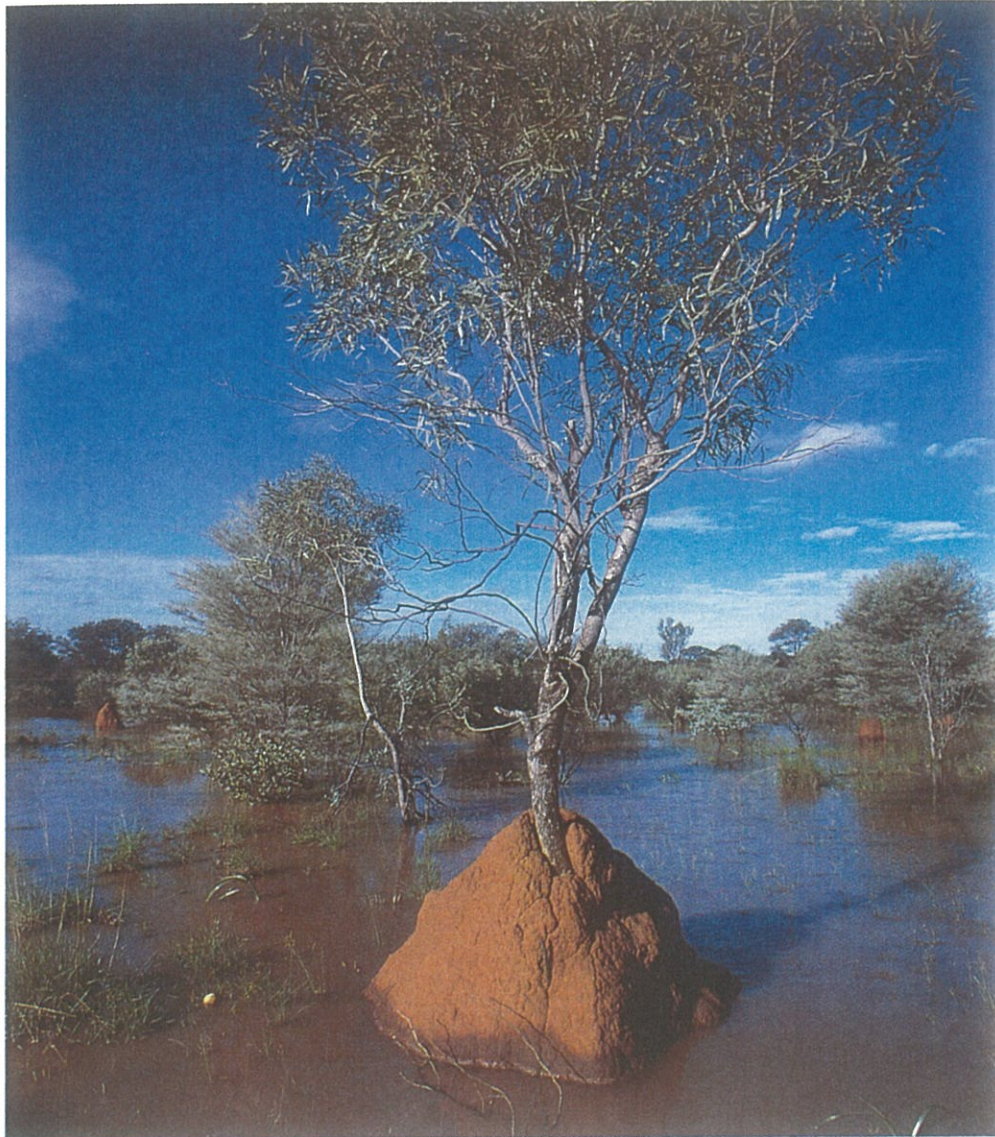


Extracts re Banded Shilt breeding in the Eastern Woodfields of WA

# RUNNING DOWN

09/5/2014



## WATER IN A CHANGING LAND

MARY E. WHITE

*Cartography: Barbara Eckersley*  
*Professional landscape photography: Reg Morrison*  
*Foreword by Graham Harris, Chief, CSIRO Land & Water*

Kangaroo Press

RUNNING DOWN: WATER IN A CHANGING LAND  
First published in Australia in 2000 by Kangaroo Press  
An imprint of Simon & Schuster (Australia) Pty Limited  
20 Barcoo Street, East Roseville NSW 2069

A Viacom Company  
Sydney New York London Toronto Tokyo Singapore

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National Library of Australia  
Cataloguing-in-Publication data

White, M.E. (Mary E.).  
Running Down: water in a changing land.

Bibliography.  
Includes index.  
ISBN 0 7318 0904 1.

1. Rivers - Regulation - Environmental aspects - Australia.  
2. Streamflow - Australia. 3. Nature - Effect of human beings on - Australia.  
4. Conservation of natural resources - Australia. 5. Environmental protection - Australia. I. Title.

551.4830994

Cover photo: *Black Flag Lake, about 30 kilometres from Kalgoorlie, Western Australia. An ancient landscape, rusty red; salt-rimmed water cool in a hot, dry world—epitomising Australia, its ephemeral waters, its intriguing mysteries...*  
PHOTO BILL VAN AKEN, SCIENTIFIC & TECHNICAL PHOTOGRAPHER, CSIRO LAND & WATER, PERTH.  
(the Author expresses her deep gratitude to Bill van Aken and the CSIRO Land & Water for making this special photograph available)

Cover and internal design: Linda Robertshaw  
Cartographer: Barbara Eckersley

Set in 9.5/11.5 pt Minion  
Printed by Imago Productions (FE) Pte Ltd

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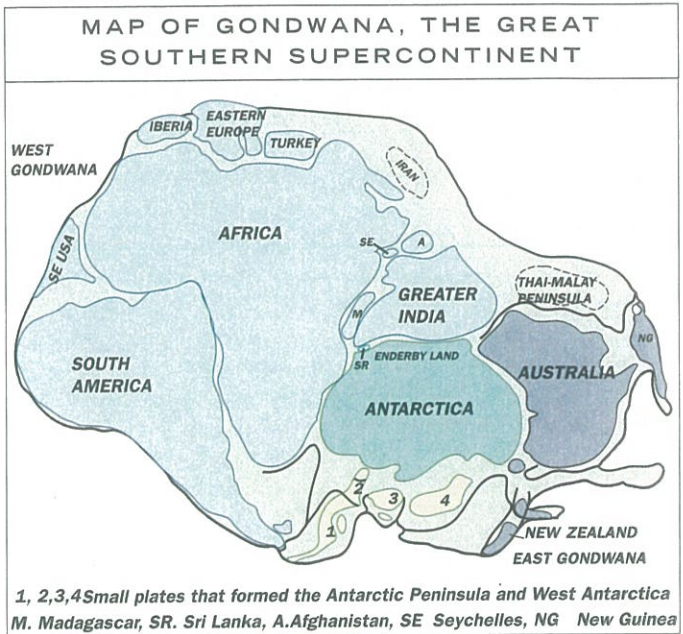
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*Opposite: Tidal drainage patterns in mangroves, Kimberley region, Western Australia.* REG MORRISON

the time of settlement—before we started to make the changes which have altered everything in this context in a most dramatic way in only 200 years, and far less in many cases. In fact, we will find that serious changes to river function and all its attendant hydrological ramifications often occurred within a couple of decades of settlement, land-clearing and introduction of foreign animals and plants. Unfortunately, we will also find that the modern systems are still out of equilibrium and the impact of our land use has continued to result in rapid degradation.

Recent findings<sup>3</sup> that rates of siltation in our rivers and on their floodplains are datable by reference to an atomic-fallout zone in sediments, which corresponds to the years when Woomera was an atomic bomb test site, have shown clearly that there is no room for complacency. Metres of mud and sand deposited on river floodplains, which were assumed to be the results of hundreds or even thousands of years of erosion, are now known to represent only 30 or 40 years of deposition. In the case of the Murrumbidgee River on the New South Wales south coast between Bermagui and Bega, which received sudden and disproportionate media attention only because of the link with nuclear warfare, a third of the deep deposits was in fact dumped in one massive flood event, in 1971.

I invite you to come with me on an exploration of the role of water in Australia through the ages, to assemble the background and big picture, so that we may understand the present situation (and because the story is fascinating in its own right). Water has shaped global environments since the beginning of Time, when the first rain



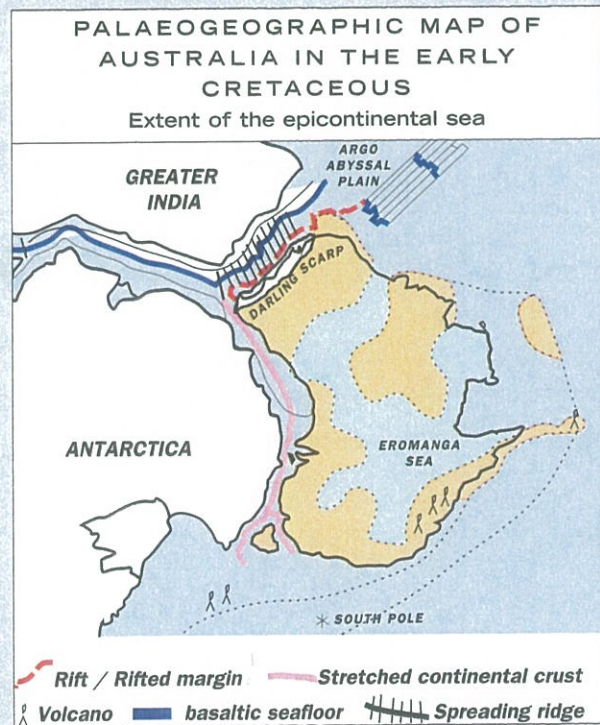
fell on the cooling crust of the new Earth and started to erode its surface: creating drainage lines, wearing down the high parts, filling the low with sediments, and then reworking it all again and again, co-operating with tectonic and geological events to create the world as we know it.

We will see a slice of the evolution of the modern Australian

### THE UPS AND DOWNS OF SEA LEVEL

Sea level changes through geological time, and even during the geologically recent climatic swings of the Pleistocene ice age, have had a profound effect on drainage patterns and landscapes. In a continent where some incredibly

ancient landforms have been preserved, major changes in global sea level in the Cretaceous and any changes throughout the Tertiary are relevant to our story, as are marine incursions into sinking continental basins which did not necessarily involve a global sea level rise. Where blocks of continental crust are uplifted or where areas of crust sink to form basins, new drainage patterns follow. The processes of erosion through time are constantly altering the nature of drainages—lowering the headwaters, decreasing the gradient of streams and rivers, stripping to bedrock in places (which is a factor in the preservation of ancient patterns such as are seen on the ancient craton blocks of Australia) and filling up low areas with sediment.



In Australia, much of the continent is inward draining, and has been so for great lengths of time. Only the narrow fringes of the continent now drain to the ocean and it is therefore the coastal rivers which have been affected by rises and falls in sea level in comparatively recent geological times. Global times of high sea level, resulting in the formation of epicontinental seas in the past, have been significant in the production of modern landscapes. The limestone Nullarbor Plain was created under epicontinental seas which invaded in the Eocene and again in the Miocene—and was subsequently uplifted; marine invasions of the sinking Murray Basin left a series of marine sedimentary rocks which date the times of inundation, and the most recent left strandlines which stand out in the modern landscape as the sea retreated.

The sea level fluctuations of the last 2 million years, the Pleistocene ice age, have resulted in the sculpturing of our modern coastlines, creating the deeply incised valleys which are now drowned (like Sydney Harbour) and the canyons on the continental shelf through which the rivers ran to the sea when the coastline was many kilometres further out during low sea level stands.

continent by tracing the development of the ancient drainage patterns, which are like character lines or wrinkles on the face of our land, and by tracing the ancient history of our present-day rivers. Australia has some of the most ancient landscapes preserved anywhere on Earth. In Western Australia, some landscapes in the Kimberleys may date back an astounding 600 million years; the drainage patterns on the Yilgarn Craton can be traced for nearly 300 million years—and it is possible to reconstruct the changes to landscapes and climate up to today. Because the ancient history is so well recorded in the western half of the continent, that aspect of our story will be covered in detail by reconstructing the changing Western Australia landscapes through time.

The chosen examples of our rivers and waters will, where possible, show their prehistoric record, and then their status before European activities impacted upon them. Records of the early explorers, travellers and surveyors, and their maps and pictures, provide this base line—and often present amazing information on just how much change there has been.

In a subject as huge as this there will be many omissions, often of well-known subjects and aspects that readers might have expected to find included. The overall picture of *Water in Australia* presented is constructed like a mosaic, from bits of all shapes and sizes, seen from all sorts of different angles and perspectives, which, when assembled, make a whole.

## GROUNDWATER

Australia's groundwater resources are very large but quality and quantity vary greatly in different parts of the land. Over about 60 per cent of the continent, the population is entirely dependent on groundwater, mainly in the arid and semi-arid regions. In other areas it is important in supplementing unreliable surface supplies. About 14 per cent of water used in Australia is groundwater.

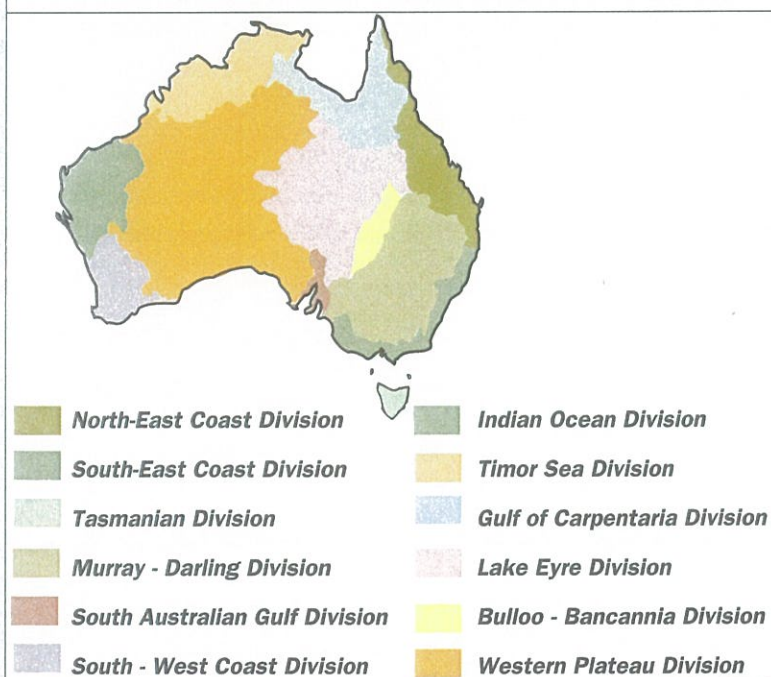
Four classes of groundwater quality are recognised: *fresh*, which is generally suitable for drinking, domestic use, irrigation and stock; *marginal*, suitable for some irrigation uses and stock; *brackish*, which is suitable for stock and some industrial uses; and *saline*, which is generally unsuitable for use.

Aquifers on the east coast (North-east Coast and South-east Coast divisions), where population is largely concentrated, are already substantially exploited, as they are in the main foodbowl area of the Murray-Darling Division. There are large amounts of relatively untapped groundwater in northern Australia (Timor Sea and Gulf of Carpentaria divisions) and Tasmania (Tasmanian Division). In arid and semi-arid regions (Lake Eyre and Western Plateau divisions) most groundwater is of marginal quality.

Aquifers are of three main types:

- **Surficial aquifers** occur in alluvial sediments in river valleys, deltas and basins, and in dune sands accumulated by wind or water. These are major sources of fresh groundwater, and are easily exploited. About 60 per cent of groundwater used comes from surficial aquifers. (Perth and other places on the Swan coastal plain obtain much water from unconsolidated sand aquifers; and Fraser Island, the largest sand island in the world, is a huge surficial aquifer feeding perennially flowing rivers.)
- **Sedimentary aquifers** occur in consolidated sediments (sedimentary rocks) like porous sandstones, conglomerates and limestone. These are continuous over large areas and contain the greatest reserves of groundwater, though much of it is of marginal quality. The Great Artesian Basin, which underlies most of the eastern half of Australia, has many water-bearing sedimentary strata, only some of which have good quality water. Thirty per cent of used groundwater is from sedimentary aquifers.
- **Fractured rock aquifers** occur in igneous and metamorphosed rocks which have been subjected to disturbance. They may extend over large areas, but contain less available water. Groundwater extracted from fractured rock aquifers amounts to 10 per cent of that used.

DRAINAGE DIVISIONS OF AUSTRALIA  
AUSTRALIAN WATER RESOURCES COUNCIL



After McMahon *et al*<sup>2</sup>

For groundwater use to be sustainable, the rate of extraction must be less than the rate of recharge. This is hard to achieve in Australia where much of the groundwater is old, especially that in sedimentary aquifers. In these the rate of lateral movement is slow, recharge often takes place in far distant regions, and it may take very long times for water to travel. In the Great Artesian Basin, water moves at only a metre a year, and the distance from major recharge areas on the Great Divide is such that water emerging at mound springs near Lake Eyre is up to 2 million years old. (See page 97-104 for information on the GAB.) In the arid and semi-arid zone, very little recharge of localised smaller aquifers takes place at all, and the water is fossil water which resulted from recharge when rainfall in the area was much higher than today. Using such groundwater is obviously an unsustainable practice.

above Jarrahmond has been reduced by only 14 per cent. Low flows at Jarrahmond are now about one-third of what they were before diversions, while a 1-in-10 year 7-day low flow, used as a base for some water quality standards, has been reduced by 75 per cent. Low flow intervals on the lower Snowy have become more frequent, showing a 14-fold increase; they now extend for longer and build up greater water deficits. There has been a reduction of 40–80 per cent in typical flushing flows in each month of the year. However, the Scheme has had only a small effect in reducing flood flows.

The hydrologic consequences of inter-basin transfers may be expected to be

more severe than those arising from within-basin re-distribution. The imposition of artificial hydrological regimes may lead to an ecosystem structure that is atypical of the river. Even the setting of 'minimum environmental flows' does not adequately protect biological values, because in-stream biota are adapted to extremes of flow where these occur naturally, and they exist in a state of dynamic equilibrium with environmental disturbances. Floods may act as cues for breeding, and by providing a productive floodplain environment for juvenile fish, increase the number which reach maturity. Floods may also improve water quality by flushing away fine deposits.

## PLEISTOCENE CLIMATIC SWINGS

The climate changes of the Pleistocene ice age, in which we are living in an interglacial, have created the Australia of today—the driest vegetated continent with more than 70 per cent under arid regimes. (A full account of how this continent changed from a green, well-watered and largely forested land 45 million years ago, when it started its northwards drift as an island continent, to become what it is now, is told in *After the Greening* and will not be repeated in this book.) The fluctuating climatic regimes of the last 2.6 million years have had a profound effect on the surface and below-surface waters of our continent. Some surprising facts emerge when a study is made of river behaviour through this small slice of geological time, and a picture emerges of a very different, and at times much less arid, Australia, even as recently as when the Aborigines first came here.

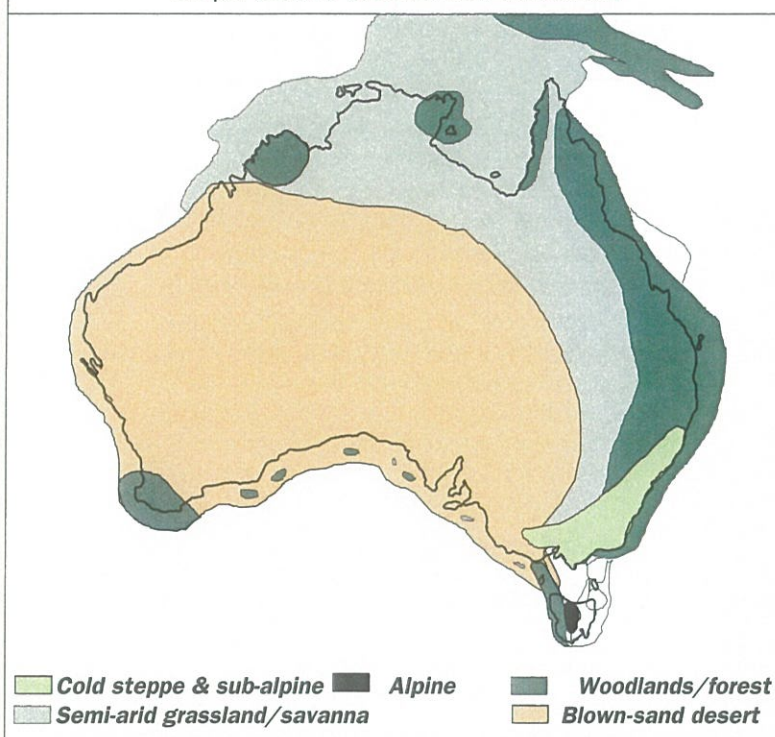
Alternating dry and wet climatic regimes across central and eastern Australia during the past 300 000 years have greatly affected Australia's rivers, lakes and dune fields.<sup>3A</sup> Fluvial conditions dominated part of the last two interglacials, resulting in large sand loads in rivers in the Simpson Desert and south-eastern Australia.

The palaeochannels of central Australia were highly competent sand-load rivers during the last interglacial. There, fluvial activity peaked about 110 000 years ago, 5000 to 10 000 years behind world temperature and sea level maxima. Then aridity spread from central Australia towards the margins, with a peak at the last glacial maximum. A less widespread wet phase between 55 000 and 35 000 years ago is associated with high lake levels and palaeochannel activity in south-eastern Australia.

The coastward spread of aridity in Australia is recorded in the sedimentary record of rivers and lakes, and in the chronology of dune formation, as we shall see in accounts of rivers and landscapes in this book. For example, on the Riverine Plain the peak in river activity in prior streams occurred at about 90 000 years ago, and operated until 85 000 years ago. Cranebrook Terrace on the Nepean River, closer to the coast, gave an age of 80 000 years for its peak flow; and coastal rivers transported sand and gravel until about 70 000 years ago.

Dunes started to form in the Eyre Basin in the last interglacial from about 95 000 years ago. On the Riverine Plain, midway between the Centre and the coast, dunes bordering streams and lakes started to form in the period

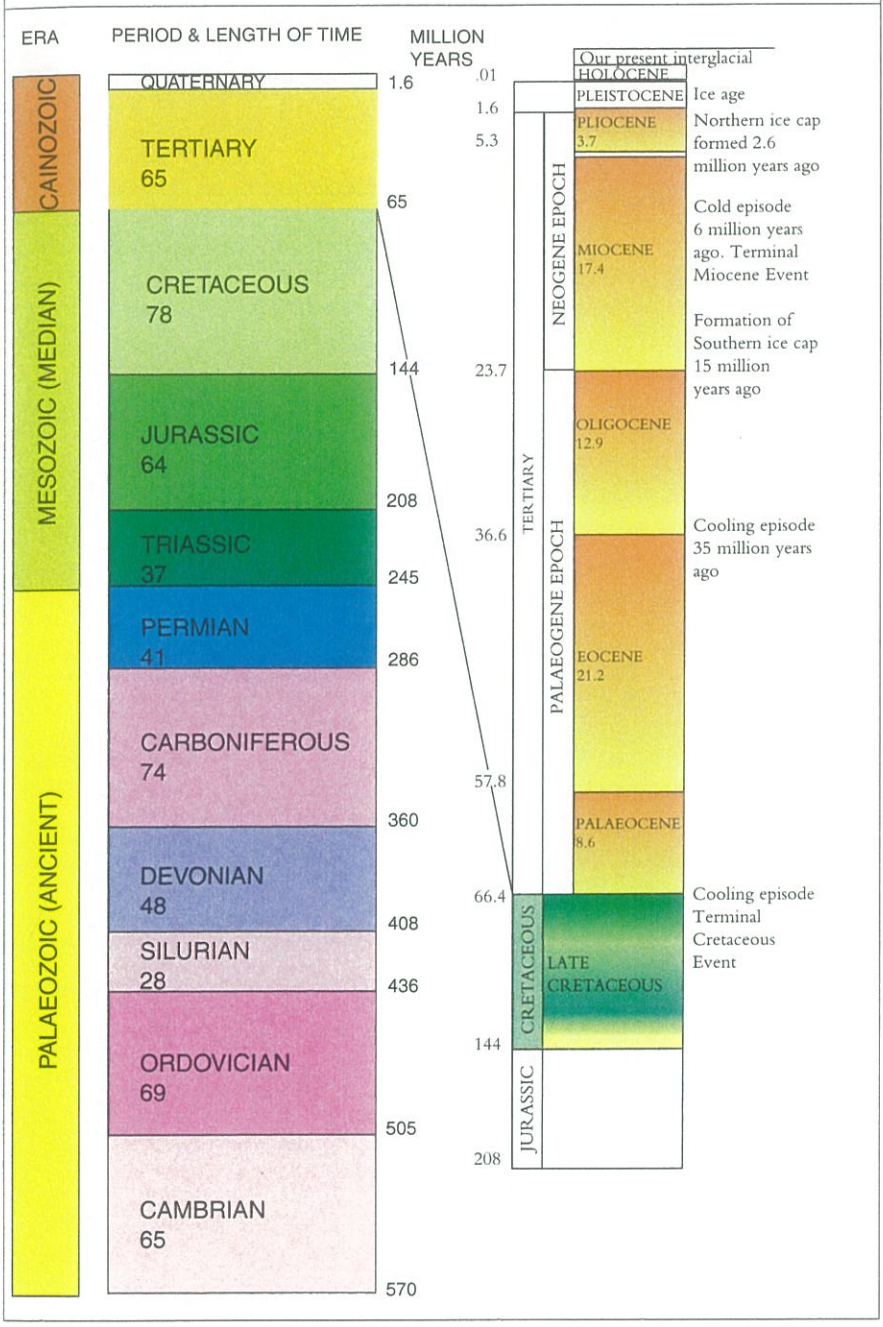
AUSTRALIA 18000 YEARS AGO  
80 per cent of the continent was desert



between 70 000 and 50 000 years ago. In the Lake George and Shoalhaven Basins, closer to and on the coast, dunes only started at about 20 000 years ago, during the last glacial maximum. At the peak of the last glacial maximum Australia was twice as dry (had half the rainfall) and twice as windy as it is now, and up to 80 per cent of the land was covered by wind-blown sand. The major dunefields assumed their present form then, and much of the Murray Basin was a salt-sand desert.

In the Holocene, the last 10 000 years, temperature and sea level have both varied. A mini-Greenhouse at 9000 years ago saw temperatures higher than today's over the continent, and increased rainfall. Maximum Holocene sea level occurred between 7500 and 6000 years ago, and sea level has been more or less stable since.

# GEOLOGICAL TIME SCALE



# RIVERS RUNNING THROUGH TIME

WESTERN AUSTRALIA—WHERE ANCIENT LAND SURFACES ENABLE  
A STUDY OF DRAINAGES THROUGH GEOLOGICAL TIME

Satellite imagery is a wonderful new tool which reveals much more than large-scale snapshots of the Earth. The geological history of the landscape in this portion of Western Australia, with the Swan Estuary in the centre, is laid out before us and can be read like a book. One of the most ancient landscapes preserved anywhere on Earth—the wrinkled, ancient Yilgarn Block—forms the eastern half, and a clear-cut line, the Darling Scarp, separates it from the geologically young Swan Coastal Plain along its western margin. The Scarp tells us about the opening of the Indian Ocean and the creation of Western Australia's coastline during the split-up of Gondwana. It marks the edge of the rift which developed between India and Australia in the first stage of our continent's separation. The low, flat plain with its dune ridges and drowned off-shore features, tells of the advance and retreat of the sea during sea level fluctuations caused by polar ice melting and building up again in interglacial and glacial stages of the Pleistocene ice age. Only 18 000 years ago, sea level was 130 metres lower than it is today, and a wide stretch of the continental shelf was exposed. The offshore islands—Rottneest, opposite the Swan Estuary, and Garden Island to the south—were raised areas on the exposed continental shelf and the coastline was many kilometres further west. Rivers cut deep channels across the continental shelf to reach the ocean. Sea level stabilised only about 6000 years ago and then the estuaries and other features of the modern coastline developed.

The themes captured in this satellite snapshot are repeated and are described in the wider context of the whole of Western Australia in this section. The State of Western Australia comprises about one-third of the continent and encompasses much that relates to other areas, so it provides an introduction. Because ancient land surfaces

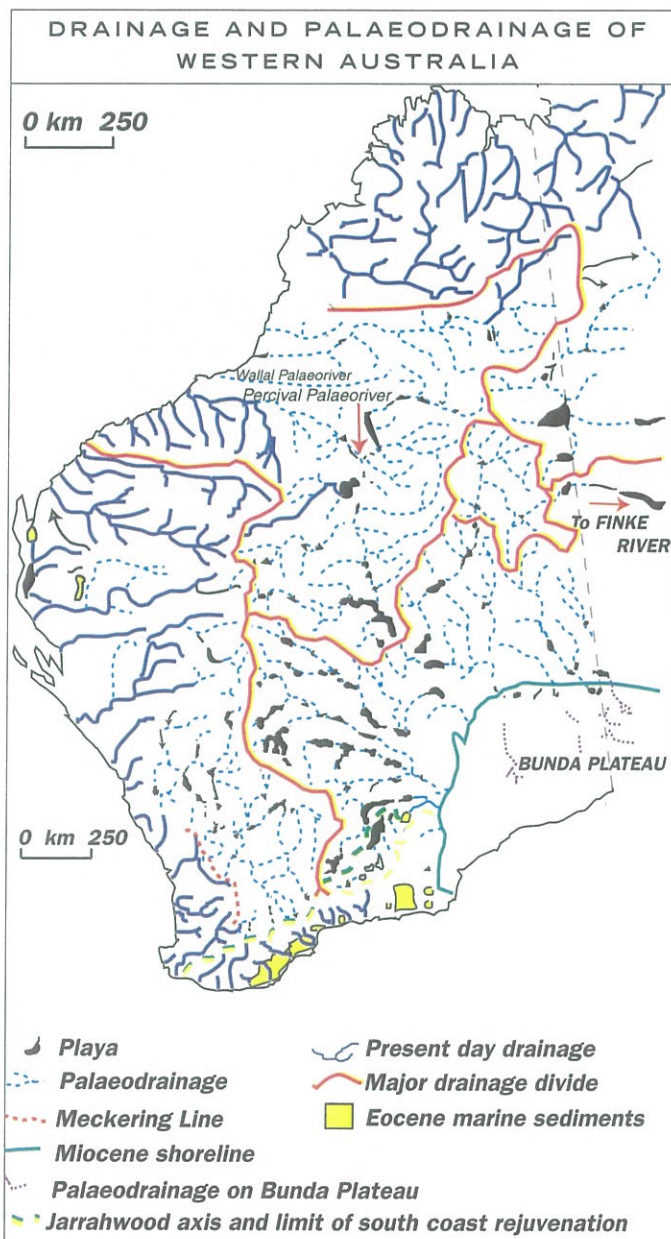
*SATELLITE IMAGE OF A SLICE OF WESTERN AUSTRALIA FROM THE COAST AT PERTH TO THE ANCIENT YILGARN PLATEAU.*

*Landsat imagery provided by Australian Centre for Remote Sensing (ACRES), Australian Surveying & Land Information Group, DIST, Canberra, and digitally enhanced and produced by Satellite Remote Sensing Services, Department of Land Administration, Perth, Western Australia.*

are preserved over large areas, the opportunity exists to trace the ancient drainage patterns—the *palaeodrainages*—and to see that modern landscapes retain a mixture of ancient and modern features. Many modern rivers lie in valleys which were carved out by *palaeorivers* incredibly long ago; chains of salt lakes in the arid areas follow drainage lines which have not seen perennial streams for many millions of years. The history of climates through the ages can be read in sediments preserved in the ancient drainages.

## THE YILGARN PLATEAU

The Yilgarn Plateau is an ancient building block (craton) of Australia, with some of the oldest rocks found anywhere on Earth and some of the oldest preserved landscapes. The satellite image on



After Beard,<sup>4</sup> and van de Graaff *et al*<sup>5</sup>

page 11 shows the low-relief patterns of creases and rumples—little changed on this scale from nearly 300 million years ago. The earliest event relevant to the modern landscapes is the Late Carboniferous to Early Permian ice age of about 290–270 million years ago when continental ice sheets ground across the already ancient surface, levelling, gouging hollows and leaving low bosses between. At first, after the ice had gone, there was no organised drainage. As time went on, rain fell, water sculpted the surface and drainage patterns etched themselves across the land, deepening with time but barely keeping up with the slow erosion that was wearing the landscape down further.

Today, a central watershed runs north to south, roughly down the middle, with elevations of about 600 metres above sea level in the north decreasing to 300 metres in the south. On its western slopes, rivers are active—including the Swan, Murchison, Gascoyne, Ashburton and Fortescue. On the eastern slopes, rivers which previously drained into the Canning, Officer and Eucla Basins have dried up and today are represented by chains of salt lakes. There are no rivers of major size flowing to the south coast, where drainage is much younger, developing after the southern continental margin tilted along a hingeline, the Jarrahwood Axis (or Ravensthorpe Ramp), which created a drainage divide between the coastal region and the Plateau about 30 million years ago.

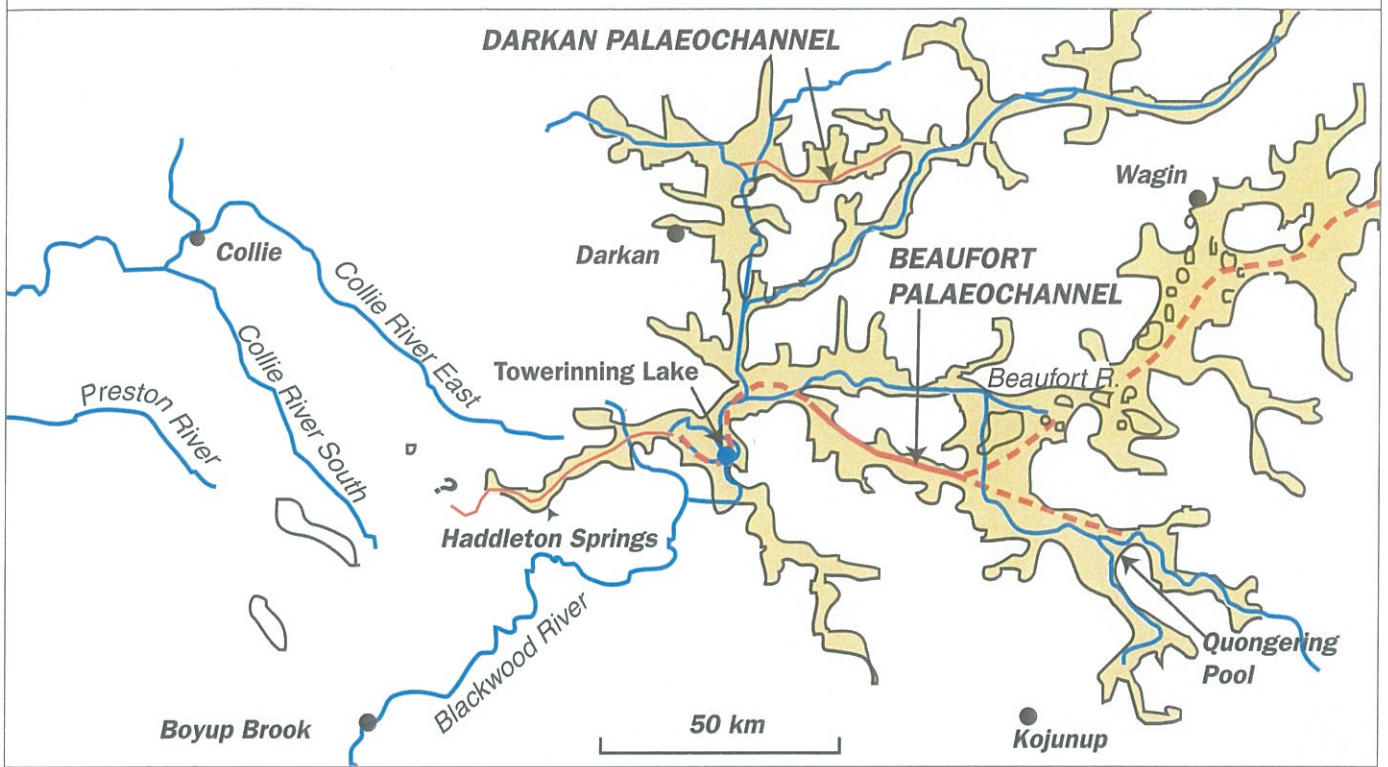
The Canning and Officer Basins were uplifted at the end of the Cretaceous and developed river systems of their own—the Canning, draining north-west, and the Officer to the south. The Eucla Basin was uplifted more than 30 million years later, after the Miocene marine incursion, to become the Nullarbor Plain (also known as the Bunda Plateau).

By the end of the Cretaceous or early in the Tertiary (65–60 million years ago), much of the Western Australian landscape was similar to today, its palaeodrainage patterns established.<sup>5, 5A</sup> Significant flow in the central-desert palaeodrainages stopped before the Mid Miocene—rivers have not been active there in the last 15 million years.

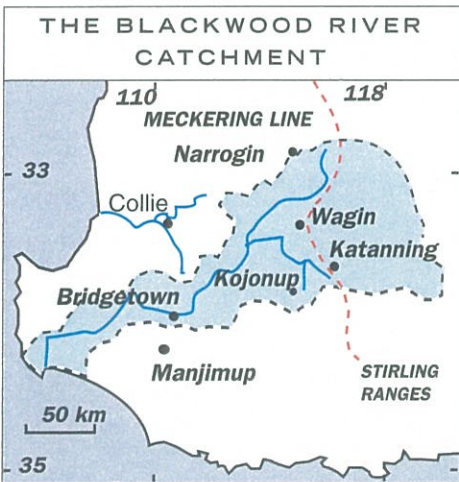
Seven major palaeodrainage provinces can be recognised:

- Valleys that drained via the Great Sandy Desert into the Indian Ocean. Remote sensing has enabled the detection of palaeoriver systems beneath the desert sands, where the salt lake chains of Percival Lake and Lake Gregory (in Canning Stockroute country) are the surface evidence for their existence.
- Valleys in the south-eastern Great Sandy Desert and north-eastern Gibson Desert which appear to have formed the only true internal drainage system in Western Australia.
- Valleys that drained via the Northern Territory into the Bonaparte Gulf.
- Valleys that drained eastward through the Northern Territory into the Finke River and hence into Lake Eyre (the playa chain of Lakes Hopkins, Neale and Amadeus—now the Central Groundwater Discharge Zone).
- South to north trending valleys in the south-western part of the State that drained into active rivers flowing into the Indian Ocean (the Avon—Swan, Canning) and the east to west flowing Beaufort and Darkan palaeochannels whose rivers probably discharged across the Darling Fault into the Perth Basin.
- Valleys that drained into the ancestral Great Australian Bight before its emergence as the Nullarbor. The presently isolated

THE BEAUFORT AND DARKAN PALAEOCHANNELS



After Waterhouse et al.<sup>6</sup>



Cowan Drainage Basin is part of this group. These drainages can be traced for hundreds of kilometres, and stop abruptly at the edge of the Nullarbor, mostly ending in playas (e.g. Plumridge Lakes, Lake Boonderoo).

- A few isolated and discontinuous palaeodrainages on the Nullarbor. Evidence suggests that the climate on the Nullarbor has been arid since its emergence, limiting surface drainage.

The age of the palaeodrainages can be determined by dating their valley-fill deposits. In the Kalgoorlie region, Late Eocene (45–34 million years old) lignitic sediments form valley fills, like the Rollo's Bore beds which are up to 120 metres thick. Under Lakes Lefroy and Cowan such beds are overlain by 30 metres of Late Eocene marine Norseman Limestone, so the palaeodrainages were established before the Late Eocene.

The Beaufort and Darkan palaeochannels on the western margin

are the first fairly complete east to west flowing palaeochannels to be recognised in the south-western sector of the Yilgarn Craton.<sup>6</sup> Part of the Beaufort palaeochannel, extending more than 60 kilometres, has been traced from Quongering Pool, 25 kilometres north-north-east of Kojonup, to Haddleton Springs. It probably discharged across the Darling Fault into the Perth Basin as the ancestor of the Preston or Collie River (or both).

The sediments in the palaeochannel comprise up to 65 metres of sands, silts and clays which record the Eocene history of the drainage system, from 45 to 35 million years ago. It was originally a meandering river system, and as the Yilgarn block tilted to the south

about 49 per cent of the upper catchment of the Blackwood River drains into Lake Dumbleyung, which only overflows about once every 20 years. The lake intercepts silt and salt from the saline headwater streams, which would otherwise freely enter the river downstream. M.E.W.

during this period, the gradient of surface flow was reduced along the palaeoriver, creating lakes in the palaeovalley (as evidenced by *lacustrine* sediments). Following this tilting, the diversion of drainage which resulted saw the modern Blackwood River capturing the headwaters of the ancestral Beaufort River and beheading it by cutting through Archaean bedrock south of Lake Towerrinning. The palaeochannel west of Towerrinning has also been cut by Darlingup and Haddleton Creeks, both of which are southward flowing tributaries of the Blackwood River. (The Blackwood catchment shows no evidence in its sedimentary record of penetration by the Eocene Sea. The modern status of the Blackwood is the subject of a case study in *Listen ... Our Land is Crying*.)

The palaeodrainages are of major economic importance in arid Western Australia. The valley calcretes which occur in many trunk valleys form the major freshwater aquifers, and in landscapes where all surface waters are saline they are a vital resource. At Yeelirrie, in the Wiluna area, carnotite-bearing valley calcrete forms a major uranium deposit. Smaller deposits have been reported from Lakes Way and Maitland near Wiluna, and from near Mt Venn. In the Kalgoorlie region, alluvial gold was mined from deep leads. Most of the deep leads are infilled tributaries of the trunk valleys of the palaeodrainage systems.

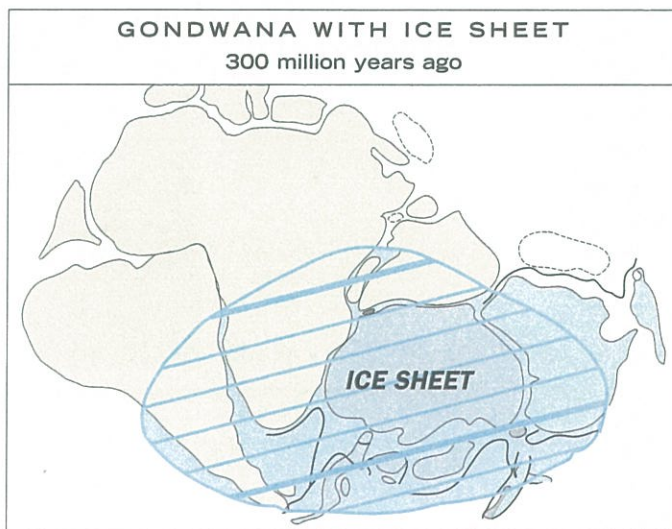
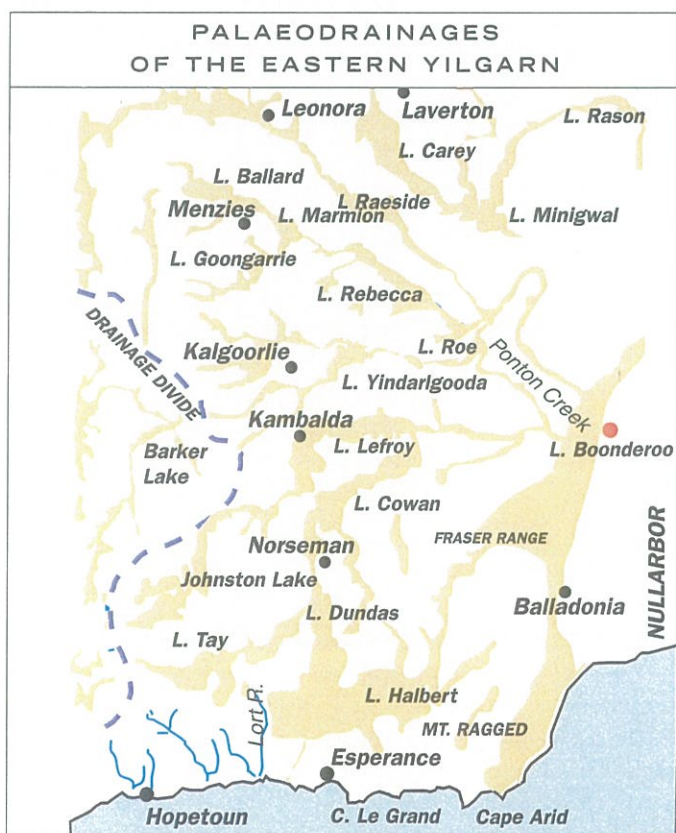
## THE KALGOORLIE REGION

Kalgoorlie lies within the Eastern Goldfields Province of the Yilgarn Craton. Mining of gold, which comes in tellurides and has to be smelted out of the rock, has had a widespread impact on the region. Furnaces needed wood, and wood trains radiated out into the countryside removing anything burnable. Water was always a problem in this arid region and a major pipeline was constructed

from Mundaring near the coast. In recent years much drilling and exploration has taken place, mapping the palaeodrainages which contain saline water to allow expansion of the mining and towns in the region.

Kalgoorlie lies at the centre of the Roe Palaeodrainage,<sup>7</sup> a Cretaceous to Early Tertiary drainage system which discharged eastwards into the Eucla Basin. The Roe palaeoriver flowed through the existing Lake Roe area. This palaeodrainage is separated by palaeo-divides from the Rebecca Palaeodrainage to the north, and the Lefroy to the south.

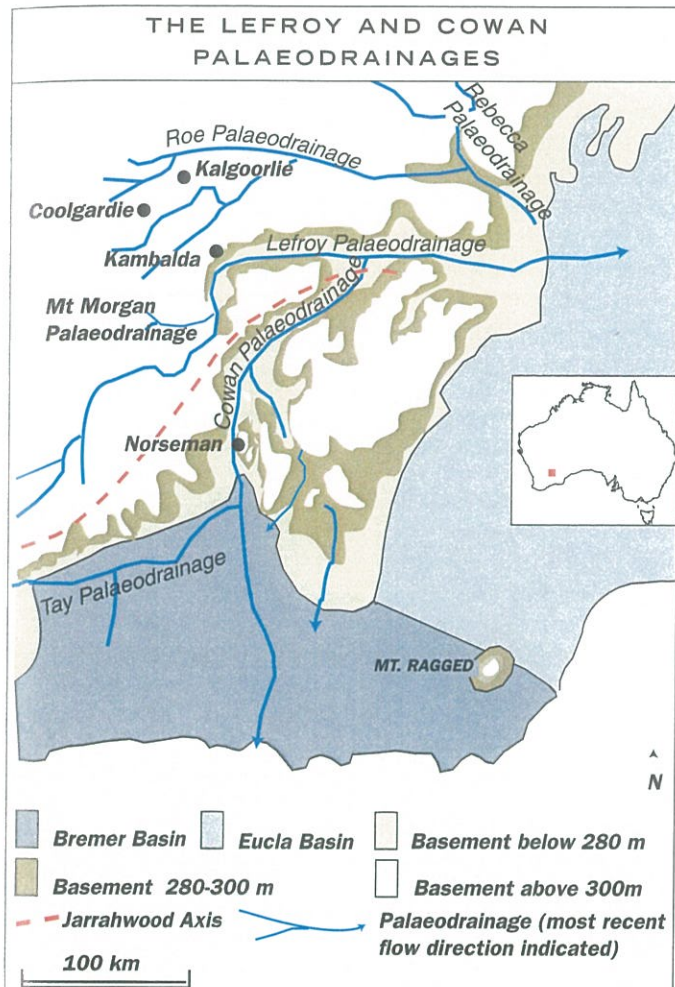
The Kalgoorlie area is part of the Yilgarn Block, with some of the most ancient landscapes preserved anywhere in the world. Gently undulating, with subdued relief, low breakaways, granite tors and greenstone ridges, and with strings of playa lakes in low areas, it reflects the amazing age of its landforms and the processes of deep weathering and erosion to which it has been subjected through geological time. It is considered possible by experts<sup>8</sup> that the area may have been land and already well planated in Precambrian times (as much as 600 million years ago) but, ignoring such speculation, and only considering evidence for which there is some proof, a time frame of nearly 300 million years is no less awe-inspiring. Flat-lying Permian fluvio-glacial rocks on the Yilgarn are evidence of glaciation during the Late Carboniferous to Early Permian ice age. Whether the massive ice sheets which covered the land then were responsible for creating the low relief landscapes, or whether they merely contributed to the flatness by further grinding down the surface over which they moved, is not known. The flat landscapes of hollows and low ridges may have characterised the region before the ice age. In either case, palaeodrainages have since have etched their creases across the ancient planated surfaces.



The north-west to south and south-east trending greenstone belts and intervening granites determine the landforms. Two predominantly greenstone belts in the north-east and south-east of the Kalgoorlie region give rise to ranges of low hills, strike ridges and broken slopes with plains between the ridges. Granite terrain in the north-west and centre of the area consists of sinuous ridges and extensive debris fans. In contrast, granite country in the south-west consists of undulating sandy plateaux with rims of exposed ferricrete, straddling a major palaeodrainage divide between the Swan-Avon Basin (draining to the west) and the Kalgoorlie region which drains to the east. Valleys have been incised into the plateaux

and plains occupy the surrounding areas. Granite hills are numerous in the south.

The chains of playa lakes occupy the palaeodrainage channels,



After Clarke<sup>9</sup>

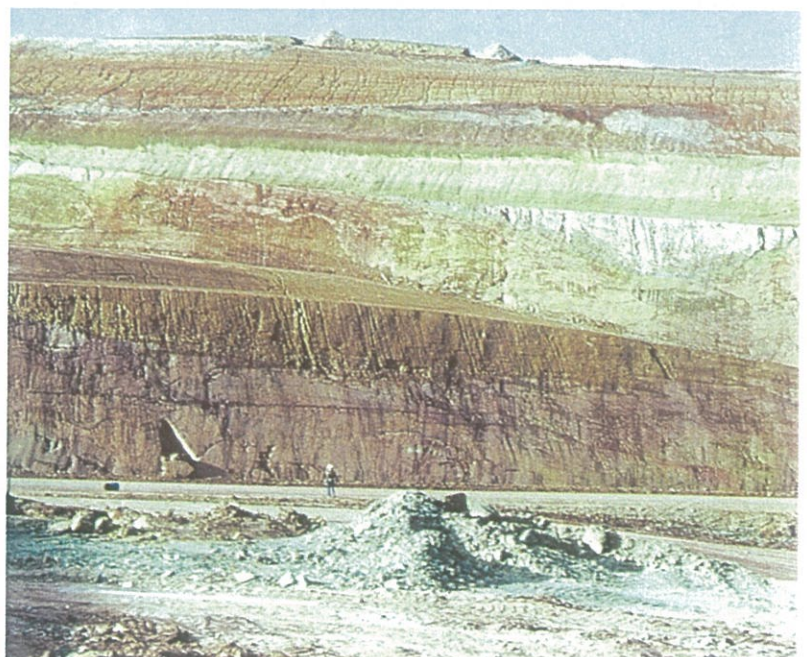
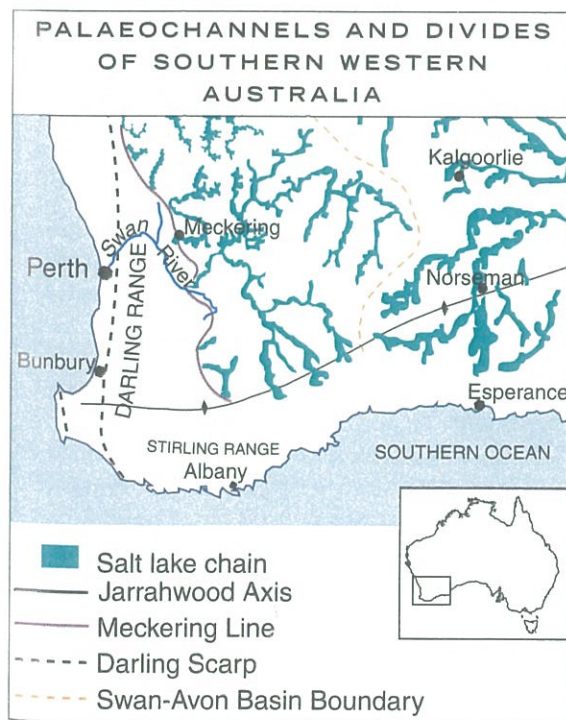
forming a dendritic pattern. Their wide valleys drained east and south-east towards the Eucla Basin, which was a sea during the Eocene and again in the Miocene before it was uplifted to become the Nullarbor, and south towards the Bremer Basin, to the west of the Eucla, which was also a sea during the Eocene.

Eocene sediments, some with plant remains and spongolite, occur as valley fill in parts of the palaeodrainage systems, penetrating as far inland from those palaeo-seas as Norseman. (Spongolite is a sedimentary rock which largely comprises siliceous sponge spicules. Sponges, which have little needles of silica in their spongy tissues, flourished in vast monoculture 'forests' in the warm waters of Eocene seas.) The valleys are older than the tectonic movements along the Jarrahwood Axis which occurred in Mid Tertiary about 30 million years ago, creating a drainage divide parallel to the south coast.<sup>8</sup>

A strong case has been made for the palaeodrainage systems pre-dating the separation of Australia and Antarctica, in which case the markedly south trending valleys (and their connections south of the Jarrahwood Axis in the Esperance region) would represent palaeoriver valleys which ran from Antarctica into Australia.

A timetable of the evolution of the Kalgoorlie region of the Yilgarn shows the following stages:

- **Permian glaciation** created a palaeoplain when ice ground across the landscapes 300 million years ago (or further denuded an even more ancient planated landscape).
- In the **Mesozoic**, slow erosion of the landscape continued. Major valleys of at least Early Tertiary age are incised into what was already a remarkably level land surface.
- **Establishment of a drainage pattern** with major valleys several kilometres wide. The modern lines of salt lakes follow these old valleys. There was a major divide between the Swan–Avon catchment and the drainage in the Kalgoorlie region.
- **The break up of Gondwana** started in the Jurassic. The broad valleys of the Swan–Avon catchment are wide at their start. They used to carry major rivers from Antarctica before rifting. A



Section at the Princess Royal Mine, Norseman, showing Eocene valley fill beneath marine limestone. AGSO

## EVOLUTION OF THE LEFROY AND COWAN PALAEODRAINAGE CHANNELS

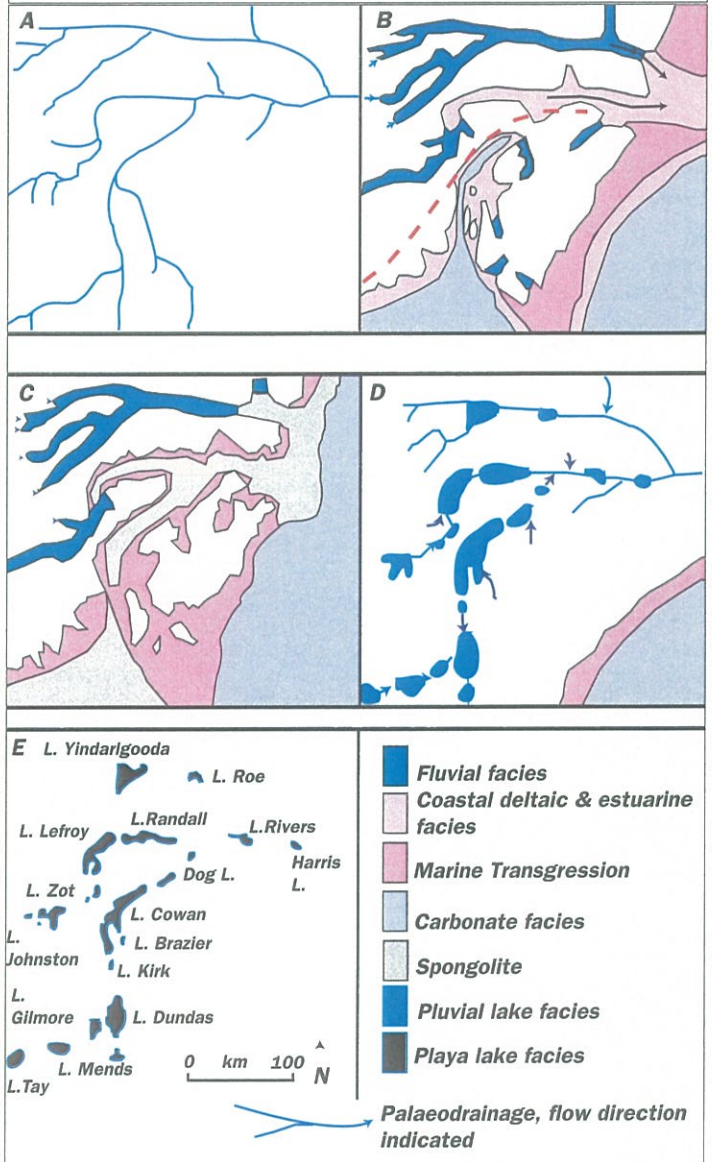


SATELLITE IMAGE: DUNDAS

Landsat imagery provided by the Australian Centre for Remote Sensing (ACRES) Australian Surveying and Land Information Group, DIST Canberra, and digitally enhanced and produced by Satellite Remote Sensing Services, Department of Land Administration, Perth, Western Australia.

Lakes Lefroy, Cowan and Dundas occur within a palaeodrainage system that may have originated in pre-Jurassic times (prior to 200 million years ago).<sup>15</sup> The acute angles formed by convergence of the Cowan and Lefroy systems indicate that the combined system originally flowed north and east. The southern end of the Cowan palaeodrainage has been truncated by the modern coastline at Esperance. Its width there is poorly defined but probably exceeds 10 kilometres. This wide palaeovalley suggests that the original palaeoriver flowed from headwaters in Antarctica, prior to the start of rifting in the Jurassic which created the Bremer Basin.

### PALAEOGEOGRAPHIC EVOLUTION OF THE SOUTH-EAST YILGARN



- A:** Palaeodrainage channel incision, post-Jurassic.
- B:** In the early to middle Eocene, lignitic silt of the Werillup Formation was laid down directly on Precambrian basement. The extent of the following Middle Eocene Tortachilla transgression (into the Cowan palaeodrainage from the Bremer Basin) is shown by the distribution of Norseman Limestone.
- C:** The more extensive Aldinga transgression saw spongolite laid down in the Lake Cowan and Dundas palaeovalleys. The seas regressed and marginal marine and freshwater sedimentary deposits followed.
- D:** Throughout the Miocene semi-permanent lake sedimentation took place and the connecting rivers started to dry. Lake sediments were becoming saline. Gypsum was being deposited in Lake Lefroy by the end of the Miocene.
- E:** The Pliocene saw aridity and salt and gypsum deposits—the Roysalt and Polar Bear Formations—in the chains of salt lakes in the wide palaeodrainage valleys.

After Clarke<sup>15</sup>

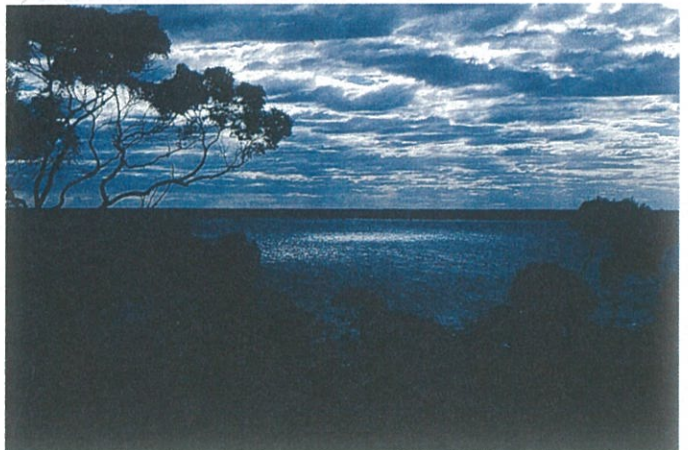
warm, wet climate, even in the high latitudes while Australia was connected to Antarctica, and high mountain ranges in Antarctica, provided water for these major palaeorivers which carved the wide valleys. Major south to north trending palaeovalley systems in the south-eastern Yilgarn, particularly the Cowan palaeodrainage, are also remains of the Antarctica connection.

- **Incision of valleys.** By the Eocene, rivers had cut a system of valleys into bedrock. The Late Cretaceous and Early Tertiary had been warm and wet, and rivers were active. During the Eocene, valley-fill sediments accumulated. An Early to Late Eocene pollen record in Lake Lefroy contains grains from 26 species in 12 genera, including 8 species of Proteaceae, 4 species of *Nothofagus* (southern beech), and tree ferns. Other pollen records of similar age in parts of the palaeodrainage systems indicate an abundance of Araucarian and Podocarp conifers in the vegetation, and *Nypa* palms and mangroves were present in marginal marine areas. The palaeovalleys obviously supported riverine rainforest.
- **Eocene marine incursions.** Two marine incursions occurred during the Middle to Late Eocene. The first, Tortachilla, led to the deposition of marine limestones in the Cowan palaeochannel; the second, more major Aldinga transgression of the Late Eocene penetrated far up valleys, and marine sediments are found at Norseman and near Lake Cowan, as much as 270 kilometres from the present coast. The Princess Royal spongolites were laid down during the Aldinga incursion.
- **Tectonic activity uplifted the area,** in some places by as much as 300 metres, while the southern edge tilted, forming the Jarrahwood Axis parallel to the coast. Some of the Eocene palaeorivers crossed this axis, as did the Cowan near Norseman, and the slope of rivers south of this Axis is reversed.
- **Landscape evolution after the Eocene.** After the filling of the valleys with Eocene sediments, weathering and erosion continued. Duricrusts were formed on surficial deposits at different times. Australia was drying out as it drifted northwards as an island continent, rivers on the Yilgarn were drying up, and those in the palaeovalleys east of the main drainage divide have not run perennially in the last 15 million years.

## LAKE BOONDEROO AND THE EASTWARD-DRAINING PALAEORIVERS

Lake Boonderoo lies on the western edge of the Nullarbor Plain, about 20 kilometres south-east of Kitchener.<sup>10, 11</sup> Ponton (Goddards) Creek, which follows the lower half of the channel in a north-west to south-east trending palaeodrainage which extends for approximately 500 kilometres, terminates in the lake. The palaeodrainage contains the string of Raeside playas, which extends from 75 kilometres west of Leonora. A large inward-draining region west of the first lake in the chain was headwaters for the palaeoriver. A second palaeodrainage, south of the Raeside, contains the Lake Rebecca playas. It joins Ponton Creek which, like all the other drainages around the edge of the Nullarbor's limestone plain, was cut short when the plain was uplifted. The palaeochannels drain the north-eastern Goldfields.

Lake Boonderoo is normally dry. In recent times it has filled only twice, with 20 years between the events:



Lake Boonderoo, November 1996. ANDREW CHAPMAN

- **1975:** A year of above average rainfall including Cyclone Trixie which deluged the Murchison and Goldfields region in February. Water remained in the lake for eight years following this event. It was suggested that over-grazing by sheep of the eastern Goldfields as far away as Leonora contributed to this lake-filling event and the added run-off enabled the water to penetrate further downstream and reach the lake. The railway bridge was washed away for the first time since World War I, and no records exist of previous flooding there.
- **February 1995:** Cyclone Bobby brought torrential rain to the north-eastern Goldfields. Rainfall figures for February in millimetres (mean in brackets) illustrate the magnitude of the rainfall event: Cashmere Downs 367 (23), Kalgoorlie 241 (12),

Leonora 285 (25), Sandstone 271 (26), and Yundamindra 347 (22). There had been some water as far south in Ponton Creek as Goddards Bridge (crossing the railway) before the cyclone as a result of some local rainfall, and it took the water from the cyclone six weeks to reach the bridge, and another week to run out across the edge of the Nullarbor and fill Lake Boonderoo. Waterbirds appeared on the lake shortly afterwards, as they do on other desert lakes whenever they have water.

## WATERBIRDS AND WESTERN AUSTRALIA'S DESERT LAKES

The playas of the Yilgarn Block in Western Australia are usually dry, salt-encrusted pans, unbearably hot in summer, freezingly cold in winter nights, and apparently devoid of life. Some of them are enormous—up to 1800 square kilometres in area. Occasionally the tropical cyclones which develop off the north-west coast degenerate into rain-bearing depressions and travel across the continent in a south-easterly direction, dumping 300–400 millimetres in three or four days. The land is flooded, and the dry salt pans are transformed into small seas. **12, 13**

A miraculous transformation occurs and abundant life appears from apparently nowhere in the playas—now lakes. It is hard to imagine how small eggs, like those of the fairy shrimp, *Parartemia*, could survive the heat, the cold, the salt and the dryness over long periods—up to ten years between good drinks in some cases—and be ready to swell and hatch and populate the saline, ephemeral waters for a brief period. But this they do in their billions.

Still more miraculous is what happens next. What signal is received, what inbuilt genetic memory and response is activated, is unknown—but within days of the filling of the lakes, banded stilts in their thousands arrive, having flown up to 1000 kilometres from permanent waters near the coast. They have come to breed, and they have been waiting for the signal to do so for five or even up to ten years! Within two weeks of the end of the cyclonic rains they have formed island colonies of 20 000 or more nests, all 30 centimetres from each other, each containing two to three eggs. Three weeks of incubation follow, and within a day of the chicks' hatching they are feeding on shrimp at the lake's edge. Small parties leave the islands, paddling downwind, feeding as they go, until tens of thousands of birds are gathered in the shallows at the end of the lake, often as much as 50 kilometres away from their nests.



Lake Barlee—full in June 1992. ANDREW CHAPMAN



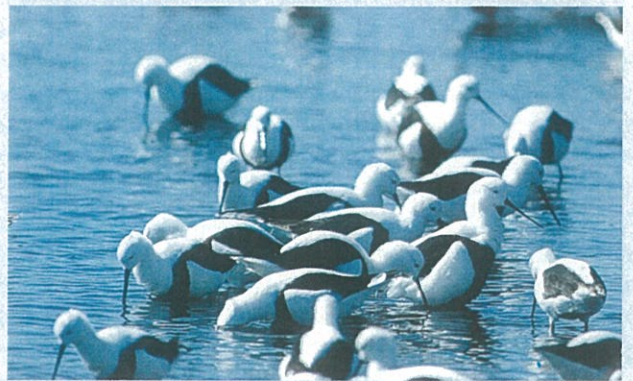
A banded stilt colony, Lake Marmion. ANDREW CHAPMAN



Stilts flying over Lake Marmion. ANDREW CHAPMAN

### BANDED STILTS

Banded stilts are Australian endemics. **12, 13** They are unique among the 214 species of wading birds in the world in that they nest colonially, lay white eggs (with a few black streaks and blotches), have white, downy chicks, put their young into creches, and have a special habitat requirement—recently flooded playa lakes—because they rear their young on brine shrimps. Only 20 nesting events have ever been recorded, three in inland South Australia, and the remainder in the southern interior of Western Australia.



REG MORRISON

It takes seven weeks for the chicks to be fully feathered and ready for the long flight home. The whole breeding event encompasses less than four months. Usually, the lakes dry within six months, becoming steadily more saline as they evaporate, and eventually killing all the shrimps. But the shrimps' magical drought-resistant eggs are safely in the silt and will wait for the next flood ... and for the next breeding event of those wonderful birds for which they provide the energy and sustenance.

While the banded stilts and the brine shrimps have this almost-beyond-belief 'coincidental' relationship, which presumably has a very long evolutionary history, other waterfowl also make use of the lakes and wetlands of the arid interior. Unlike the stilts, which only breed when they 'know' that the food source is there, other species are opportunistic and nomadic and do not restrict their breeding exclusively to the rare major events for which they may have to wait for a decade. Whenever water arrives in the arid interior—and its persistent presence for long enough to sustain waterfowl breeding is almost randomly scattered—some birds find it and use it. In exceptional rainfall years, like 1992–93 in the Goldfields region, ducks of many sorts, grebes, herons, coots, crakes, black swans, plovers, avocets, dotterels, terns and stilts were all breeding in large numbers in ephemeral freshwater lakes and wetlands as well as in the brackish to salt playa lakes.

## THE ESPERANCE REGION: *landscape evolution of the south coast of Western Australia*

At the start of the Eocene (55 million years ago) Australia lay between 60° and 30° South, but even the southern edge of the continent had a warm, wet climate. (Climate in the Middle Eocene is believed to have been subtropical; a 5°C decrease occurred with cooling and drying in the Late Eocene. Rainfall was about 1500–2000 millimetres throughout most of the period.) A proto-Leeuwin Current down the west coast of Western Australia and around the corner into the Great Australian Bight Basin provided warm water for a proliferation of sponges. Global sea levels were high and the sea entered the on-shore Bremer Basin (which roughly corresponds to the Fitzgerald National Park, with an extension along the coast eastwards into the Esperance region), and the Eucla Basin (which was to become the Nullarbor). In the Bremer Basin, a wide embayment of the Southern Ocean resulted and marine limestones, including spongolite layers which are mainly derived from siliceous sponge spicules, were laid down. Sea penetrated far up river valleys from the main embayment and also penetrated inland in the Esperance region along major palaeodrainages northwards as far as Norseman. (Palaeodrainages flowing into the Eucla Basin epicontinental sea also have spongolite deposits in west to east flowing palaeorivers of the Lefroy and Cowan palaeochannels.)

The Barren Ranges, between Bremer Bay and Hopetoun, have a wave-cut basal platform 90 metres above sea level, formed by the Eocene Sea. Peaks of the Barren Ranges and other promontories in the Albany–Fraser Province were islands in the Eocene Sea, just like the islands of the Recherche Archipelago today. The spongolite mesas in the Fitzgerald National Park are the result of the dissection of the plateau that originated from the uplift of the marine sediments after the sea had retreated. They are now 300 metres above sea level.

The Eocene Sea was at its greatest extent in the Late Eocene. After its retreat, changes occurred to the regional drainage. A new divide



SATELLITE IMAGE: LORT RIVER

*Landsat imagery provided by Australian Centre for Remote Sensing (ACRES) Australian Surveying & Land Information Group, DIST Canberra, and digitally enhanced and produced by Satellite Remote Sensing Services, Department of Land Administration, Perth, Western Australia.*



*A spongolite breakaway on Twertup Creek in the Fitzgerald National Park. Flat-topped mesas in the background are remnants of the plateau created when the marine sediments were elevated and later eroded. M.E.W.*

(the Jarrahwood Axis) developed parallel to the south coast on a line from Augusta near Cape Leeuwin, to Kojonup and Ravensthorpe, and on to the edge of the Nullarbor. This axis resulted from the uplifting of the Darling Plateau, which began in the Oligocene, about 30 million years ago, causing tilting of the south coastal region towards the south. The elevated divide which developed along this axis, the Ravensthorpe Ramp, rejuvenated rivers to its south and reversed the flow in the southern portions of ancient valleys which had carried rivers northwards into Australia from Antarctica.

Fossils in sediments in the Bremer Basin are a key to interpreting

## THE NULLARBOR AND ITS WATER RESOURCES

Drainage lines from terrain surrounding the Nullarbor extend out only a short distance onto the flat limestone plains, and surface water is limited, except after rain. The extensive cave systems within the limestone contain considerable reserves of fresh water, however. The region has been arid ever since the Miocene when it was uplifted to become a plateau. (It was under the sea in the Eocene and again during the Miocene, when its marine limestones were laid down.)



*Weebubbie Cave, beneath the Nullarbor.* REG MORRISON



*Abrakurrie Cave.* REG MORRISON

The Oldfield and Munglinup Rivers provide important vegetated corridors between the coastal strip and large tracts of natural bushland in the upper catchment. Road reserves, 20 to 200 metres wide, also provide important corridors between bush remnants.

Wetlands, in the form of permanent and intermittent lakes and swamps, occur on the sandplain. Lake Shaster, just west of the Oldfield catchment and adjacent to the coast, is one of the largest wetlands in the district. It is monitored by CALM and Birds Australia for waterbird usage. It is hypersaline and open, supporting few birds and little breeding. A number of small wetlands are present on farmland. The majority have little or no remnant vegetation, other than swamp yate and paperbark.

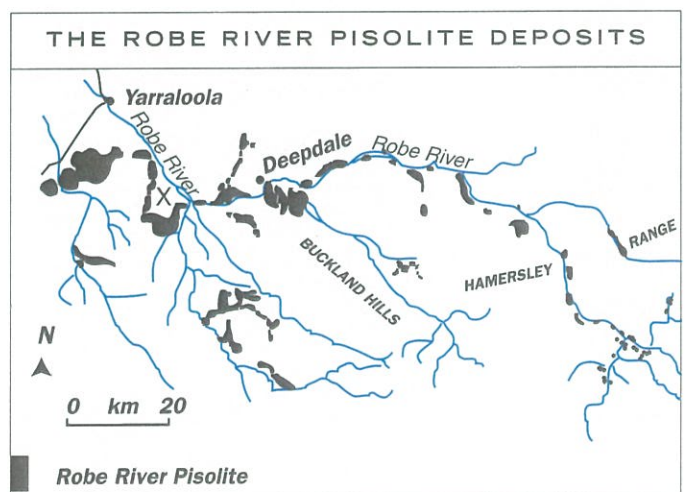
## THE PILBARA

### PALAEODRAINAGES IN THE HAMERSLEY RANGES

The courses of palaeorivers can frequently be traced by mapping features capped by duricrusts, which were formed when iron, silica or calcium-rich waters hardened valley sediments along river courses long ago, and which now form the high features in landscapes. These features have been produced by 'inversion of relief' processes in which the softer regolith materials around them have eroded away through time while their duricrusted capping has protected the sequence below them.

In the iron-rich Hamersley Ranges in Western Australia, spectacular inversions occur due to the transport of ferruginous material in rivers, such as the palaeo-Robe River system, from the upland towards the coast. Such detritus weathers and breaks down and the free iron cements the local sediments in the river channel, forming ferricrete (which is pisolitic in form, when the iron nodules are like small marbles or peas in the iron-cement matrix). The alluvial Robe River pisolite was reconstituted from weathered detritus in Eocene times (about 45 million years ago). It protected the valley bottoms from erosion, and today they stand proud as the sinuous lines of ferricrete-capped mesas, dramatic features in the west of the Hamersley Basin.

The ancestral courses of some tributaries of the Hardy, Beasley, Cane and Duck Creek palaeorivers are also preserved and left in local positive relief as a result of inversion. Some have no modern descendants, but many have migrated laterally and remain active a short distance from their precursors. Some of the inverted palaeochannels form landscape features which have persisted for 60 million years.



After Twidale<sup>17</sup>

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