Commonwealth of Australia

K-H. Wyrwoll M.Sc., PH.D., Department of Geography, University of Western Australia
and
J. E. Glover, B.Sc., Ph.D., Department of Geology, University of Western Australia

PHYSICAL FEATURES AND GEOLOGY

The Geological and Geomorphological Framework of Western Australia

Reprinted with original page numbers from the Western Australian Year Book, 1989, No. 26 35/48. Issued November 1989

Chapter 2

PHYSICAL FEATURES AND GEOLOGY

The Geological and Geomorphological Framework of Western Australia

Contributed by K–H. Wyrwoll M.Sc., PH.D., Department of Geography, University of Western Australia
and
J.E. Glover, B.Sc., Ph.D., Department of Geology, University of Western Australia

Interest in the geology of Western Australia was spurred with the beginning of the mining industry in 1850 and has continued to the present. By 1986, when mining products were valued at over $5,400 million for the year, the entire State had been mapped on a scale of 1:250,000 by the Geological Survey of Western Australia. This remarkable organisational achievement has provided a position to view the geological evolution of the western third of the continent in a global context. Furthermore, some 75 years after the pioneering work of J.T. Jutson, we now have the framework to develop the link between solid geology and *geomorphology*, and between geological evolution and *morphotectonics*.

The morphotectonic and geomorphological emphasis of this article differs from the more economic approach of previous Year Books. Readers requiring an introduction to the economic geology and mineral statistics of Western Australia can enter the literature through Collins and Baxter (1984), Ho and Groves (1987) and Jaques et al. (1986). Significant information is found in the issues of Australian Petroleum Exploration Association Journal (APEAJ) and the bulletins and other publications of the Geological Survey of Western Australia. The most comprehensive outline of the geology of the State is to be found in Memoir 2 of the Geological Survey, which is shortly to be succeeded by Memoir 3.

The geology and geomorphology is considered at two levels: (i) the scale of the continent; and (ii) the scale of individual geomorphological regions. Because large parts of Western Australia have undergone relatively uninterrupted subaerial weathering for so long, many aspects of their geomorphology are closely related to the solid geology. But, in addition, the depositional geomorphological sequences which, in Western Australia, were essentially controlled by global and regional climatic changes during the Cenozoic, also need to be considered. These sequences include the extensive areas of desert dunes, such as in the great Sandy Desert, widespread river deposition and floodplain formation, such as along the Gascoyne and Fitzroy rivers, and Quaternary coastal deposits which dominate the geomorphology of the Swan Coastal Plain.

THE MAJOR GEOLOGICAL AND GEOMORPHOLOGICAL REGIONS OF WESTERN AUSTRALIA

The major geological and geomorphological regions of Western Australia are shown in Diagrams 2.1 and 2.2 and described in Tables 2.2 and 2.3. The geomorphology is essentially shown as 'landform regions', that commonly show some correspondence to the geological divisions. The general correspondence between geomorphology and solid geology is emphasised by the older elements of the geology of Western Australia, which are the main geographical components of the broad–scale geomorphology of the region. In this approach there is a danger of over–simplification, but it forms a convenient basis from which to discuss the geomorphology and geology of Western Australia.

For the general reader, a glossary of geological terms is provided at the end of the chapter, and a geological time–scale is given in Table 2.1. Words or phrases included in the glossary are italicised when first mentioned in the text.

TABLE 2.1 – GEOLOGICAL TIME SCALE

Era	*Period*		*Epoch*	*Duration (years)*	*Years before present*
	Quaternary		Holocene (Recent)	10,000	10,000
			Pleistocene	1.5–1.8 million	1.5–1.8 m
		Neogene	Pliocene	3–5 million	5–7 m
Cenozoic			Miocene	19 million	26 m
	Tertiary		Oligocene	11–12 million	
		Palaeogene	Eocene	16 million	
			Paleocene	10 million	64–65 m
		Senonian	Maastrichtian Campanian Santonian Coniacian	35 million	
	Cretaceous	Late	Turonian Cenomanian		100 m
Mesozoic		Early	Albian Aptian Barremian Neocomian	36 million	136 m
	Jurassic			54–59 million	190–195 m
	Triassic			33 million	225 m
	Permian			55 million	280 m
	Carboniferous			65 million	345 m
Palacozoic	Devonian			50 million	395 m
	Silurian			35–45 million	430–440 m
	Ordovician			60–70 million	500 m
	Cambrian			70 million	570 m
Precambrian Eras	Adelaidean			230–530 million	800–1,100 m
Proterozoic	Undifferentiated			250–550 million	1,350 m
	Carpentarian			450 million	1,800 m
	Early			700 million	2,500 m
Archaean				2,100 million	4,600 m

TABLE 2.2 — GENERAL MORPHOTECTONIC - GEOLOGICAL DIVISIONS OF WESTERN AUSTRALIA
(To be used in conjunction with diagram 2.1)

Area	*Division*	*Subdivision*	*Diagram reference*
Western Shield	Yilgarn Block	Eastern Goldfields Province	1
		Southern Cross Province	2
		Murchison Province	3
		Western Gneiss Terrain	4
		Proterozoic rocks on or adjoining the Yilgarn Block	4 A–H
	Pilbara Block	Not subdivided	5
	Archaean inliers between the Yilgarn and Pilbara Blocks	Not subdivided	6
	Main areas of Proterozoic metamorphic and igneous rocks	Albany-Fraser Province	7
		Leeuwin Block	8
		Northampton Block	9
		Gascoyne Province	10
		Paterson Province	11
	Main areas of Proterozoic sedimentary rocks	Hamersley Basin	12
		Ashburton Trough	13
		Bangemall Basin	14A
		Nabberu Basin	14B
Remaining Precambrian areas	Kimberley region	Kimberley Basin	15
		Halls Creek Province	16
	Musgrave Block	Not subdivided	17
	Areas between region and the Kimberley Musgrave Block	Areas of Proterozoic metamorphic and igneous rocks	18 A–D
		Proterozoic basins	19 A–C
Phanerozoic areas	Sedimentary basins indicated on Diagram 2.1		

DIAGRAM 2.1

Modified National Oceanic and Atmospheric Administration (NOAA) satellite image showing the general morphotectonic–geological divisions of Western Australia. The numbers refer to Table 2.2 where the subdivisions are named (modified from Geological Survey of Western Australia, Memoir 2). NOAA image courtesy of Remote Sensing Application Centre, Department of Land Administration.

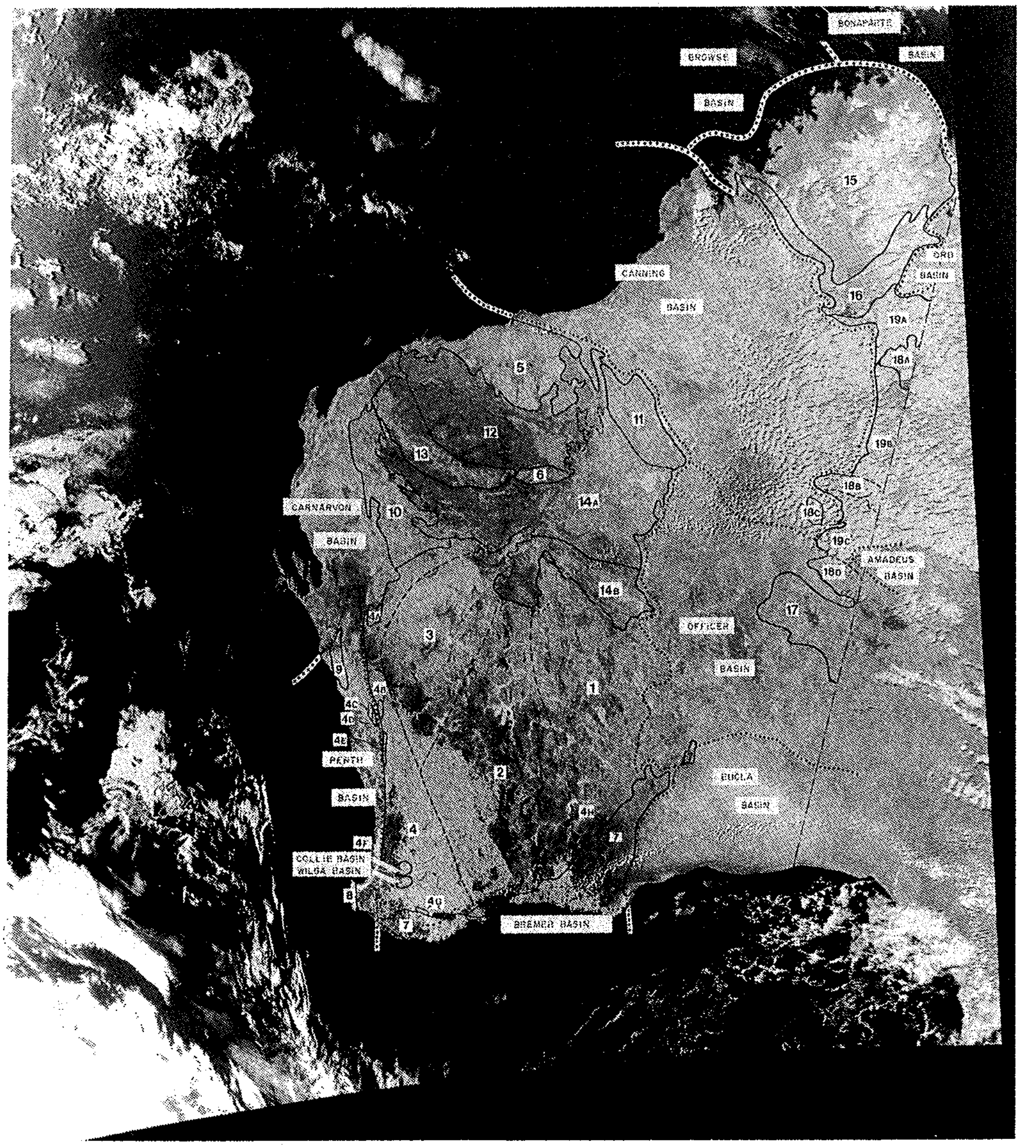


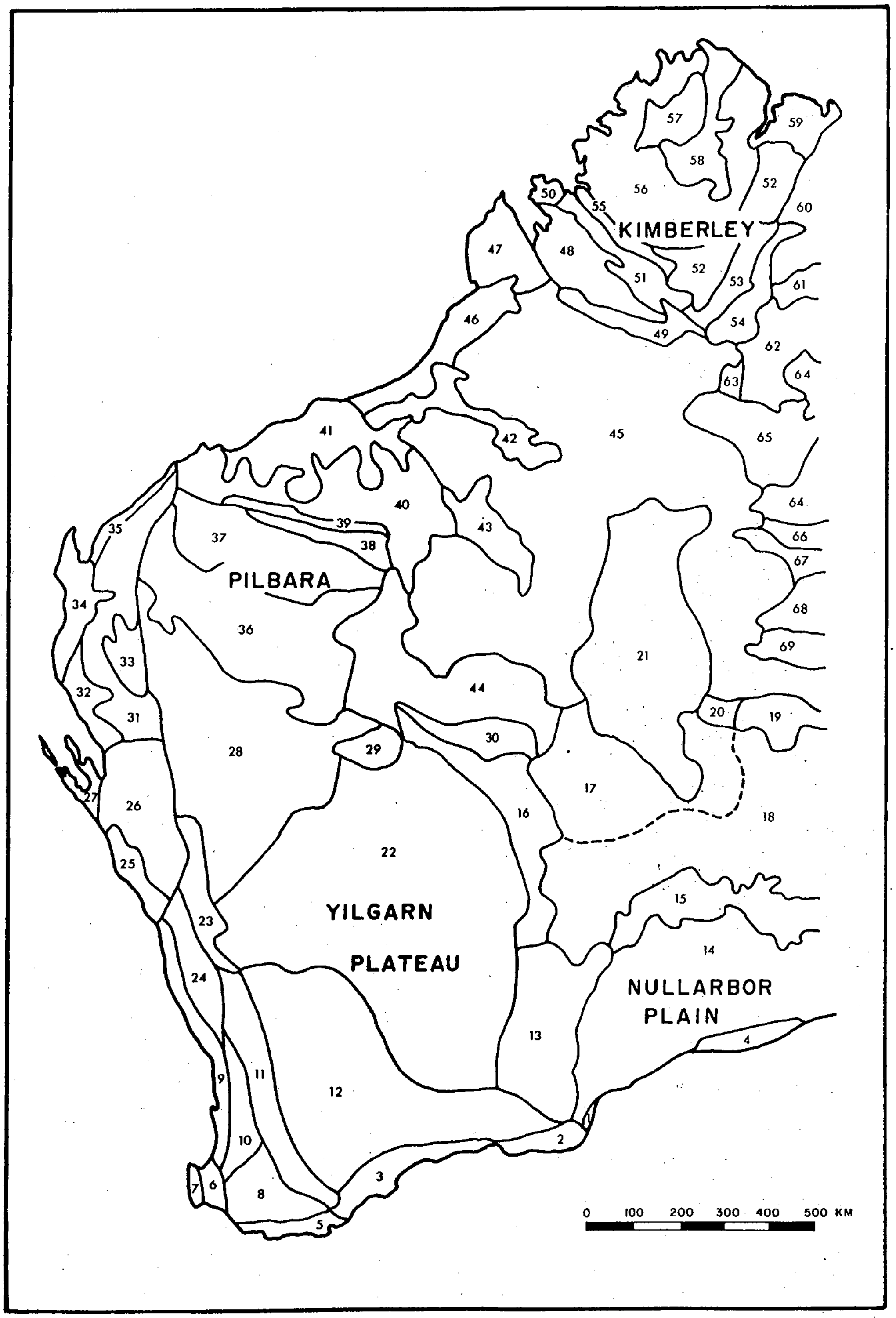
TABLE 2.3 – THE MAJOR GEOMORPHOLOGICAL DIVISIONS OF WESTERN AUSTRALIA

Reference	*Division and Description*	*Reference*	*Division and Description*
1	Israelite Plain— Narrow coastal plain with extensive dunes	19	Musgrave Ranges— Granitic ranges and rounded high hills
2	Esperance Hills— Low granite hills and plains extending as headlands and inlets	20	Warburton Ranges— Ranges and hills of basic volcanic rocks and granite
3	Stirling and Mt. Barren Hills— Hills and low ranges of granite and metamorphic rocks with intervening plains and moderately incised southerly valleys	21	Gibson Desert Plains— Sandy or stony lateritic plains
4	Roe Plain— Coastal plain with extensive dunes	22	Yilgarn Plateau— Sandplains and laterite breakaways; granitic and alluvial plains; ridges of metamorphic rocks and granitic hills and rises; calcretes, large salt lakes and dunes along valleys
5	Albany Headlands and Inlets— Granitic headlands and inlets with lagoons	23	Woodramung Hills— Low rounded ridges of folded metamorphics
6	Donnybrook Lowland— Lowland on down-faulted weak sedimentary rocks	24	Dandaragan Tablelands— Dissected plateaus and hills of sedimentary rocks, with minor laterite cappings and dry valleys; extensive sand cover in lower parts
7	Leeuwin Peninsula— Narrow granitic horst ridge with extensive cover of calcareous dune sands	25	Greenough Hills— Dissected plateaus and hills of sandstone and shale, with extensive sand cover in lower parts
8	Collie–Kalgan Slopes— Gently sloping dissected edge of plateau on granite and gneiss with laterite cappings	26	Yaringa Sandplain— Sandplain with minor dunes
9	Swan Plain— Dune ridges, mainly of limestone, and inner alluvial plain	27	Shark Bay Peninsulas— Peninsulas and islands formed by indurated limestone dunes
10	Darling Range— High plateau rim with steep western fall; remnant laterite cappings and deeply incised valleys of oceanward drainage	28	Murchison Plateau— Mainly granitic plains with out-going drainage, broken by ridges of metamorphic rocks
11	Northam Plateau— Flat-floored valleys of moderately incised oceanward drainage; older laterite remnants with breakaways on divides in east; shallow younger laterites on valley sides in west	29	Glengarry Hills— Sandstone plateau sloping north to low hills of basic volcanic rocks
12	Narrogin–Ongerup Plateau— Sandplains and laterite cappings with breakaways on divides; stripped granitic plains on valley sides; small salt lakes and bordering dunes along shallow valley floors	30	Carnegie Hills— Sandstone tablelands, stony limestone plains, salt lakes and adjacent dunes
13	Coonana–Ragged Plateau— Sandplain and stripped gneissic plains with low hills of granite and metamorphic rocks; calcretes and scattered small salt lakes along shallow valleys	31	Carnarvon Dunefield— South–north longitudinal dunes
14	Bunda Plateau— Covered karst plain of flat-lying limestone with closed depressions and caves; continuous cliff margin on south coast	32	Carnarvon Plain— Alluvial plain
15	Carlisle Plain— Sandstone plain with shallow closed depressions	33	Kennedy Range— Dissected sandstone plateau with partial lateritic cappings, covered by longitudinal dunes
16	Leemans Sand Plain— Sand plain with small salt lakes	34	North West Cape Ridges— Ranges and peninsula formed by folded sedimentary rocks and limestone dunes
17	Great Victoria Desert Dune Field— Northwest Dunes and Hills – west–east longitudinal dunes broken by low tablelands and ridges	35	Onslow Plain— Alluvial, deltaic and littoral plains; minor islands
18	Great Victoria Desert Dune Field— Main Dunefield – west–east longitudinal dunes	36	Augustus Ranges— Parallel ranges and dissected plateaus with intervening sandy lowlands
		37	Hamersley Plateaus— Dissected bold plateaus and ranges in flat lying or moderately folded sedimentary rocks
		38	Fortescue Valley— Mainly alluvial lowland

TABLE 2.3 – THE MAJOR GEOMORPHOLOGICAL DIVISIONS OF WESTERN AUSTRALIA

Reference	*Division and Description*
39	Chichester Range— Narrow range of dipping quartzite and sandstone
40	Nullagine Hills— Dissected flat-topped hills of granites and metamorphic rocks with partial lateritic cappings; narrow estuarine plain and islands
41	De Grey Lowlands— Floodplains and deltaic plains; granitic and limestone lowlands; scattered ranges of metamorphic rocks in north
42	Anketell Hills— Low mesas, buttes and stony rises of lateritized sandstone and shale among east–west longitudinal dunes and sandy plains
43	Rudall Tablelands— Dissected low sandstone tablelands
44	Stanley Hills and Dunes— Isolated sandstone ridges among west–east longitudinal dunes and sandplain
45	Great Sandy Desert Dunefield— East–west longitudinal dunes and minor salt lakes
46	Eighty Mile Plain— Coastal dunes and estuarine plain
47	Dampier Tablelands— Low sandstone tablelands, partially lateritized and with extensive sandplain cover
48	Fitzroy Plains— Floodplains and broad estuarine plains
49	Fitzroy Ranges— Scattered sandstone tablelands and ranges; extensive sandplain and east–west longitudinal dunes
50	Yampi Peninsula— Parallel ridges of quartzite and sandstone and narrow valleys of basalt; extending as a ria coast and islands
51	Napier Limestone Ranges— Limestone tableland and intricately dissected bevelled ridges; rocky karst surfaces with box valleys
52	Leopold–Durack Ranges— Prominent ranges of dipping quartzites rimming the main plateau
53	Springvale Foothills— Granite hills and minor undulating plains
54	Halls Creek Ridges— Ranges and rounded hills on granite and metamorphic rocks
55	Richenda Foothills— Rounded hills and ridges and lowlands on a belt of granite and folded metamorphic rocks with minor basalt
56	Kimberley Plateau— Sandstone plateaus with tabular high summits; ria coast and islands to north–west
57	Couchman Uplands— Undulating to hilly lower plateaus, mainly on basalt
58	Drysdale Lowlands— Undulating to hilly lowlands, mainly on basalt
59	Bonaparte–Diemen Lowlands— Dissected lateritic lowlands and minor islands; part alluvial, part estuarine coastal plains
60	Ord–Victoria Plateaus— Dissected plateaus, mainly basaltic but partly of sandstone and with local lateritic cappings
61	Birrundudu Plain— Low basaltic plain with clay soils; indeterminate drainage with large claypans
62	Tanami Sandplain and Ranges— Sandplain with scattered low ranges and tablelands and occasional granitic hills
63	Sturt Creek Floodout— Floodout with distributary channels and claypans
64	Wiso Sandplain— Sandplain with minor longitudinal dunes in South; floodplains and floodouts on margins; stony rises in North
65	Stansmore Dunefield and Ranges— East–west longitudinal dunes locally broken by narrow sandstone ranges
66	Redvers Dunefield— East–west longitudinal dunes
67	Macdonald Sandplain— Mainly sandplain with dune–fringed salt lakes
68	Amadeus Lowland— Dunefields and sandplains with scattered sandstone ranges; salt lakes and calcrete plains along lowland axis
69	Rawlinson–Petermann Ranges— Dissected sandstone ranges with prominent escarpments

DIAGRAM 2.2
The major geomorphological divisions of Western Australia. The numbers correspond to those given in Table 2.3 (after Jennings, J.N. and Mabbutt, J.A., 1986: *in* Jeans, D.N., (ed), Australia – A Geography Volume One. The Natural Environment).



MORPHOTECTONIC TERRAINS AND GEOMORPHOLOGY

The Precambrian framework

The geomorphological contrast of Western Australia with other continental masses is based upon the lack of Phanerozoic *orogeny*, and particularly Late Phanerozoic orogeny. In fact, large parts of Western Australia have been relatively stable for over 1,000 million years. However, little remains of the original landsurfaces, and the regions have been so reduced in their relief as to lose much of their erosional potential.

The antiquity of the landsurface of Western Australia is exemplified by the Yilgarn Block, which with the Pilbara and Kimberley blocks formed the geological framework of Western Australia, and controlled much of the long–term geological and broad–scale geomorphological evolution of the State. The Yilgarn Block is one of the largest areas of Archaean crust in the world. The bulk of the block—the Murchison, Southern Cross and Eastern Goldfield divisions—is a *granite*–greenstone terrain, in which arcuate belts of *metamorphosed* sedimentary and volcanic rocks (greenstone belts) lie between large areas of granitoid. High–grade *gneiss* terrains bound the western margin of the block. The gneiss terrains represent metamorphosed, and partly *migmatised, metasedimentary* sequences. Dates from detrital zircons have yielded ages of up to 4,200 million years, and represent the oldest mineral ages reported for terrestrial rocks. For the rest of the Yilgarn Block a large number of dates have been obtained. *Komatiite* lava flows in the eastern part of the block have been dated at 3,200 million years ago and *felsic volcanics* at around 3,000 million yeas ago. Recent rubidium–strontium dating for the Murchison gave ages of about 2,500 million years for a granite intruded by *porphyritic–biotite adamellite*.

The geomorphology of the Yilgarn Block is essentially one of an erosional plain, in which lithological differences and major *tectonic* lineaments are accentuated in their erosional expression. Not surprisingly, the resistant banded iron formations often form prominent ridges. Similarly, large granite domes are prominent features in the western areas of the Yilgarn Block. Even the larger *dykes* (e.g. the Jimberlana Dyke, of the Norseman region) have a clear topographic expression. Other regional–scale lithological differences are also well marked topographically, for example, the paired metamorphic belts of the Perth–Northam area, which are related to the Northam Plateau.

The western margin of the Yilgarn Block is demarcated by the Darling Fault, which has existed since the Late Proterozoic or Early Palaeozoic. It probably originated as a *transcurrent* fault, but later functioned as a normal fault with a maximum throw of about 15,000 metres. In the Donnybrook area, the Donnybrook Sandstone and Maxicar Beds abut against the Darling Scarp and extend into valleys incised into the scarp. These sediments are of Neocomian age, and are believed to have been deposited at about the time of the last major movement along the Darling Scarp. As a morphotectonic structure, bounding a continental margin, the Darling Scarp (Diagram 2.3) forms one of the 'Great Escarpments' of the world.

Unlike the Yilgarn Block, the Kimberley Block is largely covered by the later Proterozoic sediments and volcanic rocks which form the Kimberley Basin, and consequently little is known of its geology. It is known however, that the block has remained stable for 2,100 million years. The geomorphology of the Kimberleys is dominated by a series of plateaus on which major structural lineaments have strongly controlled drainage net evolution. Surficial depositional elements are generally suppressed, but important Cenozoic *alluvial* sequences are found, some of which contain diamonds.

The Pilbara Block consists of large granitoid *batholiths*, some 3,000 to 3,500 million years old, associated with older greenstone belts and younger granites and adamellites, dated at around 2,800 million years ago. The southern part of the Pilbara Block is overlain by the Fortescue Group of the Hamersley Basin (see below) which is dated at 2,700 million years ago, suggesting that major stabilisation had by then taken place. The geomorphology of the block is characterised by erosional plains, in which lithological variations are clearly expressed. The corestone plains and granite domes reflect the large batholiths.

The Proterozoic saw the development of a number of block–marginal *mobile belts* and the formation of *sedimentary basins* which led to the deposition of an intracratonic platform cover. The main stratigraphic divisions of the Hamersley Basin, which is the oldest, are:

1. The basal Fortescue Group (mentioned above), which consists largely of volcanics—flood *basalts, andesites* and *tuffs*—and subordinate sedimentary clastics;

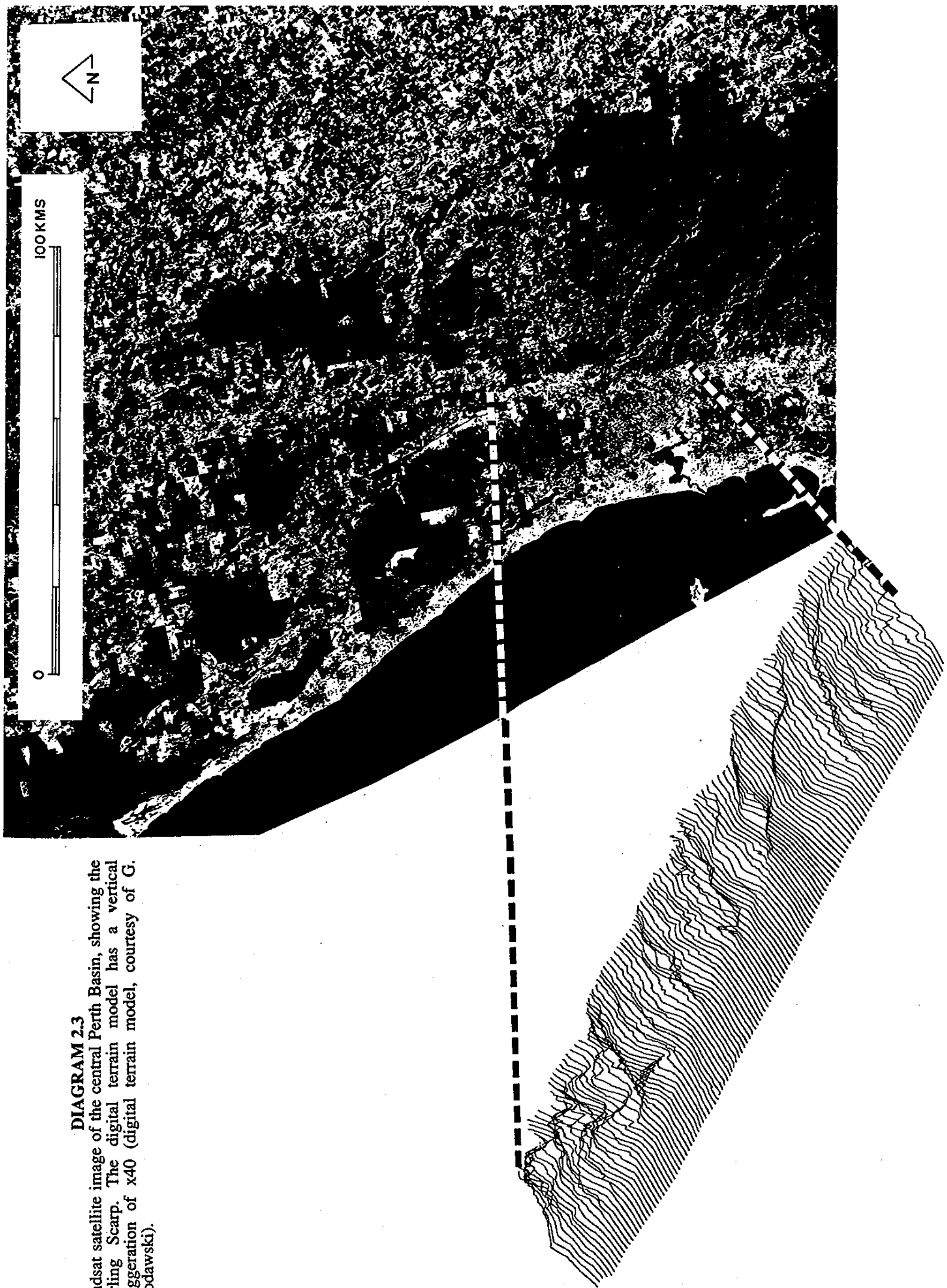


DIAGRAM 2.3
Landsat satellite image of the central Perth Basin, showing the Darling Scarp. The digital terrain model has a vertical exaggeration of x40 (digital terrain model, courtesy of G. Mlodawski).

DIAGRAM 2.4

Landsat satellite image showing the contrast in the geomorphological expression of the Pilbara Block (the northern part of the scene) and the Hamersley Basin (the southern part of the scene).

2. The Hamersley Group which contains the classic banded iron formation, shales and dolomites, extensive dolerite *sills* and large volumes of acid volcanics;

3. The Turee Creek Group, the upper part of which is dominated by a series of sedimentary clastics, including *diamictites*, carbonates and subordinate dolerites and volcanics.

The deposition of the basin infill straddles the Archaean/Proterozoic boundary (2,500 million years ago). The Hamersley Basin itself was probably *cratonised* by around 2,000 million years ago.

The geomorphological continuity of the Hamersley Basin is interrupted by the Fortescue Valley (a possible *graben*), in which alluvial deposition has taken place. Large alluvial fans debouch out of the bounding escarpments into the valley. To the north of the Fortescue River, the Chichester Range is the geomorphological expression of the Fortescue Group. To the south, the Hamersley Group forms a strongly defined, dissected plateau, on which structural and lithological controls have developed a distinctive terrain (Diagram 2.4) associated with some large landslides (Diagram 2.5).

The Gascoyne Province and Ashburton Trough are the two elements of a complex orogenic zone or mobile belt—the Capricorn Orogen—joining the Pilbara Craton to the Yilgarn Block. In the northern part, the orogen consists of folded geosynclinal sediments of the Ashburton Trough. The major structural elements are indicated by the ridge arrangement of the erosional geomorph–ology. The Ashburton Trough grades into the Gascoyne Province with increasing metamorphic grade and associated *plutonic* rocks. Overall, the formation of the Capricorn Orogen involved geosynclinal sedimentation, metamorphism, basement reworking and granitoid emplacement. The oldest dates obtained for the Gascoyne Province have been 2,000 to 2,400 million years ago. A younger set of granites have been dated at 1,600 million years ago; the orogen probably did not finally stabilise until about 1,000 million years ago.

The Nabberu Basin consists of a thick sequence of sedimentary rocks—essentially underformed clastics, iron–formation and carbonate sediments—associated with minor igneous rocks. The sequences are Proterozoic, and dates of 1,600 to 2,000 million years ago have been obtained. In the western part of the basin there was some deformation 1,700 to 1,800 million years ago, associated with the remobilisation of, and intrusions in the Gascoyne Province. The Nabberu Basin may have been an aulcogen—a continental rift which failed to develop fully—related to the *tectonics* of the Gascoyne Province.

The Bangemall Basin is a large intracratonic sedimentary basin dated at 1,100 million years ago. The succession consists of graben deposits overlain by marine *transgressive–regressive* units and stable platform deposits. The western part of the basin was influenced by tectonic activity associated with the Gascoyne Province. *Mafic* and felsic volcanic activity is evident throughout the basin, but is most pronounced in the west.

DIAGRAM 2.5

Large planar rock slides in the Hamersley Basin. The westernmost slide has a volume of just under 1 million cubic metres, and during failure attained sufficient momentum to override an opposing ridge.

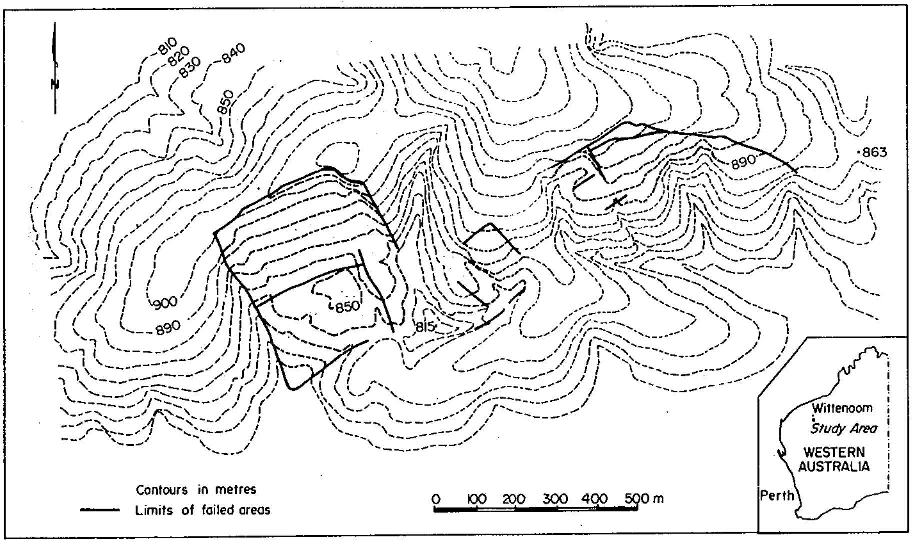
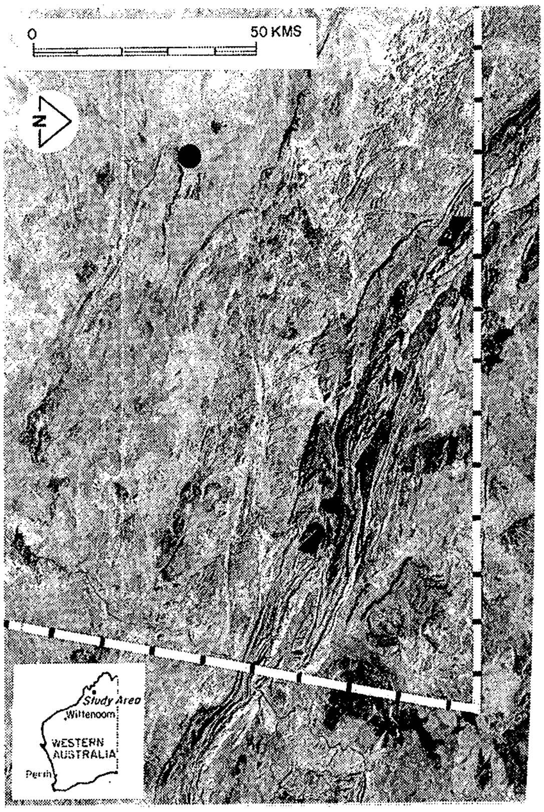
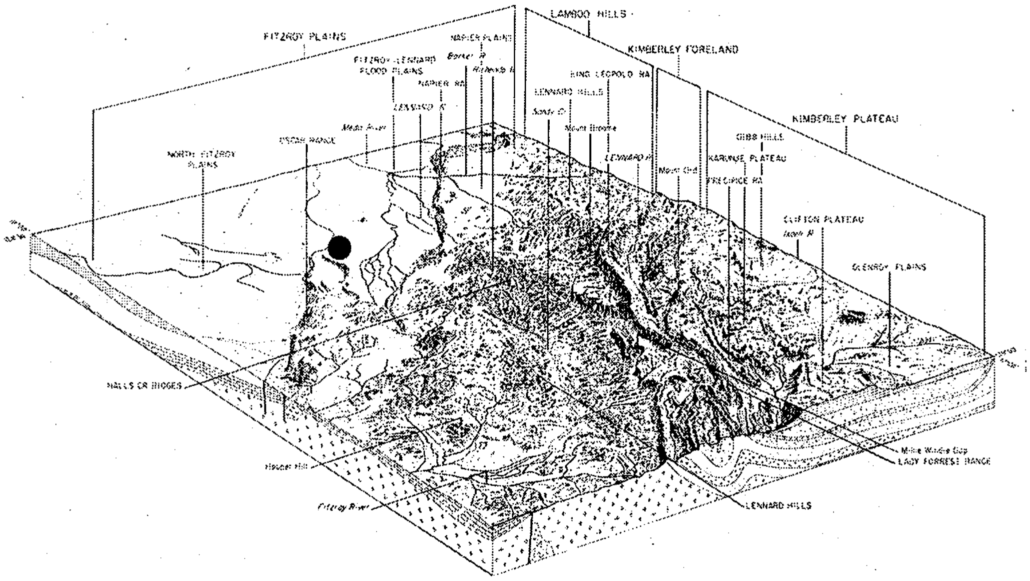


DIAGRAM 2.6

Landsat satellite image of the Lennard River area. The northwest–southeast trending ridges are Proterozoic sedimentary and associated igneous formations, which constitute part of the King Leopold Mobile Zone, which is part of the Halls Creek Province. The Devonian reef complexes which form the Napier and Oscar ranges, are also shown. The area enclosed by the broken line approximates to the area in the block diagram (from Derrick, G.M. and Playford, P.E. 1973: Lennard River, Western Australia. Geological Survey of Western Australia1:250 000 Geological Series Explanatory Notes). The 'dots' fix corresponding locations.





In both the Nabberu and Bangemall sedimentary basins, the geomorphology is closely controlled by the geology. Sand dune development is widespread. The major *playa* systems of Lakes Gregory, Nabberu, Teague, Carnegie and Wells are important depocentres in the regions; and especially Lake Carnegie, where large amounts of clastic sediments are at present being supplied to the playa. Some of these clastics result from the extensive stripping of the Permian sediments of the area which reveals older landsurfaces.

The Albany–Fraser Province is a mobile belt which delimits the southern part of the Yilgarn Block. It has been dated as being 1,200 to 2,100 million years old. Along the western margin of the Yilgarn Block the basement is generally concealed by a thick sequence of Phanerozoic sediments, and is only exposed in the Naturaliste and Northampton Blocks. Dates of 1,700 to 2,000 million years ago have been obtained for the Northampton Block and the Proterozoic basement under the Perth Basin. A granulite metamorphic event dated at 644 million years ago has been recognised in the Naturaliste Block. Little is known about the age and detailed geology of the Paterson Province, which is a Proterozoic mobile belt delimiting the eastern margins of the Pilbara Block.

The Kimberley Block and bounding Halls Creek and King Leopold mobile zones of north–western Australia are part of the wider North Australian Craton. These mobile belts have a very pronounced geomorphological expression (Diagram 2.6). The Halls Creek Mobile Zone is an Early Proterozoic geosynclinal sequence of sediments dated 2,100 million years ago, which have undergone high–grade metamorphism and are associated with dolerites, *ultrabasics* and *syntectonic* granites. This phase of tectonism spanned the interval 1,900 to 1,800 million years ago, after which the belt was cratonised. The King Leopold Mobile Belt is generally thought to correspond in both age and origin to the Halls Creek Mobile Zone. However, there is also evidence of intense folding in the King Leopold Mobile Zone around 600 million years ago.

By the end of the Precambrian the morphotectonic framework, which was to control much of the future geological evolution of Western Australia, was essentially in place (Diagram 2.7). In this framework the Yilgarn and Pilbara blocks and the associated mobile belts and sedimentary basins, are now combined and constitute the Western Australian Shield. The Shield was to remain the dominant morphotectonic element of the geology of Western Australia, and from at least the end of the Precambrian, large parts of this region were to remain as relatively stable landsurfaces.

Palaeozoic history

Present understanding of the Early Palaeozoic morphotectonic development of Western Australia is incomplete. However, it is clear that at that time Australia was part of the Gondwana supercontinent, and that during the Early Cambrian, Gondwana generally experienced continental drift and seafloor spreading. In the region which was to become the north–west margin of Australia, plates diverged, releasing extensive *tholeiitic* flood basalts. During the Cambrian, marine deposition took place in the Bonaparte Gulf and Ord basins. By Ordovician times the sea covered large parts of the Canning, Amadeus and Bonaparte Gulf basin. Marine incursions probably also affected the Browse, Ord and Officer basins but only in the Silurian did marine deposition extend as far south as the Carnarvon and northern Perth Basins. The southward migration of marine deposition with time may reflect the progressive southward opening of a divergent margin, with the development of failed arms off it.

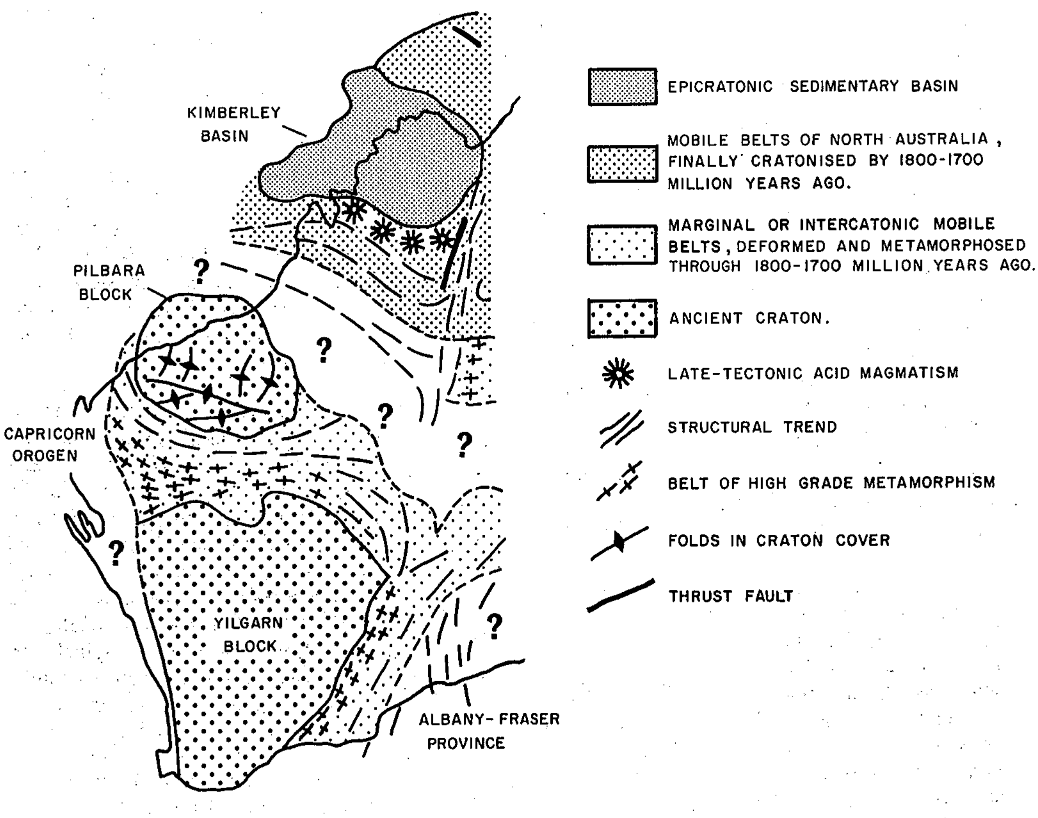
During the Middle and Late Devonian, marine conditions prevailed over much of the Canning, Carnarvon, Bonaparte Gulf and Ord basins and extensive coral reef complexes formed. In the northern Canning Basin the present Napier and Oscar ranges developed as fringing, barrier and atoll reef complexes during the Late Devonian. Today these form limestone ranges, which still reflect much of their original geomorphological expression and clearly show the original reef facies. *Karst* forms are well developed in some of the more massive limestone.

During the Early Permian, regions which were to contain the northern and western margins of Western Australia subsided, and extensive deposition occurred in the sedimentary basins. Widespread glaciation throughout much of Western Australia at this time is well documented. Glacial sediments are widely found in a stratigraphic context in the sedimentary basins, from Collie in the south to the Bonaparte Gulf in the north, but outliers of glacial deposits are also known on the Precambrian Shield, which indicate that the Early Permian ice sheet covered much of present–day Western Australia. An ice–cap covering an area of as much as 2.5 million square kilometres is possible but this is not to suggest that it was continuous. For the geomorphological development of Western Australia, Permian widespread glaciation was important. It provided a fresh start for surface denudational processes—just as the Cenozoic ice age has removed much of the weathered *mantle* that had previously covered the Canadian Shield. Similarly *isostatic* adjustments had important geomorphological repercussions. It is not, however, at all certain that any large glacial erosional forms remain in the present landscape of Western Australia.

The marine sediment sequences of the Permian were deposited in broad basins, but at the end of the Permian the depositional basins began to assume a more linear form. This change in style of the environment of deposition was associated with faulting and the development of rift valleys, so that deposition was now along axes which were to parallel the present continental margin.

DIAGRAM 2.7

The geological framework of Western Australia during the Middle Proterozoic (adapted from Clark, I.F. and Cook, B.J., 1983: Perspectives of the Earth, Australian Academy of Science).



Mesozoic: rifting and the development of the continental margins.

Along the present western margin, the Triassic saw the development of graben structures, which controlled deposition. Sedimentation began with a marine transgression, which was short lived near its southern limit but lasted longer further north. Grabens were active particularly in the Late Triassic, and accumulated over 3 kilometres of terrigenous clastic sediments in the Perth Basin, and over 4 kilometres on the central south-western part of the Exmouth Plateau.

During the Jurassic, sedimentation continued essentially uninterrupted along the western margins, but graben development was less active than in the Triassic. During the Early Jurassic, coal measures were deposited in the Perth Basin, and in the Middle Jurassic a marine transgression extended as far south as the northern part of the Perth Basin. That was when Gondwana began to break up, with a mid ocean spreading ridge entering the north-west coast of Australia. From the Late Jurassic on, most sedimentation off north-western Australia occurred in a marine environment. The Perth Basin underwent renewed graben development in the Late Jurassic, and this was the forerunner of a later episode of rifting.

During the Cretaceous the coastal margins of Western Australia began to take on much of their present form. The strong Late Jurassic graben faulting had significantly diminished by the beginning of the Neocomian. In the Early Cretaceous, tensional tectonics between Australia and Antarctica led to the formation of a large downwarp which was to become the Eucla Basin. Along the western margin, the area between the Naturaliste Plateau and the Exmouth Plateau was probably still linked to Greater India. But during the mid–Neocomian, a mid–ocean ridge developed between Australia and Greater India, accompanied by widespread uplift. At the same time India moved away from Australia and the separation has continued to the present day (Diagram 2.8). From the time of the breakup (127 million years ago) until the Early Tertiary (53 million years ago), Australia and India were separated by mid–ocean ridge spreading systems and were thus on separate *lithospheric* plates.

During the Aptian to Albian a marine transgression affected large parts of Western Australia (Diagram 2.9). Sediments of this age are widespread in the Canning, Perth, Carnarvon, Officer and Eucla basins. An interval of uplift and erosion followed in the Perth Basin. In the southern part of the Perth Basin basalts then erupted and covered extensive parts of the landscape. The development of basalt flows was linked to thermal controls on rift development in the Perth Basin at the time, as was activity along the Darling Fault.

The Late Cretaceous was again marked by a marine transgression, but the conditions controlling deposition along the western margin were quite different from those of the Early Cretaceous. Sediments deposited in the Late Cretaceous are dominated by biogenic carbonates, with only a minor influx of terrestrial clastics and generally low sedimentation rates, features which characterise the sedimentation regime of much of the western margin up to the present and reflect the negligible supply of detrital sediments from the low–relief hinterland.

DIAGRAM 2.8

Greater India and Australia at 108 million years ago (Ma). The stippled pattern between the two continents indicates the magnetic signatures. The northwest–southeast trending structure is the Argo Abyssal Plain, in which earlier sea floor spreading had taken place. The inset shows Gondwana before rifting (adapted from Veevers, J.J., (ed) 1984: Phanerozoic earth history of Australia.).

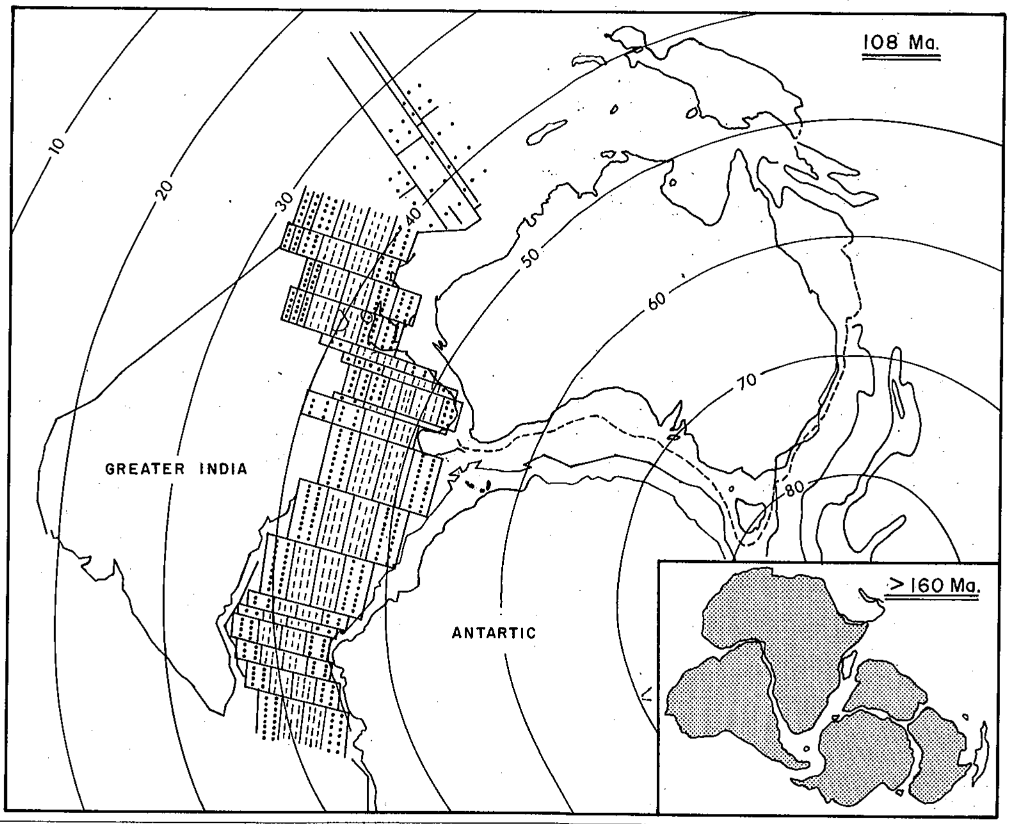
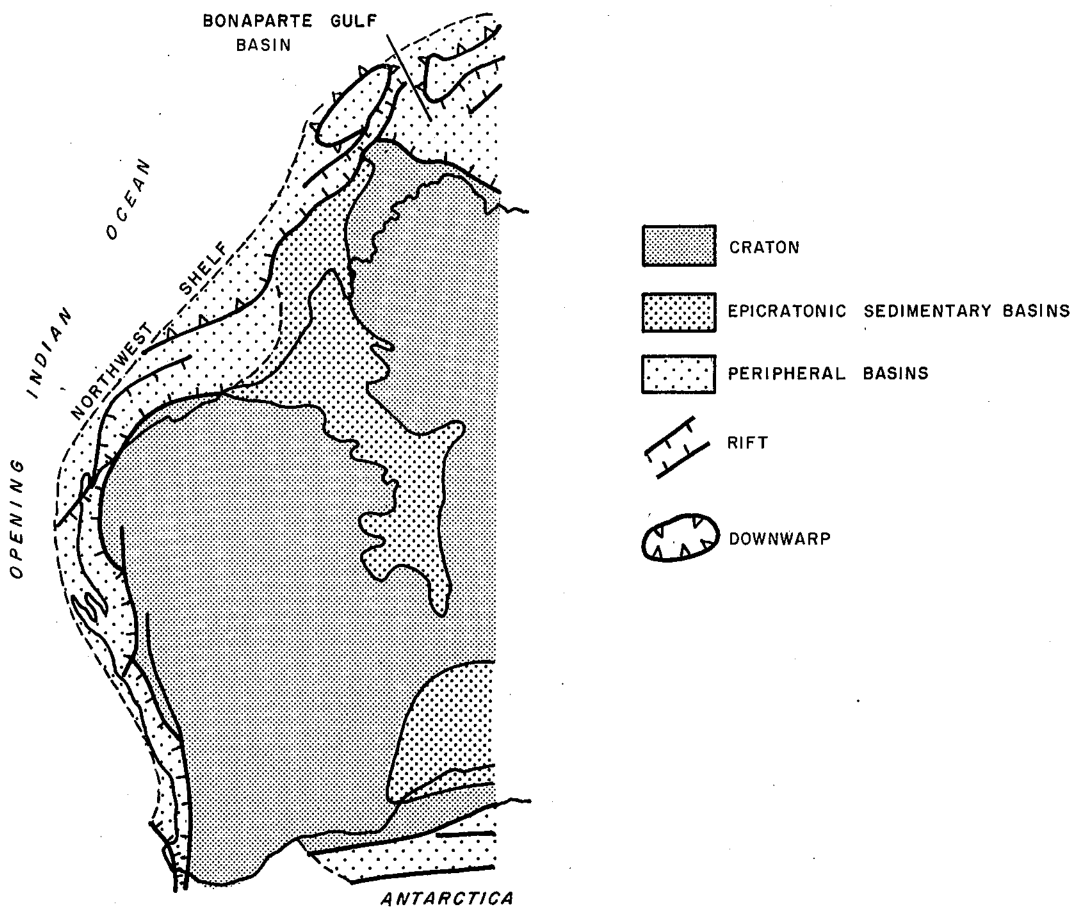


DIAGRAM 2.9
The geological/morphotectonic setting of Western Australia during the Early Cretaceous (adapted from Clark, I.F. and Cook, B.J., 1983: Perspectives of the Earth, Australian Academy of Science).



During the Late Cretaceous, the southern margin of Australia was controlled by a series of graben structures parallel to the coast. However, these were less pronounced along the southern margins of Western Australia, and here Late Cretaceous sedimentation was largely restricted to the Eucla Basin.

The relationship of deposits of Cretaceous age to the present geomorphology indicates that major elements in the landscape may be older than 100 million years. From the distribution of Late Cretaceous sediments it is clear that some of the present valleys, which cut through the scarps of the Darling and Dunsborough faults, were already in existence at that time. There is similar evidence that the lower Murchison River valley may have existed in the Cretaceous. Evidence of the upstream extension of Triassic sediments along the Greenough River valley suggests that some of the drainage in the southern Carnarvon Basin/northern Perth Basin may have existed in the Triassic. Large playa systems with complex depositional and marginal deflation features are widespread in Western Australia. They are frequently related to a network of palaeochannels which were probably active during the Late Cretaceous. From the combined evidence it is clear that major elements of the geomorphology of Western Australia are much older than generally accepted for other parts of the world. In fact, it seems that some elements of the geomorphology of the present landsurface may have survived the breakup of the Gondwana supercontinent.

Cenozoic: the development of the present landsurface

The morphotectonic framework of Western Australia was in place by the beginning of the Tertiary, but nevertheless, marine transgressions during the Paleocene, Eocene and Miocene significantly modified large areas of the western and southern margins of Western Australia (Diagram 2.10).

The Eocene saw marine transgressions extending into the western and southern coasts of Western Australia. In the middle Eocene, shallow seas penetrated into the Eucla Basin, and during the Late Eocene extended north of Norseman. The Bremer Basin, with its characteristic siltstone, *lignite* and *spongolite,* is a product of the Late Eocene transgression. These sediments were deposited over an irregular landsurface of Precambrian rocks, like that now found in the Esperance area. Marine platforms, which formed during the height of the Late Eocene marine transgression, are still evident along some Precambrian uplands, which rise above the Tertiary sediments.

The Miocene saw extensive carbonate deposition in both the Eucla and Carnarvon basins. Today Miocene limestones dominate the surface geology of the Eucla Basin, and provide the setting for one of the classic karst regions of the world.

Although the morphotectonic framework of Western Australia was established by the Early Tertiary, the details of the geomorphology of the landsurface were still quite different from those of today. This is evidenced by the existence of an extensive paleochannel network which is thought to have been still active at that time (Diagram 2.10); and climate generally was quite different from that of today. The occurrence of the mangrove palm, Nipa, in the Eocene Kings Park Formation suggests that sea surface temperatures may have been as warm as 20° to 25°C, significantly warmer than today. Pollen in Late Eocene sediments show that over southern Western Australia the vegetation resembled tropical to sub-tropical rainforest. Similar conditions prevailed over southern Western Australia throughout much of the Oligocene. Early Miocene precipitation was probably high, but more arid conditions set in during the Middle Miocene. By the Late Miocene the arid climates that today prevail over much of Western Australia, had been established, and Australia had essentially reached its present geographical position (Diagram 2.11).

The wet climates of the Early and Middle Tertiary were conducive to deep weathering; and this is likely to have taken place during the Eocene, but certainly by the Oligocene and Early–Middle Miocene. Deep weathering resulted in a weathered *regolith* and extensive *laterite* formation. The landsurface of much of Western Australia bears a strong imprint of the deep weathering event of the Tertiary, and its control on subsequent geomorphological development is well manifested in etchplain development.

It was traditionally thought that, in terms of tectonics, Western Australia had been essentially stable during much of the Cenozoic. But with the recognition of the South West Seismic Zone, the Jarradale Axis and Ravensthorpe Ramp (Diagram 2.10) and other features, this view has been modified. The most striking geomorphological expression of Cenozoic tectonic activity is in the Exmouth Gulf—Cape Range area. Here, three ranges—the Cape Range, Rough Range and Giralia Range—correspond to *anticlinal* axes initiated during post–Middle Miocene times by reverse movement on underlying normal faults. The Cape Range is the dominant of the three, reaching a height of some 300 metres. The range has been deeply dissected during uplift, which has continued to the present. This is witnessed by warped and uplifted Quaternary reef complexes which now form a staircase along the western flank of the range. On the Yilgarn Block, fault scarps a metre or so high and tens of kilometres long have formed within historic times. Such fault scarps are rapidly eroded and are only incomplete indicators of past seismic activity.

The Late Cenozoic left a significant geomorphological imprint on the landscape as a result of the climatic changes which occurred during this time. The importance of deep weathering for an understanding of the geomorphology is fundamental, but equally striking is the geomorphological expression of the arid climates which first set in during the Late Tertiary. Repeated extensions of the arid zone occurred during the Pleistocene, and resulted in the development of desert dune sequences, which are now stabilised and are found well outside their climatic range (Diagram 2.12). Although no convincing dates are available for these events, it is generally thought that arid zone advances were coincident with global glacial maxima, and that the last massive extension of the arid zone took place at about 18,000 years before present.

DIAGRAM 2.10

Major palaeochannels and Tertiary marine sediments and shorelines. The Meckering Line separates the poorly defined streams of the inland region from the more incised coastward draining rivers. The limit of rejuvenation along the south coast is related to the Ravensthorpe Ramp (from van de Graaff, W.J.E., Crowe, R.W.A., Bunting, J.A. and Jackson, M.J., 1977: Zeitschrift für Geomorphologie, 21).

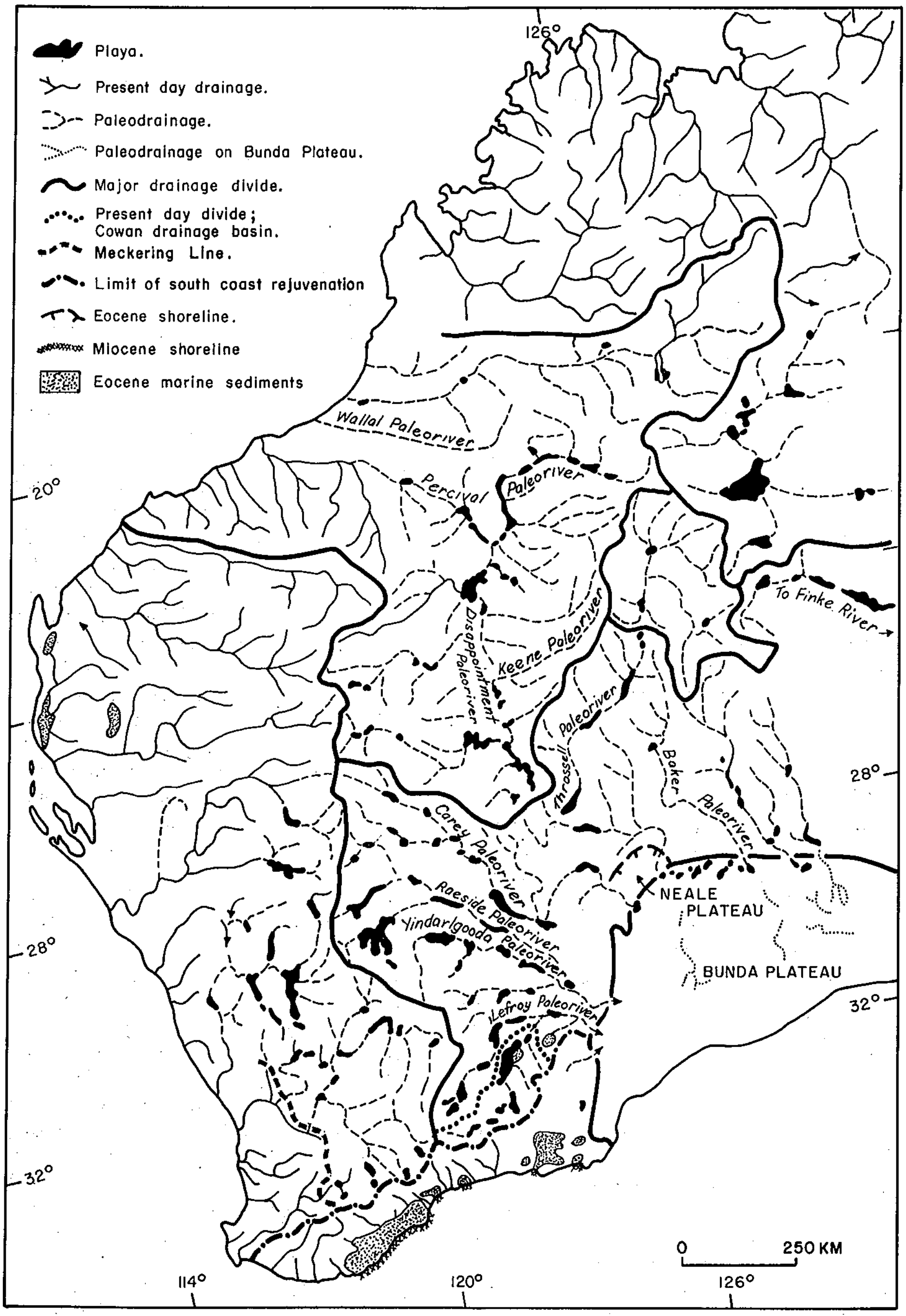
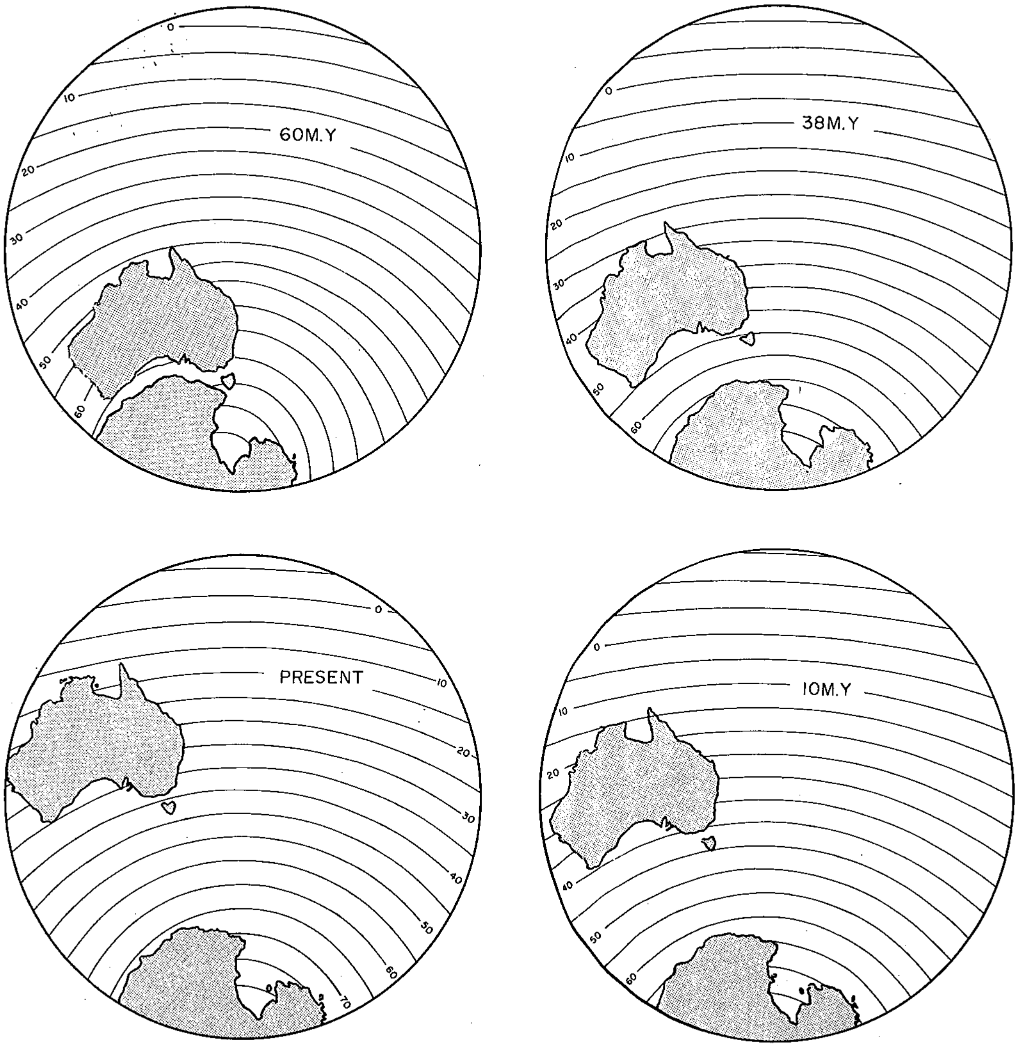


DIAGRAM 2.11
The position of Australia during the Cenozoic (after Crook, K.A.W., 1981: *in* Ecological Biogeography of Australia. A. Keast (ed)).



Quaternary changes in climate caused variations in the hydrology and sediment supply characteristics of streams. These changes controlled alluvial deposition and resulted in formation of alluvial fills and terrace complexes along the major rivers of Western Australia. The Gascoyne, Fitzroy and, on a smaller scale the Swan River, all possess well-developed terrace forms flanking their present courses (Diagram 2.13). In the Geraldton area, extensive alluvial deposition, linked to changes in sediment yield processes, took place during the early part of the Late Quaternary. It is now known, from radiocarbon dates, that significant parts of the Swan and Helena river terrace fills were deposited since around 40,000 years before present. In the Carnarvon Basin, the large wedge of sediments associated with the avulsion of the lower Gascoyne River was deposited over the last 120,000 years.

During the Late Cenozoic global ice volume changes significantly altered sea level. Thus, during the last interglacial–glacial–interglacial cycle, from about 130,000 years ago to present, sea level along the Western Australian coast ranged from +8 metres 120,000 years ago to –50 metres at

DIAGRAM 2.12
The present occurrence of Late Pleistocene (?) desert dunes in the central coastal areas of Western Australia.

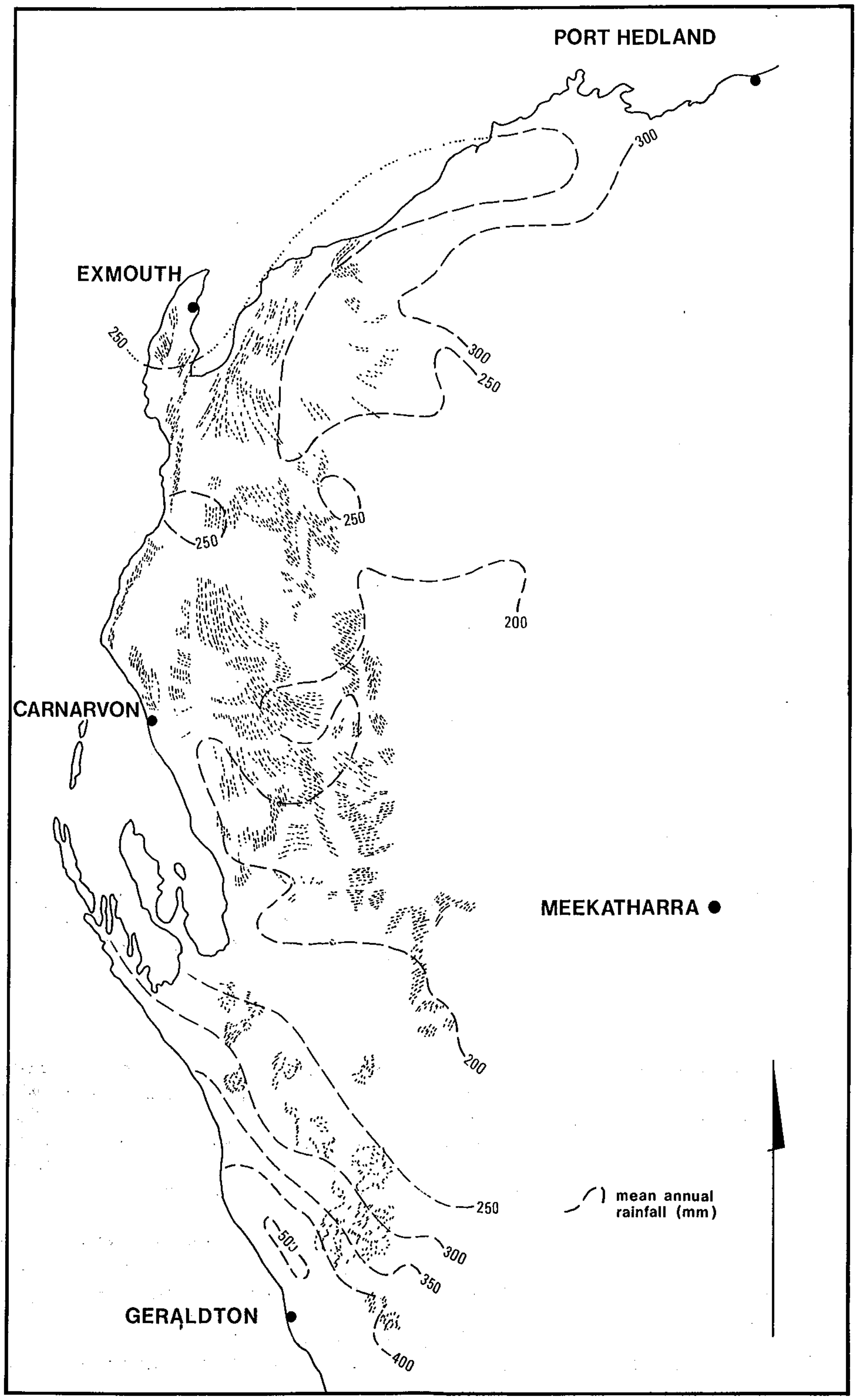
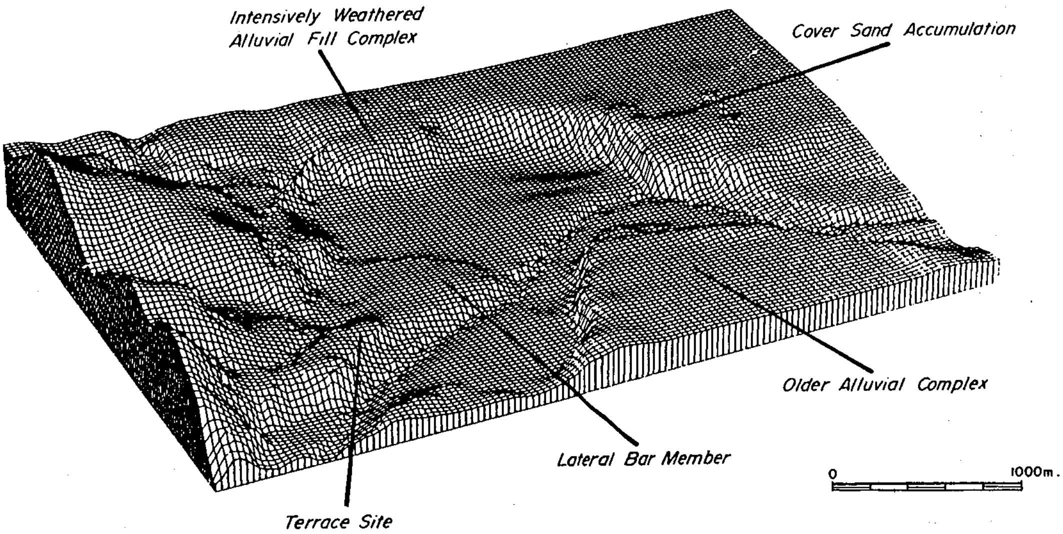


DIAGRAM 2.13
The terraces and associated deposits of the Swan River immediately downstream of the Darling Scarp (vertical exaggeration approximately x5). The digital terrain model is a view from the north–east.



18,000 years ago, and reached its present level (or slightly above) by 6,500 years ago. These changes in sea level have influenced geomorphological evolution along many coastal areas in Western Australia.

During the Late Tertiary or Early Pleistocene, shoreline complexes, now at heights of 90 to 115 metres (Eneabba and Ridge Hill Shelf)—and 20 to 80 metres (Yoganup Formation), were deposited in the Perth Basin. They were the initial sequences of a series of coastal barriers which formed in the Perth Basin throughout the Quaternary.

In the course of the Late Cenozoic there was a significant change in the nature of coastal sediments in the Perth Basin. The older barrier sequences are essentially siliciclastic deposits, whereas the younger Pleistocene barriers are carbonate rich. The Tamala Limestone sequences which dominate much of the coastal plain of the Perth Basin, and which in the Carnarvon Basin have led to the development of the distinctive Shark Bay region, are a Middle to Late Quaternary phenomenon.

Significant geomorphological modifications have taken place over many parts of Western Australia in the last 150 years, linked to European land use practices; consequently rates of sediment yield may well be an order of magnitude higher than earlier in the Late Cenozoic. Widespread erosion is evident in many catchments and high rates of sediment supply are changing the hydraulic and sediment regimes of streams. Wind erosion is equally widespread, and in the most severely affected catchments, such as the Gascoyne, the loss of the vegetation cover has resulted in the local mobilisation of former desert dunes, giving rise to fears of desertification.

GLOSSARY

Adamellite: Granitic rock in which 10 to 15 per cent of the felsic constituents are quartz, and in which the ratio of alkali feldspar to total feldspar is between 35 and 65 per cent.

Alluvium: Unconsolidated sedimentary material transported by a river and deposited on flood plains, estuaries and deltas.

Andesite: Very fine crystalline extrusive rock of volcanic origin composed largely of plagioclase feldspar with smaller amounts of dark–coloured mineral (hornblende, biotite or pyroxene)—the extrusive equivalent of diorite.

Anticline: An arch–shaped fold in which the younger strata remain at the top of the succession.

Aphanitic: Referring to the texture of an igneous rock in which the crystalline components are not distinguishable by the unaided eye.

Basalt: An *aphanitic* crystalline rock of volcanic origin, composed largely of plagioclase feldspar and dark minerals such as pyroxene and olivine – the extrusive equivalent of gabbro.

Batholith: A large intrusive mass of igneous rock, typically granite, outcropping over at least 100 square kilometres and extending to an unknown depth. Batholiths are particularly characteristic of orogenic belts in subduction zones.

Biotite: A black, brown or dark green ferromagnesian mica, abundant and widely distributed in igneous and metamorphic rocks.

Craton: The large, relatively immobile (stable) portion of continents, consisting of shields and platforms, which has remained unaffected by orogenic activity for commonly several periods of time.

Diamictite: A coarse sedimentary rock that is not sorted, or is poorly sorted, and contains particles of many sizes.

Dyke: A tabular intrusion of igneous rock, normally of intermediate grain size, that cuts discordantly through the surrounding rock.

Felsic: An acronym derived from feldspar and silica, and used to describe light–coloured silicate minerals such as quartz, felspar and felspathoids.

Gneiss: A coarse grained crystalline rock formed during high–grade regional metamorphism of igneous or sedimentary rocks, characterised by a banded appearance and linear orientation of minerals.

Graben: A block of the Earth's crust, generally with a length much greater than its width, that has dropped relative to the blocks on either side.

Granite: A coarse grained acid igneous rock, consisting mainly of quartz, alkali felspar and mica, with various accessory minerals. It occurs in intrusive bodies from crystallised magma, or the 'granitisation' (metasomatic transformation) of pre–existing rocks.

Isostasy: A condition of equilibrium in the Earth's crust. Assuming that the lighter continental masses float on a denser medium, changes in crustal elevation must be compensated in some way at depth.

Karst: A topography formed over limestone, dolomite or gypsum and characterised by sinkholes, caves and underground drainage.

Komatiite: Lavas with a high magnesium content, thought to be unique to the Early Precambrian.

Laterite: Weathered material composed principally of the oxides of iron, aluminium, titanium, and manganese; laterite ranges from soft, earthy, porous soil to hard, dense rock.

Lignite: Coal of relatively recent origin, intermediate between peat and bituminous coal; often contains patterns from the wood from which it formed. Also known as brown coal.

Lithosphere: The outer, rigid shell of the solid Earth, overlying the less rigid athenosphere. The lithosphere comprises the crust (both oceanic and continental) and that part of the mantle (the lithospheric mantle) above the athenosphere to which the crust is mechanically coupled. The total thickness of the lithosphere varies between about 50 and 100 kilometres below the Earth's surface.

Mafic: A general term describing ferromagnesian minerals.

Mantle: The section of the Earth's interior between the crust and the outer core, bounded at the top by the Mohorovicic discontinuity and at the base by the Gutenberg discontinuity.

Metamorphic rock: A rock formed from pre–existing solid rocks by mineralogical, structural and chemical changes, through the action of heat or pressure or both.

Metasediment: A sediment or sedimentary rock which shows evidence of metamorphism.

Migmatite: A very high–grade metamorphic rock in which extremes of temperature and pressure have induced partial melting so that the rock has taken on some of the characteristics of igneous texture.

Mobile belt: A long, relatively narrow region where crustal mobility by magmatism, metamorphism and tectonic activity has led to widespread deformation.

Morphotectonics: Refers to the relationship between geomorphology and tectonics irrespective of scale.

Orogeny: An episode of tectonic activity (folding, faulting, thrusting) and mountain–building usually related to a destructive plate margin.

Plate tectonics: The interaction of the large rigid sections into which the Earth's lithosphere is divided. There are eight major plates and numerous smaller ones.

Playa: A low, essentially flat, part of a basin or other undrained area in an arid region.

Plutonic rock: Igneous rock which has formed from magma which has crystallised as an intrusion at depth in the crust and is coarsely crystalline.

Porphyry: An igneous rock in which phenocrysts (large conspicuous crystals) are enclosed in a very fine–grained to aphanitic matrix.

Regolith: The layer or blanket of unconsolidated rocky debris of any thickness that overlies bedrock and forms the surface of the land.

Regression: Retreat of the sea from land areas, and the consequent evidence of such withdrawal.

Sedimentary basin: An area of continued subsidence of the crust that accumulates sediment over a prolonged period.

Shield: A major structural unit of the Earth's crust, consisting predominantly of Precambrian metamorphic and igneous rocks which have remained unaffected by later orogenics.

Sill: A tabular igneous intrusion that is oriented parallel to the planar structure of surrounding rock.

Spongolite: A rock or sediment composed chiefly of the remains of sponges.

Syntectonic: Refers to a geologic process or event occurring during tectonic activity.

Tectonics: A branch of geology dealing with the broad architecture of the outer part of the Earth, that is, the regional assembling of structural or deformational features, a study of their mutual relations, origin and historical evolution.

Tholeiite: A variety of basalts composed principally of plagioclase, pyroxene, and iron oxide minerals as phenocrysts in a glassy ground mass.

Transcurrent fault: A strike–slip fault characterised by a steeply inclined surface.

Transgressive deposit: Sediment deposited during transgression (landward extension) of the sea.

Tuff: Consolidated volcanic ash, composed largely of fragments produced directly by volcanic eruption; much of the volcanic material represents finely comminuted crystals and rocks.

Ultrabasic: Of igneous rock, having a low silica content, as opposed to the higher silica contents of acidic, basic, and intermediate rocks.

Volcanics: Igneous rocks that solidified after reaching, or nearing, the Earth's surface.

REFERENCES

Bowler, J.M. (1976), Aridity in Australia: age, origins and expressions in aeolian landforms and sediments. *Earth Science Reviews* 12, 279–310.

Bunting, J.A. (1986), Geology of the Eastern Part of the Nabberu Basin, Western Australia. *Geological Survey of Western Australia* Bulletin 131

Butt, C.R.M. (1981), The nature and origin of the laterite weathering mantle, with particular reference to Western Australia, *in* Doyle, H.A., Glover, J.E. and Groves, D.I. (eds), *Geophysical prospecting in deeply weathered terrains.* Geology Department and University Extension, The University of Western Australia, 11–29.

Collins, L.B. and Baxter, J.L. (1984), Heavy mineral–bearing strandline deposits, associated with high–energy beach environments, southern Perth Basin, Western Australia. *Australian Journal of Earth Sciences,* 31, 287–292.

Fairbridge, R.W. and Finkl, C.W. (1978), Geomorphic analysis of the rifted cratonic margins of Western Australia. *Zeitschrift für Geomorphologie* 22, 369–389.

Gee, R.D. (1979), Structure and tectonic style of the Western Australian Shield. *Tectonophysics.* 58, 327–369.

Geological Survey of Western Australia (1975), The Geology of Western Australia. *Geological Survey of Western Australia,* Memoir 2.

Glover, J.E. and Groves, D.I. (eds) (1981), Archaean geology: Second International Symposium, Perth. *Geological Society of Australia* Special Publication No. 7.

Harris, L.B., (1987), A tectonic framework for the Western Australian Shield and its significance to gold mineralization: a personal view, *in* Ho. S.E. and Groves, D.I. (eds), *Recent advances in understanding Precambrian gold deposits.*

Geology Department and University Extension, The University of Western Australia, 1–27.

Ho, S.E. and Groves, D.I. (eds) (1987), *Recent advances in understanding Precambrian gold deposits*. Geology Department and University Extension, The University of Western Australia.

Hocking, R.M., Moors, H.T. and van de Graaff, W.J.E. (1987), Geology of the Carnarvon Basin Western Australia. *Geological Survey of Western Australia,* Bulletin 133.

Jackson, M.J. and van de Graaff, W.J.E. (1981), Geology of the Officer Basin, Western Australia *Bureau of Mineral Resources,* Bulletin 206.

Jaques, A.L., Lewis, J.D. and Smith, C.B. (1986), The kimberlites and lamproites of Western Australia. *Geological Survey of Western Australia.* Bulletin 132.

Johnstone, M.H., Lowry, D.C., and Quilty, P.G. (1973), The geology of southwestern Australia—a review. *Journal of Royal Society, Western Australia,* 56, 5–15.

Logan, B.W., Davies, G.R., Read, J.F. and Cebulski, D.E. (1970), Carbonate sedimentation and environments, Shark Bay, Western Australia. *American Association Petroleum Geologists,* Memoir 13.

Lowry, D.C. (1970), The geology of the Western Australian part of the Eucla Basin. *Geological Survey Western Australia,* Bulletin 122.

NcNaughton, N.J. and Dahl, M. (1987), A geochronological framework for gold mineralisation in the Yilgarn Block, Western Australia, *in* Ho, S.E. and Groves, D.I. (eds), *Recent advances in understanding Precambrian gold deposits.* Geology Department and University Extension, 29–49.

Department of Mines (1987), *An overview of mining in Western Australia,* 44p.

Muhling, P.C. and Brakel, A.T. (1985), Geology of the Bangemall Group. *Geological Survey of Western Australia,* Bulletin 128.

Mulcahy, M.J. (1973), Landforms and soils of southwestern Australia. *Journal Royal Society of Western Australia,* 56, 16–22.

Playford, P.E., Cockbain, A.E. and Low, G.H. (1976), Geology of the Perth Basin, Western Australia. *Geological Survey of Western Australia,* Bulletin 124.

Plumb, K.A. (1979), The tectonic evolution of Australia. *Earth–Science Reviews,* 14, 205–249.

Purcell, P.G. (ed) (1984), The Canning Basin, W.A. *Proceedings of Geological Society of Australia/Pet Expl. Soc. Aust. Symposiums Perth.*

Quilty, P.G. (1984), Mesozoic and Cenozoic history of Australia as it affects the Australian biota, *in* Cogger, H.S. et al, (eds), *Arid Australia.* Australian Museum, Sydney, 7–55.

Trendall, A.F. (1983), The Hamersley Basin, *in* Trendall, A.F. and Morris, R.C. (eds), *Iron–formation, facts and problems.* Elsevier, 69–123.

Twidale, R.R., Horwitz, R.C. and Campbell, E.M. (1985), Hamersley landscapes of the north–west of Western Australia. *Review de Geologie Dynamique et de Geographie Physique,* 26, 173–186.

van de Graaff, W.J.E. (1981), Paleogeographic evolution of a rifted cratonic margin : south–west Australia—discussion. *Palaegeography, Palaeo–climatology, Palaeoecology,* 34, 163–172.

van de Graaff, W.J.E., Crowe, R.W.A., Bunting, J.A. and Jackson, M.J. (1977), Relict Early Cainozoic drainages in arid Western Australia, *Zeitschrift für Geomorphologie,* 21, 379–400.

Veevers, J.J., (ed) (1984), *Phanerozoic earth history of Australia,* Oxford, Clarendon Press.

Q73179/12/89-25-T235