, G. W. et al. 1993). Hope Island, having a core of large linear dunes, is an excellent example.

6.4.5.3 Aesthetic, Scientific and Conservation Values

The overall aesthetic or natural beauty value of the Pleistocene dune desert is considered to be low. Although these sediments have contributed substantially to the geomorphic and therefore ecological diversity of the area, their intrinsic natural beauty in comparison to the very extensive dune deserts such as the Little and Great Sandy Deserts of Western Australia, and other deserts in the World, is low.

The scientific value of the Pleistocene dune desert is considered to be moderate. At North West Cape, the Pleistocene dunes overlie Last Interglacial marine sediments, therefore post-dating that time and elsewhere, overlie coastal and alluvial sediments (Wyrwoll, K.-H., Kendrick, G. W. et al. 1993) providing evidence for the advance of the dune desert concomitant with increasingly arid conditions in the Late Pleistocene. These sediments provide very valuable palaeoclimatic information for this important period in our ecological history.

The conservation value of the Pleistocene dune desert is considered to be moderate. Apart from being a repository of palaeoclimatic information, these sediments also have very important contemporary ecological roles. One role, as a marine substrate, has been described previously (Section 6.4.5.3). Another role is as very significant rainfall infiltration zones providing recharge to the fresh groundwater system in the Bullara Sunkland and other areas.

6.4.6 Cainozoic and Cretaceous Sediments and Fossils

6.4.6.1 Introduction

Cainozoic (Tertiary) and Cretaceous sediments, containing very important fossils, crop out in the Giralia Range. This anticlinal range extends from Sandalwood Peninsula at the southern end of Exmouth Gulf south-southwest to Round Knob Hill, a distance of about 100 km. It has been extensively eroded, exposing substantial areas of Cretaceous sediments in the core of the fold and Cainozoic sediments in the deeply dissected western limb.

A number of palaeontological aspects make this an area of considerable interest and importance. The first concerns Cretaceous microfossil assemblages. With the Cretaceous break-up of Gondwana and high global sea levels, Cretaceous sediments are well represented in Australasia in extensive passive margin basins and vast interior (intracratonic) seas (Henderson, R. A., Crampton, J. S. et al. 2000). The interior seas were essentially estuarine and closed, covering more than 60% of Australia's present day land surface, with water depth less than 100 metres (Campbell, R. J. and Haig, D. W. 1999). The marginal seas, although shallow as well, were open to the young Indian Ocean and provided well stratified normal-marine depositional conditions (Haig, D. W., Watkins, D. K. et al. 1996).

A diverse assemblage of foraminifera, nanoplankton and radiolaria is found in the deposited sediments. These microfossils have been, and continue to be, essential in palaeobiogeographic studies. For example, it has been recognised that open marine surface-water temperatures changed during the Cretaceous from warm (Tethyan) to cool, that differences in salinity, temperature and dissolved oxygen levels existed between the silled interior seas and the marginal seas, and that rapid evolution in the Australian formaminifera occurred (Henderson, R. A., Crampton, J. S. et al. 2000). Furthermore, as described in Section 5.6.3, it has been established that a series of major extinction events during the Early Cretaceous (Aptian-Albian and Turonian) marine flooding of the continent, were caused by a series of oceanic anoxic events (OAEs).

The second palaeontological aspect concerns vertebrate and invertebrate macrofossils. The following list and brief descriptions are extracts from an undated (?2003) letter from Drs Long and McNamara (WA Museum) to Mr Blake (owner, Giralia station) regarding the significance of the Giralia Range fossil sites.

a. This is the only significant Cretaceous – Tertiary (K-T) boundary sequence in Australia.
b. The Miria Formation has the most diverse late Maastrichtian ammonite assemblage in the World, with important biogeographic links to Antarctica, South America, India and North America (Henderson, R. A. and McNamara, K. L. 1985a; 1985b; Henderson, R. A., Kennedy, W. J. et al. 1992).
c. The Miria Formation also produces the greatest diversity of late Maastrichtian gastropods, brachiopods and bivalves in Australia, also with important biogeographic links (Darragh, T. A. and Kendrick, G. W. 1991a; 1991b; Craig, R. S. 1999, 2000).
d. The Miria Formation has produced Australia's largest pterosaur (based on a partial ulna bone), a flying reptile with 3.9 to 5 metre wingspan (Bennett, S. C. and Long, J. A. 1991), Australia's most diverse Late Cretaceous shark tooth assemblage and important records of a therapod dinosaur bone (Long, J. A. 1992) and mosasaur bones (Long, J. A. 1998).
e. The Cardabia Formation has produced Australia's richest Palaeocene echinoid assemblage, and is one of the most diverse in the World (McNamara, K. L. 1999).
f. The Boongerooda Greensand has produced a diverse assemblage of Palaeocene shark teeth, with the first and only records of some species (*Palaeocarcharodon, otodus obliquus)* for Australia.
g. The Boongerooda Greensand also contains an important brachiopod (*Tegulorhynchia boongeroodanesis)* (McNamara, K. L. 1983). Evolution of this brachiopod and its descendants has become a classic example of evolution, read from the fossil record.

6.4.6.2 Outstanding Aspects or Features

As a palaeontological site, the Giralia Range is outstanding for its richness of macro- and microfossils and due to the extensive Cretaceous outcrop, is a superb location that is contributing to regional and global biogeographic and zoogeographic studies. An example is the resolution of dinosaur forms – whether they represent extensive intercontinental distributions or Australian endemic forms convergent on the forms of other continents (Henderson, R. A., Crampton, J. S. et al. 2000).

Another example concerns the Cretaceous marine biota. It is strongly pandemic with western Europe and North America, across groups as disparate as reptiles, ammonites, bivalves and foraminifera, such as is found in the Upper Maastrichtian Miria Formation, probably due to the developing seaway connection between the Tethys and new Indian Ocean at that time (Henderson, R. A., Crampton, J. S. et al. 2000).

Finally, the Giralia Range is the only significant Cretaceous – Cainozoic (Tertiary) (K-T) boundary sequence in Australia.

6.4.6.3 Aesthetic, Scientific and Conservation Values

<u>The overall aesthetic or natural beauty value of the Giralia Range fossil sites is considered to be very low</u>. Although occurring in a conspicuous, dissected range, which dominates the local landscape, the sites have little intrinsic aesthetic appeal.

<u>The scientific value of the Giralia Range fossil sites is considered to be very high.</u> For the scientific reasons outline above, the Cainozoic and Cretaceous sediments and fossils occurring in this area are very important for Australian and global palaeogeographic, palaeoclimatic and other studies to further understanding of the transition from strongly pandemic to strongly endemic speciation as Gondwana fragmented.

<u>The conservation value of the Giralia Range fossil sites is considered to be high.</u> Clearly, in order for the scientific studies highlighted above to be undertaken, the sediments and fossils

need to be conserved. Studies are continuing and access to undisturbed sites and *insitu* material needs to be maintained.

6.4.7 Lake MacLeod

6.4.7.1 Introduction

Lake MacLeod is a large , saline coastal lagoon or salt lake, and is the surface expression of or 'window' into an important and remarkable hydrogeological groundwater system. The lake lies at the southern end of Bullara Sunkland, a linear topographically subdued physiographic unit occupying the Bullara Syncline (which at its northern end, lies between the Cape Range and Giralia Range Anticlines). Other physiographic units involved in the hydrologic system include the low anticlinal limestone 'ranges' to the east and west of the lake 'panhandle', the small playa lakes, sandplains and inland drainages (Cardabia Creek, Lyndon and Minilya Rivers) to the east of the lake, and the sandy coastal plain and ocean to the west. These units are described in more detail in Section 5.5.4

6.4.7.2 Outstanding Aspects or Features

The lake system supports a range of habitats including salt pans, mangrove stands, saltbush and samphire plains, and is a major migration stopover and drought refugia for shorebirds. These wetland habitats and the dependent biota are described more fully in the Draft Nomination for the Ningaloo - Cape Range World Heritage Property (GoWA in prep).

Apart from the biological aspects, the outstanding feature of this lake is its principal recharge mechanism. Hydrological recharge involves the lateral movement of seawater from the coast to the lake, through highly permeable, karst limestone aquifers over a distance of up to 20 km. The difference in water level between the ocean and basin generates hydrostatic pressure, forcing seawater inland to the lake, ultimately discharging as springs and maintaining several permanent pools and brine sheets. The hydrologic environment has been comprehensively studied by researchers from The University of Western Australia [see Shepherd (1990) and references therein]. This remarkable hydrogeological recharge mechanism is largely intact and is one of only six locations globally, several of which are degraded.

There is also episodic freshwater recharge via surficial drainages, only becoming volumetrically significant following heavy rainfall events in the catchment. Nevertheless, this recharge may be very significant in maintaining an anchialine habitat for cavernicolous biota in the peripheral Miocene limestone aquifers. This aspect is also yet to be comprehensively studied.

6.4.7.3 Aesthetic, Scientific and Conservation Values

<u>The overall aesthetic or natural beauty value of Lake MacLeod is considered to be moderate.</u> Assessing the aesthetic or natural beauty of Lake MacLeod is difficult. Although it is a landscape feature of considerable extent, comprised of a range of landforms and habitats, comparable in natural beauty with other major salt lakes of the World such as Lake Disappointment, Western Australia, Lake Eyre (North and South), South Australia and the Great Salt Lake, Utah, it is less scenically striking than many other, albeit freshwater, lakes of the World. If compared only with other salt lakes, then its value would be 'high'.

<u>The scientific value of Lake MacLeod is considered to be high.</u> The Lake MacLeod hydrological seawater recharge system is outstanding and highly unusual, and in excellent functional condition. Interaction of freshwater recharge in the anchialine zone and its importance in habitat and species maintenance is also under studied. Further scientific investigations here and in the related Cape Range karst system, are likely to reveal even more

ecologically significant abiotic and biotic relationships in these remarkable surface and subterranean ecosystems.

The conservation value of Lake MacLeod is considered to be very high. Clearly, in order for future scientific studies to be undertaken, the geomorphic, habitat and biological components need to be conserved. However, the principal reason for a 'very high' value is that Lake MacLeod is critically important for life-cycle maintenance of several water and wading birds which breed here, and as a stop-over location for migratory shorebirds; these aspects are comprehensively covered in the Draft Nomination for the Ningaloo - Cape Range World Heritage Property (GoWA in prep).

7 Synthesis & Conclusions

Clearly, the Ningaloo – Cape Range – Exmouth Gulf area has diverse and remarkable natural environments. Even with the limited biological studies of the area, the rich cavernicolous fauna of the limestone karst system is widely recognised. This fauna, which has probably been better studied than the surface invertebrate fauna and possibly even the flora, contains a high proportion of endemic genera and species, extensive adaptation to subterranean conditions, and markedly disjunct elements, either from their usual habits or only known from other continents. Explanation of these biogeographic aspects and patterns is incomplete but is closely related to the geological evolution of the area.

This report describes the geological evolution and geomorphic features of the area, in order to provide context for its biological evolution (addressed elsewhere) as part of its nomination for inclusion on the World Heritage List for its natural features. A discussion of aspects of geological heritage is given in Section 6.2 and specific criteria for assessing the outstanding universal value, including the important attribute of completeness or integrity, are provided in Section 6.3. For each the three components of the World Heritage Outstanding Universal Value (OUV), namely aesthetic or natural beauty, scientific and conservation values, a five tier rating system is used, ranging from very low to very high value. The assessment is at international or global level, rather than the lower national, regional or local levels.

Whilst the area is subject to claims on its natural resources, principally high-grade limestone, hydrocarbons, water, native forage, scenery and wilderness, this synthesis of geological and related knowledge is done objectively, without favour or prejudice to the various resource-use proponents. If nomination succeeds, it is an essential requirement that a management plan be developed for the property in order to meet a number of primary management objectives including but not limited to the protection, conservation and presentation of the World Heritage values, however the effect of meeting this and the other objectives on individual stakeholders and enterprises is not considered here.

The tectonic and sedimentary processes, and the landscape and biological evolution of the Ningaloo – Cape Range – Exmouth Gulf area are very closely related to the break-up of the Gondwanan supercontinent. This process commenced well to the northwest on the Argo Abyssal Plain at about mid-to late-Jurassic time, then progressively 'unzipped' our continent in an anticlockwise direction. For the Ningaloo – Cape Range – Exmouth Gulf area, the onset of rifting and generation of new seafloor on the Gascoyne and Cuvier Abyssal Plains occurred at the start of the Cretaceous Period (141 Ma). The Carnarvon Basin, which had formed much earlier as an intracratonic basin in response to failed rifting events, became much more active. With the progressive separation of Greater India from Australia, mostly marine sedimentation occurred in various subsiding continental-margin basins, including the Exmouth and Gascoyne Sub-basins. These sub-basins contain the rocks now exposed in the Ningaloo – Cape Range – Exmouth Gulf area. Climatic and depositional conditions changed at mid-Cretaceous time, resulting in the deposition of mainly pelagic biogenic carbonates, part of which are now exposed as the characteristic limestone karst in the ranges of the area. The main post-Jurassic sedimentary units are (in stratigraphic younging order): the Early Cretaceous Winning Group, mainly comprised of clastic sediments, then the conformably overlying Late Cretaceous carbonate units Toolonga Calcilutite, Miria Marl, followed by the Palaeogene Cardabia and Giralia Calcarenites, and finally the Neogene Cape Range Group.

The ranges, of which Cape Range is the largest, were formed through tectonic compression in the Late Miocene or early Pliocene, in response to initial collision between the Australian and Asian plates along the Banda Arc – Java Trench in the Indonesian archipelago. Following this uplift and later sea level fall, the area has been subject to various coastal marine and terrestrial geomorphic processes. These processes continue, and are essential for the maintenance of habitats and the various life forms they contain.

One of the most striking geomorphic processes has been the development of the karst system. Comprising Cape Range, the fringing Ningaloo Reef and coastal plains, it is a complex hydrogeological system, with an 'island-type' aquifer regime, which supports a distinctive cavernicolous biota. Geomorphically, it is an outstanding example of karstification initiated during a wet climatic phase but mostly developed under severe arid glacial or periglacial conditions, and now providing refugia habitats under present-day warm, dry conditions. This landform has high natural beauty values, very high scientific values and very high conservation values.

Although hosting the karst system, the anticlinal ranges are also considered as geological and landscape features in their own right. The ranges are dominated by the Cape and Giralia Ranges, but also include Rough Range and several other low ranges to the south in the Lake MacLeod area. Geologically, they are outstanding examples of an unusual, well preserved tectonic style, involving transfer and tear faults, arising from a major shift in orientation and location of spreading centres from the Argo Abyssal Plain to the Cuvier – Gascoyne Abyssal Plains. Typified by Cape Range, the atypical fault geometry maximised the uplift effect arising from the early Pliocene or Late Miocene compression, and co-beneficially, demonstrates very well, the tectonic transition from a passive divergent margin (the separation of Greater from Australia) to an active convergent continental margin (Australian – Asian Plates collision). Accordingly, the scientific values for geological research, educational and reference purposes are very high, as are the conservation values. When considered alone and simply as landscape features, the natural beauty values are low. Cape Range in particular does contribute to the high aesthetic values of the whole area, mainly as an elevated 'platform' from which to view the wonderful land and seascape panoramas.

On the western flank of Cape Range four principal wave-cut terraces are particularly well preserved. These geomorphic features developed as sea levels fell, reflecting highstand strandlines. Although incompletely studied, they constitute key pieces of evidence of local and regional Pleistocene sea levels. Also important in Pleistocene studies are the dune deserts. Like the terraces, these sediments are incompletely studied but are providing valuable palaeoclimatic information for the Late Pleistocene Epoch. Overall however, the global scientific significance of the terraces and desert sediments is probably limited and accordingly, the World Heritage scientific values are moderate; if however, any of the three presently undated terraces prove to be older than 400 Ka, then the Global scientific value would be increased considerably. The natural beauty values for both geomorphic features are low, but the conservation values are high, consistent with the very high conservation values of the Cape Range karst system and the anticlinal ranges.

Cainozoic and Cretaceous sediments and fossils, very well exposed in the Giralia Range and elsewhere, are of great scientific importance. The Cretaceous section of the geological record is providing evidence of very widespread marine transgressions at this time and, more importantly, very detailed evidence of extinction events caused by oceanic anoxic events.

Importantly, recognition of these anoxic events is not possible in the deposits of the interior seas because of their normal condition of anoxic bottom waters. However, in the marginal seas where anoxic conditions were not the norm, these extinction-inducing events can be recognised, as recent work in the Giralia Range at C-Y Creek shows. Here, the principal event occurred at the Cenomanian – Turonian boundary, dated at 93.5 Ma, just before maximum sea level (250 m above present level) at 92 Ma. This Cretaceous marine inundation was the highest of the entire Phanerozoic Eon and occurred at an important time in our geological evolution when the Australian continent was being shaped as a separate entity as the Indian and Southern Oceans progressively opened.

During this time and into the Cainozoic, biological evolution responded to substantial gradients in climatic parameters, including stronger seasonality and changed ocean temperatures, created principally by the re-arrangement of continental masses as Gondwana broke up. This response is reflected in multiple wide-scale extinction and speciation events, changing from strongly pandemic generic affinities to increasingly endemic patterns. The very rich vertebrate and invertebrate fossil fauna of the Giralia Range area is providing key information to the global understanding of this biological transition. The Giralia Range location is the only significant Cretaceous – Cainozoic (Tertiary) (K-T) boundary sequence in Australia. Accordingly, the scientific values are very high, the conservations values high and the aesthetic values very low.

In the south of the proposed nomination area lies the renowned salt lake, Lake MacLeod. It is a 'window' into a substantial and remarkable saline hydrogeological system, supporting an important and complex ecosystem. It has high World Heritage scientific values, very high conservation values and moderate natural beauty values. Although located up to 20 km inland, recharge is predominantly from the sea, via highly permeable subsurface limestone aquifers, in response to tidal 'pumping'. This very unusual recharge mechanism has engendered several saline habitats, notably including mangrove stands, samphire and saltbush flats. Importantly, it also provides an essential stopover location for large numbers of migratory shore birds. Lake MacLeod is an outstanding natural heritage feature of national and international importance.

In conclusion, the Lake MacLeod - Ningaloo – Cape Range – Exmouth Gulf area is gaining national and international recognition as a place of considerable importance. It contributes an abundance of outstanding natural heritage features, each with multiple intrinsic values (Table 3). Importantly, together, the geological and geomorphic features, as outlined above and in more detail elsewhere in this report, and the biological features described in the Draft Nomination for the Ningaloo - Cape Range World Heritage Property (GoWA in prep) present an intriguing story of geological and biological co-evolution and interaction. These features are very well preserved and accessible here. This area is pivotal to the complex story of Gondwanan fragmentation, both in the tectonic sense of transposed and rotated oceanic spreading centres, and in the biological sense of the change from pandemism to endemism.

An indicative boundary for an area that could be nominated under natural heritage criterion (i) is shown on the map in Figure 17. This boundary is drawn to include the suite of features which, together, provide the evidence of the geoevolutionary history of the western margin of the Australian plate. The boundary is also designed to satisfy requirements for conditions of integrity for this World Heritage criterion as defined in the Operational Guidelines (WHC 2002).

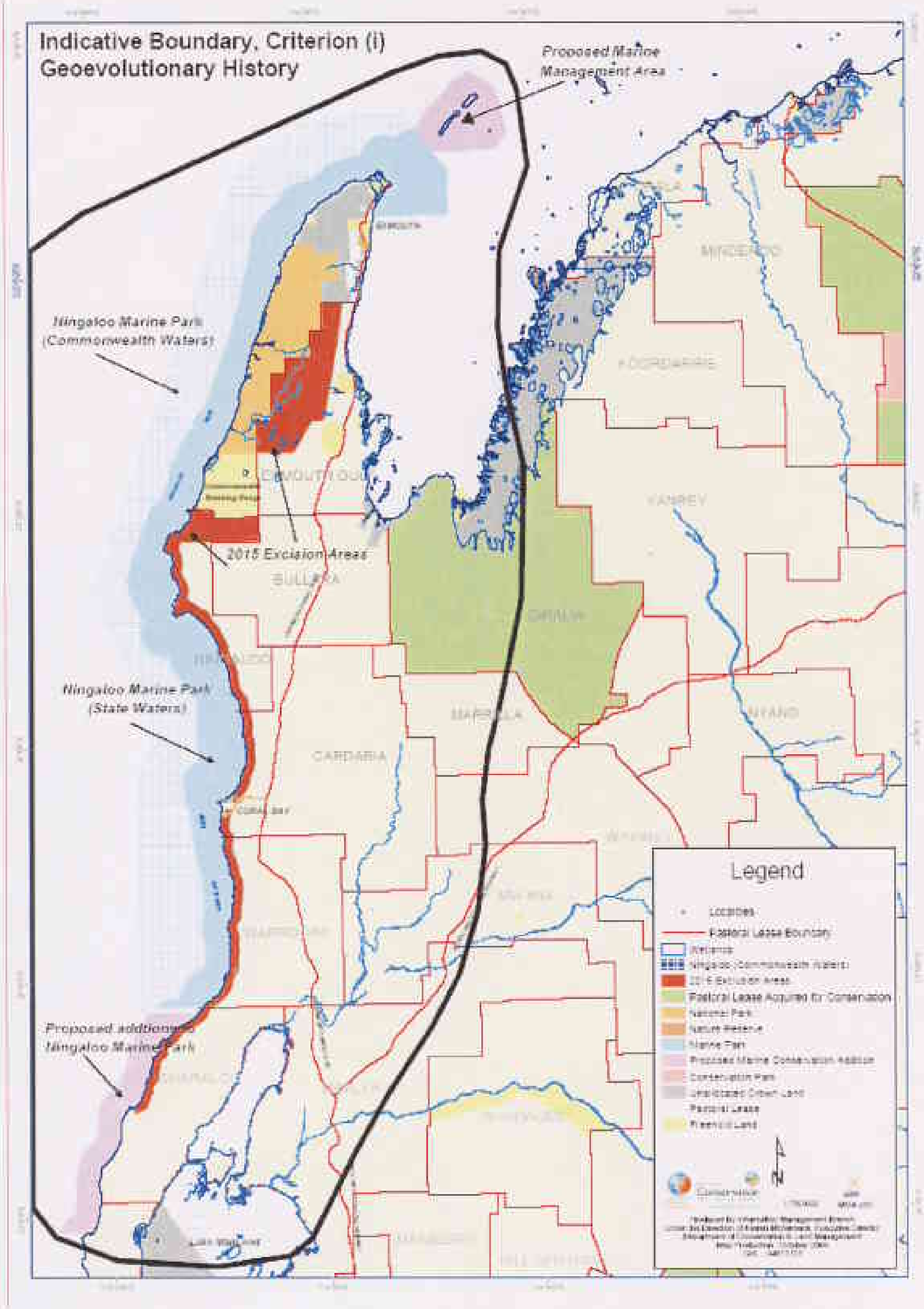


Figure 17. Indicative boundary for a World Heritage nomination under natural heritage criterion (i), geoevolutionary history.

Clearly, biological evolution cannot be 'divorced' from the geological 'substrate' on which it is fundamentally dependent. Here, one is able to retrace the history of evolution from entirely marine-based life to mixed marine and terrestrial life. Emergence of the Ningaloo – Cape Range – Exmouth Gulf area reflects sea level changes resulting from the interaction between tectonics and climate. Compressed into the geological record is evidence of continental rifting, new oceanic crust and new oceanic currents, melting and freezing of polar icecaps, uplift of new continental margin and changed sediment depositional regimes. The high concentration of diverse landforms and life forms here has arisen from the tight juxtaposition of a number of globally and locally significant events through a relatively short (150 Ma) geological period. We must be very careful to not destroy this great natural richness and, applying the words of Ian McHarg (1996 p. 103) to this area, (originally applied to Straten Island, New York) "it is a [very] special place - its geological history has made it so".

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