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Evolution of the river systems of the south-west drainage division, Western Australia

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Abstract

Drainage of the central Yilgarn System is confined within two north-south watersheds, the previously described Central Watershed and the Median Watershed defined here. Runoff today is either intermittent or inactive, but the entire system is gathered to a single outlet through the Median Watershed where it escapes to the Avon. The shape of the catchment with prevalence of north-south alignments, many directed to south coast rivers, suggests that the System originated with southerly drainage. The System is bounded on the south by a watershed parallel to the south coast which formed in the middle to late Cretaceous by marginal uplift of the craton during separation from Antarctica, causing reversal of drainage. There appears to have been a simultaneous down-warp along the line of the present Yilgarn River, the "Chin-Smith lineament". Before uplift the rivers incised canyons into the rifted margin of the continental platform. Subsequently the margin sagged towards the rift forming the Ravensthorpe Ramp and carrying down the valleys as submarine canyons. Along the western part of the south coast there is a secondary axis of uplift, the Stirling Range Axis, 50 km further south. On the eastern side there is evidence for a palaeoriver, the Woolgangie, which has been truncated by the Lefroy-Cowan System. Drainages to the west coast formed in the Mesozoic bounded inland by the Median Watershed. In the early Cretaceous, uplift was associated with continental separation. An extensive canyon was incised at the edge of the rift and later drowned. High sea level prevailed in the Perth Basin to the Late Cretaceous. Regression then promoted rejuvenation of the rivers. The Brockman, Mortlock North Branch and Avon owe their alignments to the Chittering and Jimperding Metamorphic Belts. In the Late Eocene, marginal uplift of the craton by 150-200 m in a belt 80 km wide brought up the Darling Range and caused diversions of drainage. Headwaters of the two Moore Rivers (north and east branches) were diverted to the south, as was the upper Mortlock (north branch). Further down, the Mortlock was relocated some distance east. The combined Avon and Yilgarn Rivers were diverted north, from a westerly course, to join the Mortlock. The Arthur and Beaufort Rivers were cut off from the Collie catchment and diverted to join the Blackwood. Depth of the palaeochannels here and beneath the Avon-Yilgarn afford proof of Darling Range uplift. Monadnocks in the Darling Range which have also been cited as evidence for uplift have been identified and mapped.

Introduction

Mulcahy & Bettenay (1972) divided the State into six "major drainage divisions", and Bettenay & Mulcahy (1972) gave a more comprehensive description of valley form and surface features of the South-West Drainage Division. This included centrally the catchment of the Avon and its tributaries (their Avon System, here called the Swan-Avon System) and laterally in the south-west some smaller catchments grouped as the West Coast, Blackwood and South Coast Systems (Fig 1). In addition they included a Monger System to the north-west comprising drainages connecting to the Moore River (Fig 2). These authors foreshadowed their intention to produce a series of papers in which the other drainage divisions would be discussed and it is regrettable that they did not appear. The present study deals with the South-West Drainage Division, omitting the Monger System for reasons of space.

Studies of the surface features of the Western Shield have declined in number in the past twenty years, after numerous publications in the 1960s and 1970s, although new topographic and geological information has continued to become available mainly from two sources. First, the latest sheets to appear in the National Topographic Map Series at scales of 1:100 000 and 1:250 000 (NATMAP, Canberra); these are contoured at 50 m intervals and show abundant spot heights, whereas few heights were previously available. They enable a much better understanding of the conformation of river catchments and of the major features of the whole Western Shield which are difficult to appreciate on the ground owing to the general flatness of the country. Secondly, a 1:250 000 series of geological maps has been completed (Geological Survey of Western Australia); these conform to the grid boundaries and sheet names of the topographic series and provide a complementary treatment of surface features.

It is now possible to reassess the drainage systems in the light of accurate mapping (*cf* diagrams in Mulcahy & Bettenay 1972) and to go beyond descriptions of soils and valley forms to consider the past history and evolution of the drainage as has been done by Clarke (1993, 1994) and by Kern & Commander (1993) for the catchments surrounding the playa lakes of L Lefroy, L Cowan and L Yindarlgooda which lie adjacent to the South-West Drainage Division to the east (Fig l). They were able to draw upon a large body of subsurface data obtained by drilling which showed the location and geological history of palaeochannels. Within the South-West Division, few comparable data are so far available but recently Salama (1997) reported on drilling and sounding in the alluvia of the lower part of the Yilgarn River (as named by Bettenay & Mulcahy 1972) for 135 km from Lake Baandee down to its confluence with the Avon. In recent years there have been other reports on alluvial and lacustrine sediments in palaeodrainages east of the Darling Range (Wilde & Backhouse 1977; Hill & Merrifield 1993; Waterhouse *et al.* 1995), all of which are relevant to the evolution of the drainage. Further unpublished data collected in the course of groundwater exploration are held by the Water and Rivers Commission.

Methods

The necessary detail showing heights above sea level, the location of active watercourses, of intermittent or inactive drainage lines and watersheds, was obtained from the latest maps in the National Topographic Map series, scale 1:250 000 (NATMAP, Canberra). A version of each sheet comprising this detail was reduced to 1:1 000 000 and assembled into a general map of the Drainage Division which after further reduction appears as Fig 1. The standards to which the 1:250 000 topographic sheets have been produced vary quite widely in some cases. While all are contoured, abundant spot heights are usually given in addition on sheets covering the interior but are very few on those for the west and south coasts, e.g. Perth, Pinjarra, Collie, Pemberton-Irwin Inlet and Mt Barker sheets. In these cases 1:100 000 sheets were used. Such detailed heights were required for stream gradients and the watersheds. Other relevant mapping was Beard's (1998) study of the position of the central watershed of the Western Shield which bounds the Drainage Division on the east, the "major continental divide" of Bettenay & Mulcahy (1972). Beard (1998) also plotted the lateral east-west watershed dividing the Swan-Avon and Monger Systems, with a substantial revision. Bettenay & Mulcahy (1972) extended their Avon System far to the north with a hypothetical Ninghan palaeoriver leading south through Lake Moore, whereas this lake has been shown by later authors (Beard 1973; van de Graaf *et al.* 1977) to belong to the Monger System. These watersheds are shown in Fig 1.

Results

General Overview

Fig 1 shows the South-West Drainage Division, excluding the Monger System to the north, and with parts of the Roe, Lefroy and Cowan drainages to the east. The South-West Division is bounded on the east by the central watershed of the Western Shield and on the north by the watershed with the Monger System. Both of these have been mapped and described by Beard (1998). They are situated on broad expanses known as sandplains (Bettenay 1984) which Beard (1998) held to preserve portions of a plateau surface formed by denudation during the Mesozoic prior to the mid-Cretaceous. They are remarkably even and continuous. The central watershed rises gently from a height of 415 m in the south to 495 m at its junction with the Swan-Avon/ Monger watershed which similarly slopes down gently towards the edge of the Yilgarn Craton at 250 m. Heights along the watersheds shown in the figures are derived from spot heights, contours and survey beacons. Internal watersheds include those separating catchments draining to the west coast and the major south coast watershed which is the inland limit of drainages to the southern coastline. In addition this study brings to light a new and important watershed, termed the Median Watershed as it divides the South-West Division roughly in half. It trends NNW-SSE parallel to the west coast and about 200 km inland. Taking a course of NNW it leaves the south coast watershed near Ongerup, and running more or less parallel to the Pingrup River, passes west of Lake Grace, slightly west of Corrigin and to Mt Stirling where it is crossed by the Yilgarn River. North of this gap at Mt Caroline the watershed resumes, passing west of Kellerberrin, between Trayning and Wyalkatchem, east of Lake Wallambin and on to join the Swan-Avon/ Monger watershed. The Median Watershed is remarkably linear and regular in height and is breached at only one place, a relatively narrow gap between the granite inselbergs of Mts Caroline and Stirling. As the name Stirling already appears rather frequently on the map of Western Australia I propose to name this feature the Caroline Gap. In more pluvial times, all drainage from the huge interior catchment of the Yilgarn and its tributary rivers was concentrated here to escape to the Avon River. Otherwise the Median Watershed effectively separates all drainages flowing directly to the west coast from the interior drainages which I propose to name here the Yilgarn System, regarding it as separate from the Avon System as it appears to have had a different origin and history. It is remarkable that the catchments of all the west coast rivers terminate at the Median Watershed while the drainage from the further interior breaks through at a single point. Taking into consideration also that the drainages in the southern half of the Yilgarn System are aligned with rivers on the south side of the south coast watershed, it seems logical to assume some history of drainage reversal.

In the context of the whole Western Shield, the Median Watershed can be seen to represent a bifurcation of the Central Watershed (Fig 2), which in the north is central to the Shield and trends approximately north-south (Beard 1998) but at its junction with the Yilgarn/Monger watershed it swings to the south-east for a long distance (300 km) and then back to the south-west (Fig 1). The Median Watershed can now be seen to be continuous with the watershed between the Yilgarn and Monger Systems and to constitute a bifurcation embracing the Yilgarn System. This adds to the impression that the Yilgarn System was originally directed towards the south coast, not the west. It may be suggested that the shape of the Yilgarn System indicates that it formerly included the upper portions of the Lefroy and Cowan drainages, and has lost them by river capture. In this event the Central Watershed would have continued to the south-east, although there is no trace of a watershed today.

However, Beard (1998) pointed out that a valley south of Woolgangie is aligned to one of the very few gaps in the Central Watershed and that this axis may be continued through the north-south alignment of Lake Johnston to another gap in the watershed between the Lefroy and Cowan drainages and so through Lake Tay and Pyramid Lake, and another gap, to the south coast. It is suggested that this alignment reveals a palaeoriver, to be termed the Woolgangie Palaeoriver.

Description of the Median Watershed

Where it leaves the south coast watershed, the Median Watershed is 339 m above sea level; northward it soon rises to 350 m, and the 400 m contour is crossed west of Lake Chinokup. From here, heights of 350-400 m are maintained and the watershed is crested almost entirely with sandplains. On the Corrigin map sheet a maximum height of 435 m is attained at Traysurin Hill east of Harrismith; thereafter heights are steadily between 350 and 400 m and the association with sandplains is maintained. North of Corrigin beyond Wogerlin Hill (> 350 m) the sandplain has been eroded and becomes a stony plateau with granite outcrops (Beard 1980). On the Kellerberrin map sheet the watershed passes through Pantapin at 350 m but in dissected country where the heights are maintained by granite outcrops. Between Mt Stirling (^{3} 365 m) and Mt Caroline (340 m) is the gap where the channel of the Yilgarn River passes, marked with a spot height of 229 m. North of Mt Caroline the watershed is at first only at 300 m, rising rapidly to 336 m and to 350 m west of Kellerberrin. At Jeljelabine Well 8 km further north, there is a col between 300 and 350 m suggesting a possible former drainage outlet to the Mortlock River. Otherwise, from here to the north end of the Median Watershed, heights are between 350 and 400 m. Patches of sandplain reappear and become more or less continuous from 25 km north of Kellerberrin. As argued by Beard (1998), these sandplains are considered to preserve portions of the Mesozoic surface of the plateau, so that the Median Watershed is of considerable antiquity. Erosion has affected the Watershed for as much as 50 km north and south of the Caroline Cap, but otherwise its surface is generally well preserved.

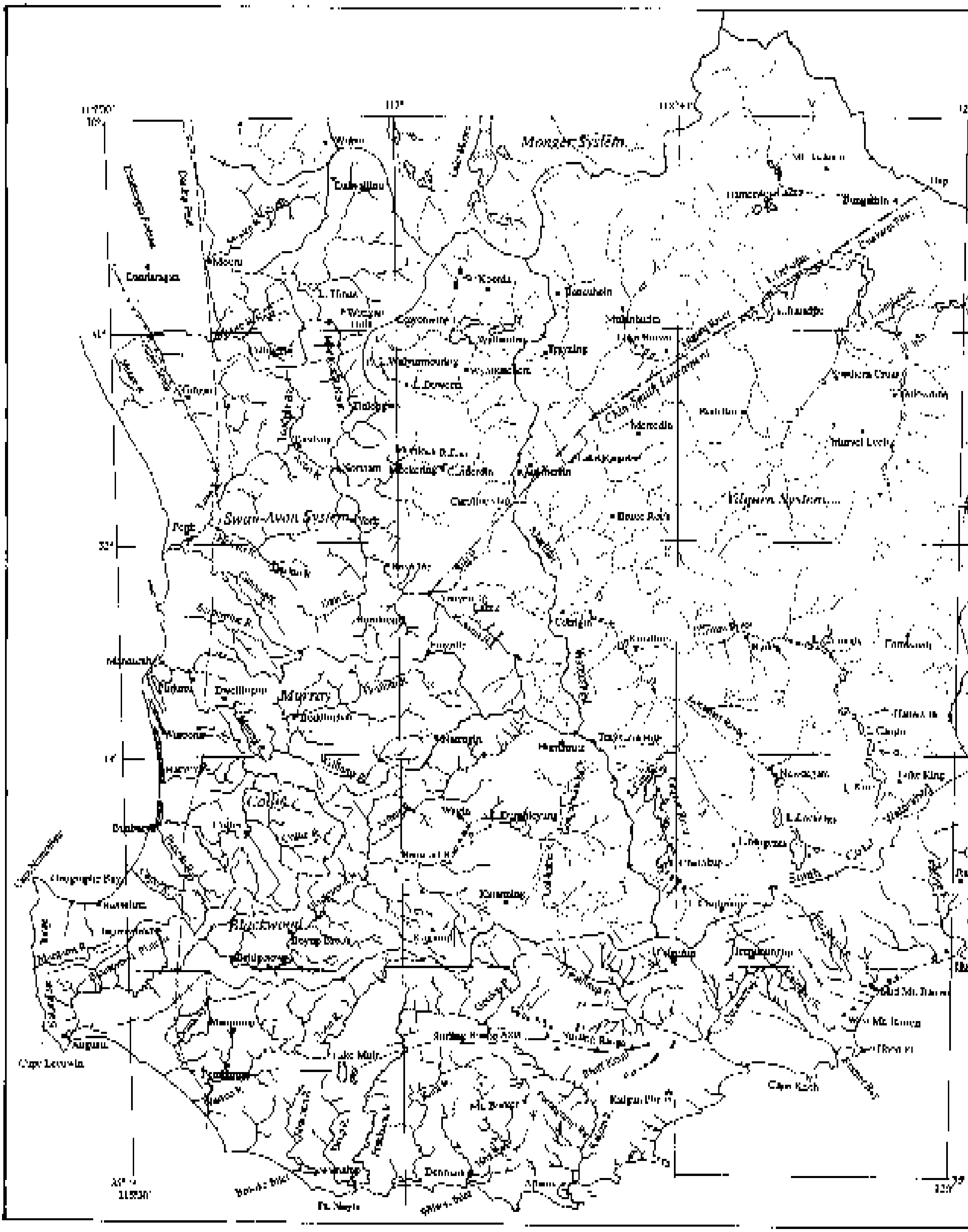
The Swan-Avon System

A sketch profile of the Swan-Avon-Yilgarn Rivers was included by Bettenay & Mulcahy (1972) but a more accurate plot taken from topographic maps is now possible (Fig 3). Heights are from spot heights, contours and bench marks along the way. Length is measured along the valley ignoring minor winding in the case of active watercourses, and directly across playas and salt flats where drainage is intermittent.

The Swan-Avon System falls into several distinct parts. The lowest portion known as the Swan River (reaching the sea at Fremantle; Fig 3) flows across the coastal plain after emerging from the Darling Range at Walyunga, receiving as tributaries the Helena and Canning Rivers which arise in the Range. Above Walyunga the river comes down through the Darling Range in a deeply incised valley on a steep grade, falling 120 m in 62 km (1.93 m km^{-1}). On the coastal plain the grade is only 0.38 m km^{-1}. On its passage through the range, the river receives two tributaries from the north, the Brockman River and the Julimar Brook, with the Toodyay Brook coming in higher up at Toodyay. The Brockman River continues the alignment of the Moore River further north, following the line of the Darling Fault, but has moved a few kilometres to the east of the fault by exploiting the Chittering Metamorphic Belt (Wilde & Low 1978) where some members are more erodible than the common granite.

Above the confluence with the Brockman, the river is known as the Avon because the early settlers on the Swan discovered it independently and did not realise that it was in fact the upper Swan River. The Avon proper rises 200 km to the south-east, near Harrismith, and flows through broadly undulating agricultural country. Between Toodyay and Northam the grade is 0.65 m km^{-1}, above Northam through York and Beverley it is slightly less, averaging 0.52 m km^{-1} as far as the Yenyening Lakes. At Northam, the Avon is joined by the Mortlock River, which actually consists of two separate streams although they are named as the North and East Branches. The North Branch comes down from as far as Dalwallinu while the East Branch has a complicated catchment further inland. The North Branch forms a conspicuous north-south alignment with the Avon and Dale Rivers as they have all exploited the Jimperding Metamorphic Belt (Wilde & Low 1978), forming a distinctive topography of rounded hills that is characteristic of these valleys (see York Vegetation System, Beard 1979). In the far north of the North Branch catchment, there are signs of diversion of drainage where west-trending tributaries are ponded at Lake Hinds and turned to the south instead of continuing west to the Moore River. Further downstream between Goomalling and Bolgart, the Mortlock River runs southward parallel to the Toodyay Brook with about 25 km between them, and the geological map (Wilde & Low 1978) shows this interfluve as a broad area of colluvial deposits. It forms a nearly flat plain scattered with small lakes at a general height of 240-260 m, standing about 50 m above the Mortlock River on the east side. This can be interpreted as an abandoned valley of precursors to the present rivers. The Mortlock River today flows due south in a valley floored with alluvial deposits as far as Hulongine. The grade from Lake Hinds to this point is 0.96 m km^{-1}. From Hulongine down to the confluence with the Avon at Northam, the Mortlock River turns more to the west in a narrower valley, suggesting a steepening of grade, but this is hardly significant, being 1.05 m km^{-1} over this distance.

In the catchment of the East Branch, drainage in the north is first collected in Lake Wallambin and the Cowcowing Lakes with a channel to the west through salt flats and small playas as far as Lake Walyormouring, altitude ^{3} 268 m (lake level variable). The grade on this stretch is very low, only 0.23 m km^{-1}. Drainage further to the west is blocked by a north-south ridge running at 320 to 340 m, though there is a gap <300 m south-west of Lake Walyormouring, which may indicate a former outlet to the Mortlock North Branch. Drainage at the present day turns south-east to Lake Dowerin (251 m) where it continues to the south through salt flats and small playas until, between Kellerberrin and Cunderdin, it turns west through Meckering to become the active Mortlock River. On the map this sinuous course appears unlikely, traced only through inactive channels, but the levels and


Swan-Avon System
Murray
Collie
Blackwood
Geographe Bay
Augusta
Cape Leeuwin
Lake Muir
Mandurah
Pinjarra
Harvey
Bunbury
Busselton
Northam
Meckering
York
Narrogin
Wagin
Katanning
Merredin
Bruce Rock
Denmark
Lake King

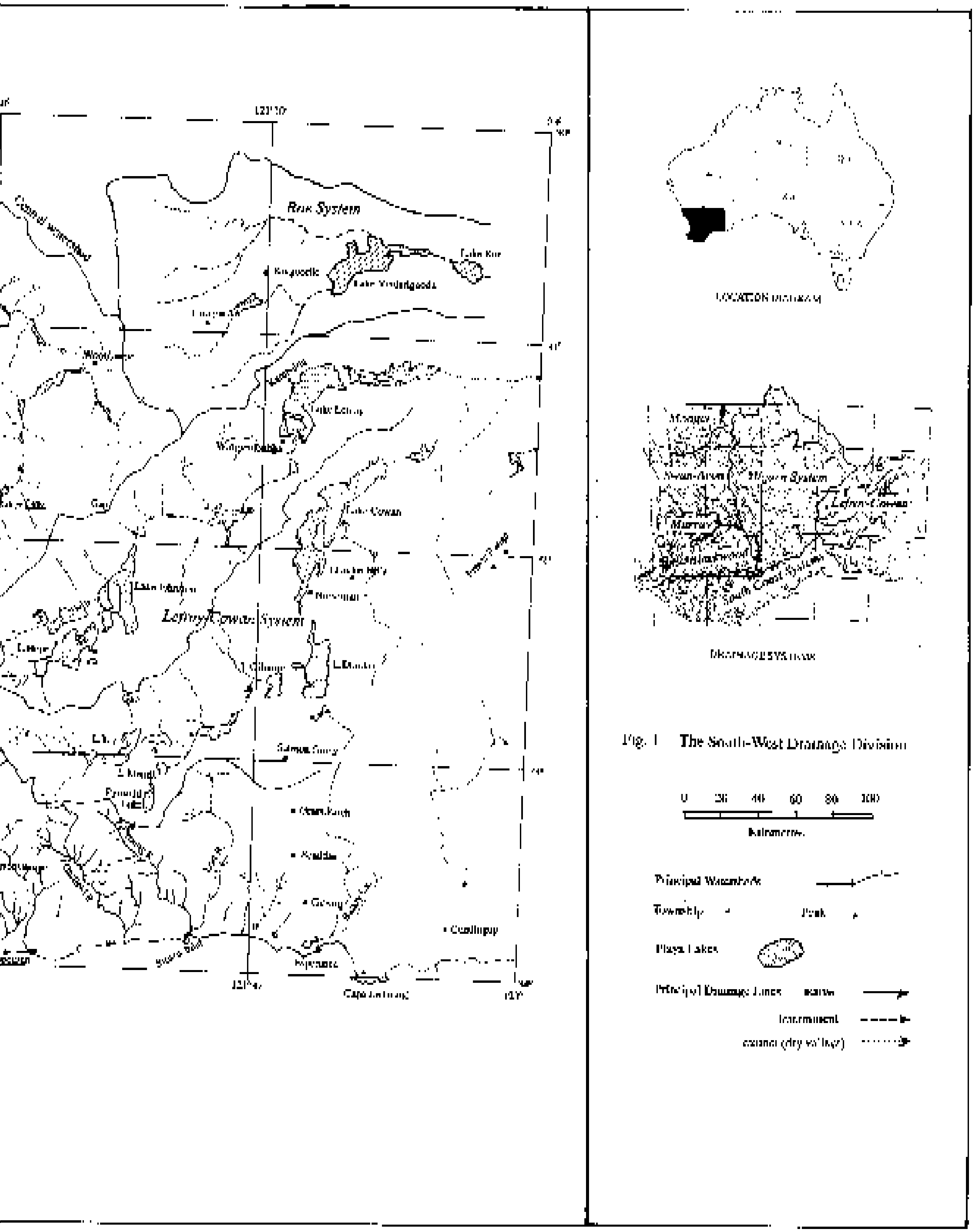


Fig. 1 The South-West Drainage Division

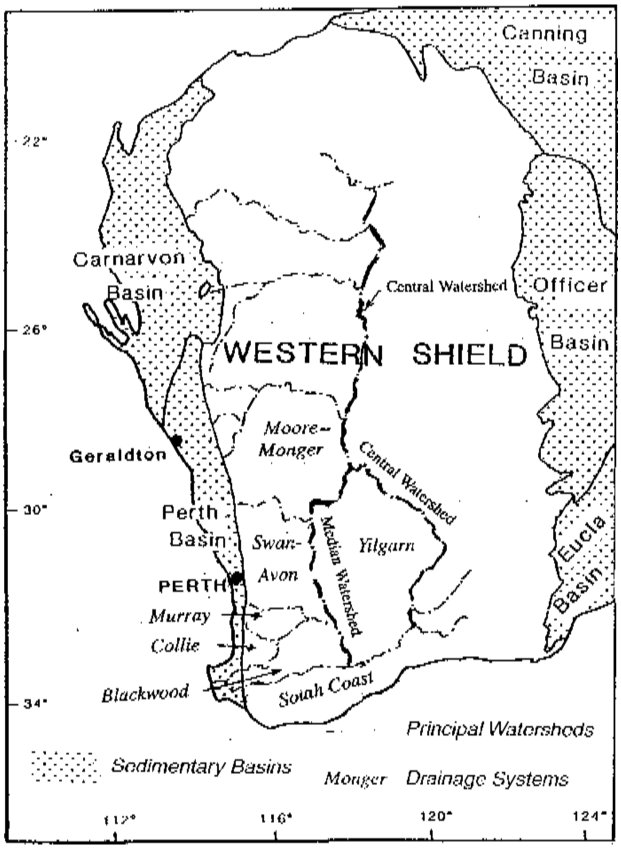


Figure 2. The Western Shield showing the Central Watershed, Median Watershed and other principal watersheds.

mapping of the salt lands prove it to be factual. The average grade from Lake Walyormouring to Meckering is as much as 0.60 m km^{-1}, but after crossing the well-known Meckering Line (Mulcahy 1967) it steepens to 1.28 m km^{-1} to Northam.

At the Yenyening Lakes, 20 km south-east of Beverley, the Avon River is joined by an intermittent channel which in more pluvial times must have brought in the entire run-off from the inland plateau, a huge area extending 300 km to the east and 400 km north to south. This channel comes down 70 km from the Caroline Cap in the Median Watershed, as described above. Salama (1997) showed that this channel, locally called the Salt River, overlies a deeply incised palaeochannel about 70 m deep below the present surface, and relatively narrow. By contrast, the grade of the palaeoriver is only 0.35 m km^{-1}, much the same as the present day and implying sluggish flow. Samples from two boreholes at the Yenyening Lakes were found to be no older than Miocene, contrary to expectation of an Eocene date in keeping with other deposits reported east of the Darling Range by Wilde & Backhouse (1977), Hill & Merrifield (1993) and Waterhouse *et al.* (1995). Salama (1997) accepted the suggestion of Mulcahy *et al.* (1972) that the Avon had formerly flowed over the present Darling Range through the Darkin Swamp and down the course of the Helena River, and considered that a general uplift of the Darling Plateau had ponded drainage in the lower Yilgarn River with formation of a "huge lake" which had eventually drained laterally through the present Avon. This will be discussed later.

The West Coast System

South of the Swan-Avon River there are some small active rivers rising in and draining the Darling Range, principally the Murray and Collie Rivers. The Swan River has two tributaries rising in the Darling Range, the Helena and Canning Rivers, which unite with it on the coastal plain. South of these is the short Serpentine River which peters out on the plain, then the larger Murray River which reaches the sea at Mandurah via the Peel Inlet. The Murray has two tributaries, the North and South Dandalup Rivers, which come down from the Range and join it at Pinjarra. Upstream the Murray River is formed by the union of two tributaries, the Hotham and Williams Rivers, which rise 300 km from the mouth beyond the Darling Range between Pingelly and Narrogin, close to the source of the Avon at an altitude of 350 m. The Hotham and Williams Rivers flow west through undulating agricultural country. On meeting the Darling Range the Hotham turns south just west of Boddington for 20 km to join the Williams River. The combined stream, now the Murray, flows west and north-west in a deeply incised valley, to emerge from the Range 5 km north of Waroona, and thence north to Pinjarra and west to the Peel Inlet. From the watershed at the source of the Hotham, the river descends steeply to the 300 m contour. Then in 105 km to Boddington at 217 m it drops 83 m *i.e.* 0.80 m km^{-1}. Below Boddington to the vicinity of Dwellingup, winding through the Darling Range, it drops 80 m in 108 km, 0.74 m km^{-1}, essentially the same grade. However, measuring from a spot height of 132 m on the river south of Dwellingup, the grade abruptly steepens to 5.3 m km^{-1} falling 112 m in 21 km. Thereafter on the coastal plain the grade is 0.62 m km^{-1}. This situation recalls the Swan River below Toodyay to its emergence onto the plain. The vertical height is about the same but the grade on the Murray is far steeper.

South of the Murray River the much shorter Harvey River rises only 20 km into the Darling Range. Further south lies the catchment of the Collie River which has a total length of 130 km. The relief of the Darling Range dies away towards the south so that the Collie River is not so deeply incised. The river system consists mainly of the east and south branches of the Collie River together with its tributaries, the Bingham and the Harris. The general trend of the whole system is west. The middle course of the Collie River from the 250 m contour down to the town of Collie at about 190 m falls 60 m in 50 km, or 1.2 m km^{-1}. Below Collie, the construction of the Wellington Dam complicates the assessment of grade. However, with the aid of figures supplied by the Water Corporation, it is possible to see that the original grade steepened materially to drop 170 m to the coastal plain, 3.8 m km^{-1}. From the foot of the dam wall to the plain the fall is ^{3} 110 m in 20 km, 5.5 m km^{-1}. This steep grade is similar to that on the Murray River, but the total fall is greater over a longer distance. The small short catchments of the Preston and Capel Rivers complete the West Coast System.

The Blackwood System

The Blackwood River has a large catchment of curious shape presenting a number of anomalies apparently due to diversion of drainage. The river is 300 km in length (measured directly from source to mouth) and is formed

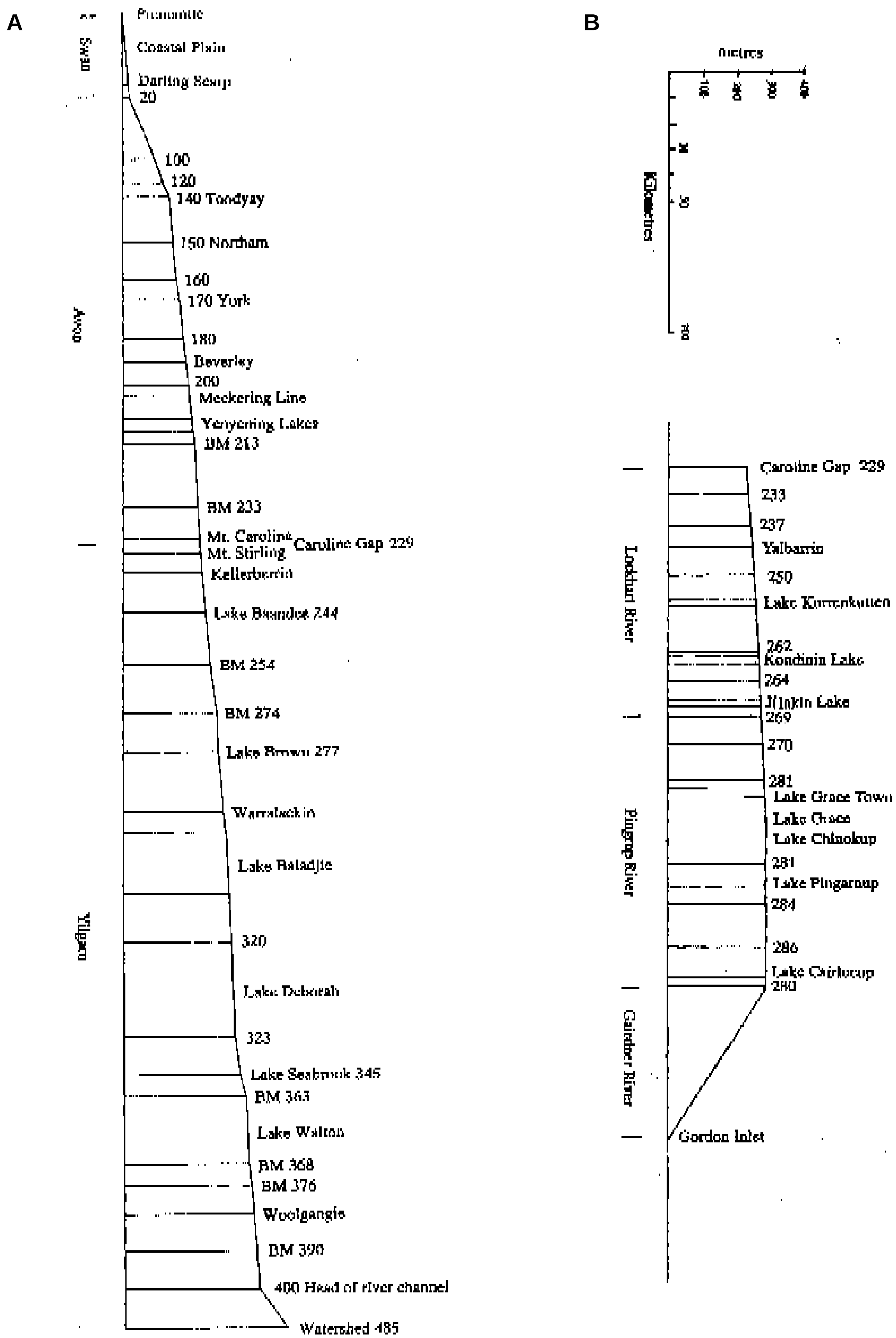


Figure 3. Profile of **A**, the Swan-Avon River and Yilgarn River North Branch; and **B**, the Yilgarn River South Branch.

by the union of two main tributaries, the Arthur and Beaufort Rivers. The Arthur rises near Harrismith in the same area as the sources of the Avon and Murray Rivers and flows south-west through undulating agricultural country on a grade of 0.60 m km^{-1}. There is a well defined watershed of 300-400 m in altitude between it and the Beaufort River, which rises further east where rainfall is lower, the country flatter and drainage intermittent. Two headwater streams, the Coblinine River and the Dongolocking Creek, form a conspicuous north-south alignment though higher up the Coblinine takes a westerly course parallel to the adjacent watershed. This section has a low grade of only 0.17 m km^{-1}. The combined drainage enters Lake Dumbleyung (³ 257 m, water level variable). This is a permanent salt lake but is said to have been dry before land clearing in the vicinity. Below Lake Dumbleyung to the junction with the Arthur River, the grade is moderately low, 0.50 m km^{-1}, but the prevalence of salt flats and playas is probably due more to lack of water than to low grade. Below the confluence, the Blackwood River proper is permanent, flowing in an extremely sinuous course incised into a relatively narrow valley only 20-40 km wide. Passing Boyup Brook and Bridgetown on a westerly course, the Blackwood eventually crosses the Darling Fault onto the Blackwood Plateau, turning south against the Naturaliste Ridge to meet the sea at Augusta. Owing to the sinuosity of its course it is difficult to measure the length of the river along this section and to estimate grade. Distance along the valley is 220 km giving a grade of 1.0 m km^{-1} but the actual distance along the river's course is probably twice as great, and the grade about 0.50 m km^{-1}.

The recent discovery of Eocene sediments (Waterhouse *et al.* 1995) buried in palaeochannels of the Beaufort and Arthur Rivers in the vicinity of their confluence appears to show that at that epoch drainage was ponded by some epeirogenic movement, escaping as the modern channel of the Blackwood was formed. This evidence is considered below with that of Salama (1997) in the Avon System.

The South Coast System

The South Coast System consists of a large number of relatively short rivers flowing to the south from a continuous watershed only 60 to 120 km inland, but stretching 650 km from Cape Leeuwin to Salmon Gums (Fig 1). Further east the country is both drier and flatter and the watershed ceases to be traceable. Cope (1975) attributed the formation of this watershed to a line of uplift called the Jarrahwood Axis, named after a small settlement on the Blackwood Plateau. It will be seen from Fig 1 however that the watershed on which Jarrahwood is situated is actually the northern watershed of the Blackwood catchment formed (as will be shown later) by an uplift of the Darling Range. At the southern extremity of this uplift, the watershed continues to the north-east and is unrelated to the South Coast Watershed marking the other side of the Blackwood catchment. It is suggested here that the name Jarrahwood Axis is not correctly applicable to the latter. Cope (1975) regarded it as a hinge line formed in the course of separation of Australia from Antarctica in the Early Tertiary. To the south the Darling Plateau sagged towards the rift, forming a slope called the Ravensthorpe Ramp which extends off-shore to the edge of the continental shelf. On-shore, the rivers of the South Coast System have developed. Cope(1975) essentially regarded the Axis as a hinge line along which the surface of the stable Darling Plateau took on a southerly slope, rather than as a line of epeirogenic uplift. He noted that his data appeared to show a "slight reversal of dip" to the north of the axis, but information available at the time was insufficient to confirm this. The South Coast Watershed appears, at the western end where it divides the Blackwood from the Donnelly, Warren, Tone and Frankland Rivers, as an inconspicuous ridge with heights of 300 to 350 m. Along this stretch there are no obvious signs of gaps in the watershed or north-south drainage alignments to suggest former channels across it. However Wilde & Backhouse (1977) reported a small Eocene fossiliferous deposit on the crest of this watershed 26 km west-south-west of Kojonup. South and east of Kojonup, maximum heights on the watershed rise to just under 400 m. South of Katanning and as far as Ongerup, the watershed lies on a broad plain at 300-350 m asl which breaks abruptly on the southern edge to headwaters of the Gordon and Pallinup Rivers. From Ongerup east to the junction with the Central Watershed, there is again a broad plain often with small salt lakes and with less of an abrupt fall on the south. Heights of 380 m occur locally but are generally below 350 m or as low as 300 m. Low levels occur at the cols on alignments between the Pingrup and Gairdner Rivers (spot height of 289 m), between the Lockhart and Fitzgerald Rivers (< 300 m by contours) and between the Camm and Phillips Rivers (< 350 m contour). Grades along the watershed are rather low on either side of these cols whose position is chiefly indicated by the drainage alignments. We have no data on possible palaeochannels. East of the junction with the Central Watershed at 415 m, the actual South Coast Watershed and Cope's Jarrahwood Axis separate. The latter is expressed by a well-marked continuous ridge running to the north-east whose heights vary from 344 to 441 m. A col at about 350 m is situated due south of the long axis of East Lake Johnston. Further to the north-east this ridge passes between Lakes Lefroy and Cowan. Lake Lefroy itself is at 295 m and spot heights of 380-390 m are common on the watershed which ends where the eastward alignments of the two lakes come together.

The South Coast Watershed proper continues in a general easterly direction from the junction with the Central Watershed declining in height from 415 m to 330 m north of the Oldfield River and to 250 m at a col south-east of Pyramid Lake. Curving round the headwaters of the Lort River, the watershed is on a flat plain at about 250 m. Further to the east it becomes impossible to trace any actual watershed as there are no drainage channels at the present day and the country becomes lower and flatter. There are two north-south alignments of small playas divided by transverse sand dunes which may indicate the presence of palaeochannels.

The Ravensthorpe Ramp (Cope 1975) is well named since it is along the stretch from Jerramungup to Ravensthorpe that it is steepest and most conspicuous. The Gairdner River here has a grade of 3.0 m km^{-1} (Fig 3B). East of Esperance, drainage becomes inactive and it is no longer possible to trace any watershed. In the western sector where country south of the watershed is at its widest, drainage is complicated by a second axis, parallel and 50 km further south (Fig 1). This was reported but not named by Muhling *et al.* (1985). I term this the Stirling Range Axis as it passes along the line of the Range (maximum height 1060 m) at its eastern end and is prolonged to the west as an inconspicuous watershed at 250-300 m. The Gordon River takes a westerly course north of the Axis for 50 km before breaking through to become the Frankland River. Still further west, the Axis is responsible for the plateau carrying Lake Muir and associated swamps (altitude 170 m). The Stirling Range is formed of Proterozoic sedimentary rocks interpreted as uplifted in the Cainozoic along faults (Myers 1990a). The present study indicates that at least two phases of uplift must be considered, an earlier uplift after which dissection of the Range and formation of Chester Pass and Red Gum Pass took place, and a later and lesser uplift in which drainage through the passes was broken off. The highest point in both today is at 310 m whereas the plain on the north side of the Range is at about 230 m. The difference is too great to be due to valley fill. Uplift of the Range has diverted the Gordon River to the west and the Pallinup to the east, and created a flat plain between their headwaters which has no external drainage at the present day and is strewn with small salt lakes. While the Pallinup River escapes to the sea today by joining the Corackerup Creek, there are signs that at first it may have had an outlet around the eastern end of the Range to the Kalgan River, as indicated by a chain of salt lakes which stand at 120 m, well below the level of the Kalgan Plains to the south of them.

The Yilgarn System

The Yilgarn System embraces all the drainage of the interior plateau, focussed to escape at one point through the Caroline Gap. Little flow takes place today except in years of exceptionally high rainfall when the channels are known to flush out in whole or in part. All the drainage is therefore mapped as intermittent or inactive, the latter being dry valleys in the far east and north-east. The System divides naturally into north and south parts, whose courses are united just above the Caroline Cap. The north branch was named the Yilgarn River by Bettenay & Mulcahy (1972); the south branch has three main components which they named the Pingrup, Lockhart and Camm Rivers. These names are conserved here. Fig 3A shows the profile of the Yilgarn River from the Avon confluence along its main channel through Lakes Brown, Baladjie, Deborah, Seabrook and others to the Central Watershed east of Woolgangie, a distance of 525 km. Fig 3B shows the south branch from the Caroline Gap by the Lockhart and Pingrup Rivers to the col marking the head at Lake Cairlocup, and thence down the south-flowing Gairdner River to the sea. The Yilgarn River drops 200 m in 525 km from the head of channel to the Avon confluence (Fig 3A), a grade of 0.38 m km^{-1} which is similar to the 0.35 m km^{-1} calculated by Salama (1997) for the distance below Lake Baandee. The descent is not entirely even since valley fill is locally unequal, and where playas are formed these are more or less level followed by a drop to the next one; however, the overall slope is reasonably uniform and is adequate for discharge during years of high rainfall.

Grades on the south branches (Pingrup, Lockhart and Camm Rivers) are very low. Along the Lockhart section (Fig 3B) in 170 km the fall is 41 m (0.24 m km^{-1}) and along the Pingrup section in 135 km it is only 5 m, virtually level. This stretch includes the lengthy playas of Lake Grace and Lake Chinokup which extend for 50 km. The highest point in this alignment is at 286 m asl in a gap in the South Coast Watershed, beyond which the Gairdner River takes a course south to the sea, falling 286 m in 95 km, a grade of 3.0 m km^{-1}. The upper Lockhart and Camm Rivers show a similar conformation with extensive playas and lead also to gaps in the South Coast Watershed in alignment with the Fitzgerald and Phillips Rivers. The low grade in the upper reaches of all these makes it unlikely that any significant discharge takes place.

Cope (1975) was uncertain whether his Jarrahwood Axis forming the South Coast Watershed was merely a hinge line at the top of the Ravensthorpe Ramp or was accompanied by uplift. We can be tolerably certain that where the Axis abuts the Yilgarn System there was prior drainage across it, but we do not know whether this flowed north or south. This gives four alternatives, based on uplift or no uplift, north or south drainage. With no uplift and northward drainage, there is no reason for the extremely low grades in the upper courses of the Pingrup, Lockhart and Camm Rivers. With uplift and northward drainage, there is even less reason for this; grades would have steepened. With no uplift and southward drainage, the rivers would have continued to flow south across the Jarrahwood Axis and deepened their beds. With uplift and southward drainage, the rivers north of the Axis were reversed and conform to the profile in Fig 3B. This last alternative is therefore preferred.

It is assumed from the general shape of the Yilgarn System and the prevalence of north-south alignments (more precisely, NNW-SSE at right angles to the south coast, or possibly structurally controlled by the trend of the greenstone belts), that the entire System originally flowed south into Antarctica. After reversal along the south coast axis, a new outlet was developed at the Caroline Gap. It is possible that this particular point was determined by a down-warp simultaneously with the elevation in the south and parallel to that axis. This is not unlikely or impossible since tectonic movements in the south of the Yilgarn Craton were contemporary with a very major event, the separation from Antarctica. In the geological survey of the Jackson area, Chin & Smith (1983) drew attention to a "major lineament" which trends WSW across the southern part of the Jackson map sheet, controlling the major drainage. It runs from the Clarkson Flats ENE of Lake Deborah, through Lake Deborah West and Lake Baladjie. Beard (1998) showed that still further to the east it is aligned to a gap in the Central Watershed. It is apparent from Fig 1 that if extended to the WSW the lineament passes through the Caroline Gap and on towards the Yenyening Lakes. The whole main channel of the Yilgarn River below Lake Deborah conforms approximately to this lineament. It could be due to coincidence but is certainly suggestive. Chin & Smith (1983) showed that the lineament is parallel to a Proterozoic dyke suite that transects all Archaean lithological boundaries, "suggesting that it is related to the fracture system which controlled the dykes". It may be felt that a feature of Proterozoic origin is unlikely to be controlling Tertiary palaeodrainage, but perhaps this lineament represents a line of crustal weakness which was exploited by Phanerozoic epeirogeny. I propose that it be named the Chin-Smith lineament.

Discussion

The Lefroy-Cowan and Roe Systems

Some discussion of the drainage systems further east of the South-West Division (Fig 1) is relevant as these have been previously studied, the Roe Palaeodrainage by Kern & Commander (1993) and the Lefroy and Cowan Palaeodrainages by Clarke (1993, 1994). The development of these has been primarily controlled by tectonic movements in the Eucla Basin. In Clarke's view, drainages developed initially towards the north and were deflected more and more to the east as the Eucla Basin subsided. The Cowan palaeoriver in particular flowed north from the direction of Antarctica. This situation remained stable until major subsidence in the Eucla Basin in the Middle Eocene brought about the Tortachilla transgression where the valleys were flooded and sediments deposited. Significant differences between deposits in Lake Lefroy and Lake Cowan show that they were not connected at this stage, Lake Cowan being open to the sea on the south. Clarke (1994) thought that the Cowan drainage had been reversed to the south by the uplift of the"Jarrahwood Axis" represented by the present watershed between the Lefroy and Cowan drainages. Clarke preferred to date this to the Jurassic instead of the Eocene as proposed by Cope (1975), but this must be considered too early. It seems far more likely that the drainage reversal took place at the time of separation of Australia from Antarctica, beginning in the Eocene. In the Late Eocene, an even more extensive transgression, the Aldinga, took place with renewed flooding of the valleys and sedimentation. The term Aldinga has since been changed to Tuketja (Clarke *et al.* 1996). This episode implies still greater subsidence of the Eucla Basin and adjacent land areas with steepening of grade by the rivers so that Lake Cowan was captured by the Lefroy. Lakes Tay, Mends and Dundas continued to be connected to the sea on the south. By the Miocene, flow through the system more or less ceased largely because uplift of the Eucla Basin and adjacent land reduced grades. At the present day, Lake Cowan at 260 m is higher than Lake Dundas (241-244 m), from which a southward palaeochannel can be deduced through country of the same altitude for some 40 km until it descends towards the coast at Esperance. Lake Gilmore at about 240 m belongs with Lake Dundas but the lakes to the WSW should not be shown (as by Clarke 1994) as connected to these as they are lower (Lake Tay 236 m, Lake Mends < 240 m, Pyramid Lake 237 m) showing original drainage to the south. The final elevation of the Eucla Basin has left these lakes on a plateau which is still undissected by the Lort, Young and Olfield Rivers, and where there is very little fall, if any, from one lake to another. Sediments dated as Miocene-Pliocene in Lake Tay (Bint 1981) can be attributed to the rejuvenation of these lakes on their plateau situation during a later pluvial interval.

The history of the Roe Palaeodrainage further north described by Kern & Commander (1993) is similar except that the only evidence of marine sedimentation is well downstream, 180 km east of Kalgoorlie. The valley-fill deposits in the upper catchment are fluvial and lacustrine, and exclusively of Late Eocene age.

The Yilgarn and South Coast Systems

As with the Lefroy-Cowan System, the historical development of the Yilgarn and South Coast Systems has been strongly affected by the separation of Australia from Antarctica and associated movements in the Eucla Basin. The interpretation given here is largely based on Middleton (1991). Separation from Antarctica began in the Jurassic with formation of a transcurrent fault situated along the present southern edge of the continental shelf. Subsidence occurred locally in two places forming the Albany and Eyre sub-basins with half-grabens which became covered with Jurassic sediments. The rift so formed gradually widened. Drainage from the north poured over the edge of the continental platform incising canyons. As the rift widened to form a seaway by the Late Neocomian, the edge of the plateau slumped towards the rift carrying down the canyons below sea level. This is the origin of the numerous submarine

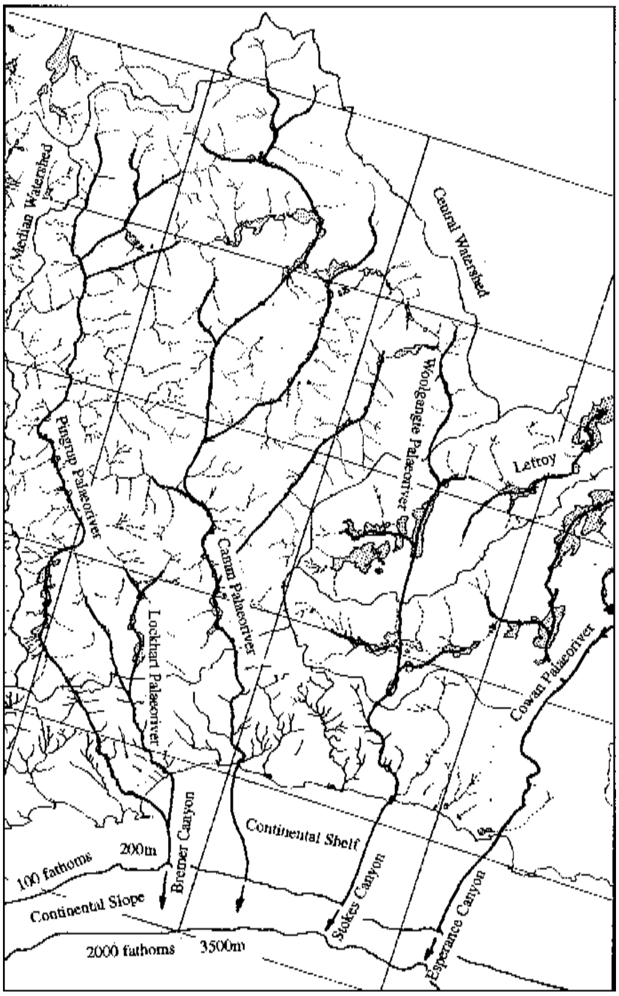


Figure 4. Palaeodrainage of the Yilgarn, Lefroy and Cowan Systems, epoch Late Cretaceous (bold lines) with probable connection to submarine canyons.

canyons along this coast mapped by von der Borch (1968) who also later described this mode of formation (von der Borch *et al.* 1970). The existence of such canyons has been difficult to explain and might usefully form the subject for another paper dealing specifically with the south and west coasts of Western Australia.

The palaeodrainage at this epoch, Late Neocomian, with south-flowing rivers directed to the edge of the continental shelf which was then the shoreline, is shown in Fig 4 with hypothetical connections to the three major canyons named by von der Borch (1968). The south-flowing Woolgangie Palaeoriver is included in this diagram as part of the Yilgarn System and is connected to the Stokes Canyon. Further east, the Cowan Palaeoriver, flowing south at that time, is shown connected to the substantial Esperance Canyon. It is suggested that the middle course of the Woolgangie Palaeoriver now represented by the Johnston Lakes, was captured at some time by the Lefroy drainage. The group of Lake Tay, Lake Mends *etc.* is believed always to have been separate from the Cowan drainage.

The sagging of the continental margin created the Ravensthorpe Ramp, sloping down to the south from a hinge line at plateau level to the edge of the continental shelf. This movement also generated a slight uplift along the axis and a slight downwarp along the Chin-Smith lineament, reversing drainage in the southern half of the Yilgarn System, to find a new outlet at the Caroline Gap. The relative movements involved are not great. The cols at the upper end of the Pingrup, Lockhart and Camm Rivers are at 289, 300 and 300-350 m and probably do not contain any appreciable depth of valley fill. The course of the Yilgarn River along the Chin-Smith lineament descends from 320 m at Lake Deborah to 229 m at the Caroline Gap but there is substantial valley fill, say an average of 50 m, so that the basement descends from 270 to 180 m. The difference in level is not great but sufficient to enable reverse flow in the drainage. Without some depression along the Chin-Smith lineament it would appear that uplift along the South Coast Watershed could not have reversed drainage effectively, unless the South Coast Watershed was originally uplifted more and has since partly subsided. Low grades at the source of southern rivers may support this supposition.

Sea floor spreading between Australia and Antarctica halted in the mid-Aptian, to be renewed in the Eocene (Middleton 1991). It is probable that the formation of the Ravensthorpe Ramp was a gradual process, which cannot be precisely dated, taking place in the Cretaceous. It had been formed by the Middle Eocene when sediments of the Plantagenet Group were deposited upon it. Renewal of the sea floor spreading was accompanied by major subsidence in the Eucla Basin so that the Lefroy-Cowan drainages were flooded and the sea invaded the Ravensthorpe Ramp. It seems probable that the whole southern edge of the Yilgarn Craton was tilted down to the east at this time, since the transgression was widest in the east. West of the Lefroy-Cowan area there is no evidence for a general Eocene transgression inland although it has been suggested by various authors (*e.g.* Wilde & Backhouse, 1977) when they reported thin sediments dated as Eocene from two localities near Kojonup at altitudes of 310 and 320 m, close to the south coast watershed and on its north side. However these can be regarded as of fluviatile origin.

Evidence for the dating of the drainage reversal in the south of the Yilgarn System can be deduced from Salama (1997). When discussing the sequence of events in the West Coast Systems (see below) it will be shown that the data indicate that the Yilgarn River must at one time have flowed directly west across what is now the Darling Range. At some stage, concluded to have been in the Late Eocene, an uplift of the Darling Range plateau ponded the river into a huge lake which found a new outlet down the Avon from Beverley to Toodyay. The Yilgarn River must have established its channel through the Caroline Gap prior to the Late Eocene and quite some time before since a deep gorge was excavated. The tectonic movements on the inland plateau and the reversal of drainage must also have taken place well before the Late Eocene, probably in the Cretaceous. This is in accord with the evidence from the south coast. Cope (1975) proposed an Eocene date for the formation of the Jarrahwood Axis and the Ravensthorpe Ramp. Clarke (1994) objected to this as being too late, and preferred the Jurassic. This on the other hand is manifestly too early since it cannot precede rifting between Australia and Antarctica. A Middle to Late Cretaceous date would seem to be a necessary compromise.

The West Coast Drainage Systems

Just as the separation from Antarctica and associated epeirogeny were crucial to development of the south coast systems, the contemporaneous separation from land to the west and tectonic movements in the Perth Basin have affected the drainage to the west. The treatment here follows the description given in Cockbain (1990). The river systems of the Yilgarn Craton are believed to have originated in or before the Jurassic (Beard 1973; van de Graaf *et al.* 1977; Clarke 1994). Triassic and Jurassic sandstones deposited thickly in the Perth Basin demonstrate erosive activity on shore. In the Early Cretaceous there was uplift coincident with the beginning of continental separation on the west, and the rivers pouring over the edge of the rift formed a large and complex canyon which with later sagging of the continental margin has become the submarine canyon of today west of Fremantle (von der Borch 1968). This canyon has at least four branches, probably receiving drainage concentrated here from all this part of the coast, since no other has been located.

During the Neocomian as the continental margin sank again, the sea re-entered and rivers discharged into shallow marine waters. Valley-fill deposits such as the Bullsbrook Formation (non-marine) were laid down in valleys cut into the Darling Scarp. After a brief regression in the Aptian, high sea level was established for the remainder of the Cretaceous and the rivers discharged into deep water. There is no similar evidence for high sea level on the south coast at this time. In the Perth Basin, sedimentation continued but at a slower rate. Sandstones were thinner and accompanied by carbonates. This seems to show diminution of erosion on shore which could be due to reduction of grade in the rivers resulting from levelling of the land surface and / or the development of a denser and more widespread plant cover following the diffusion of the angiosperms in the Albian-Aptian as

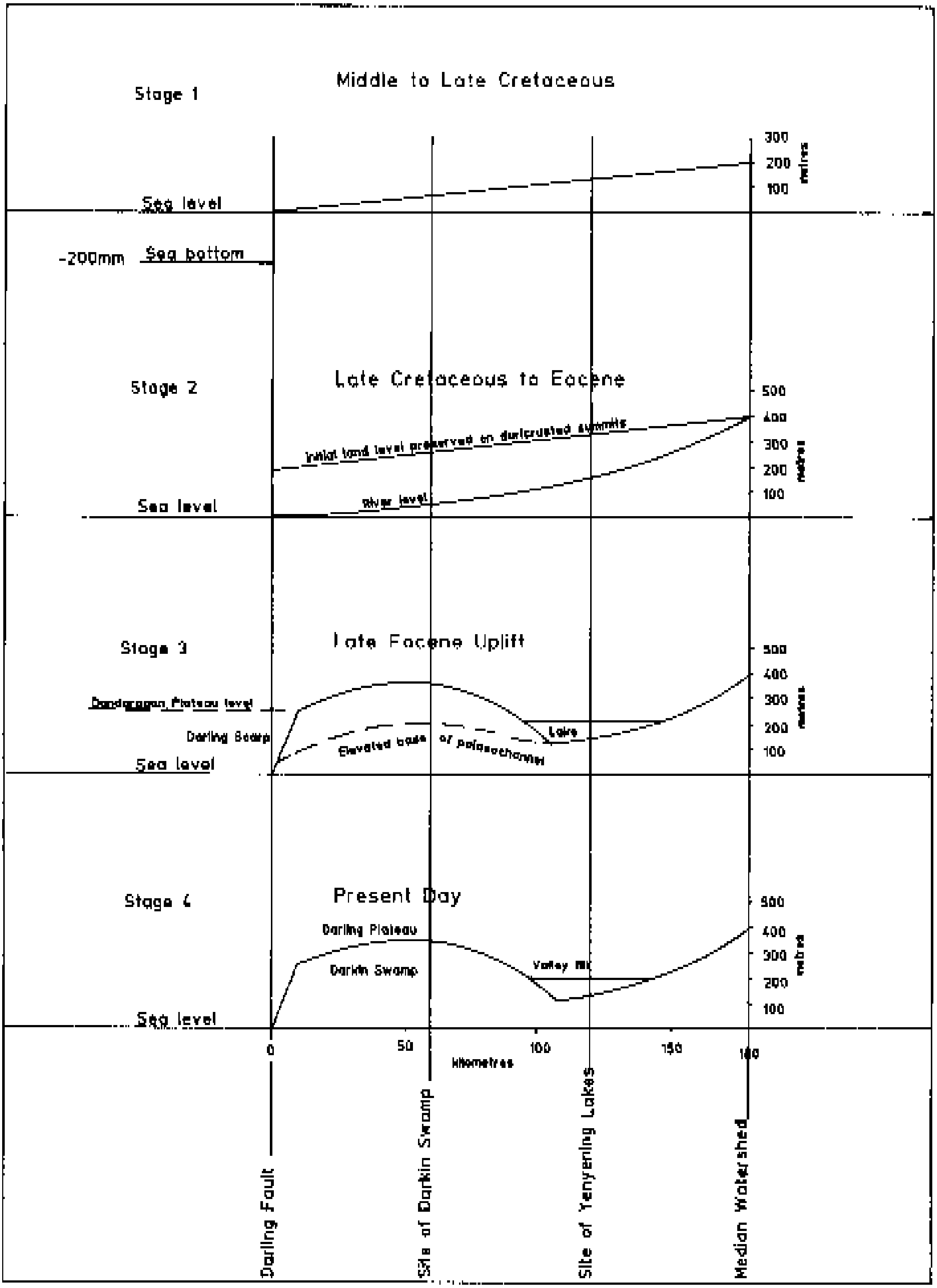


Figure 5. Scale diagrams showing development of drainage in the Swan-Avon System.

suggested by Beard (1989). In the later Cretaceous after deposition of the Poison Hill Greensand, marine transgression of the Perth Basin began to recede, exposing the sea floor (Playford *et al.* 1976). However this surface was evidently not far above sea level. The Dandaragan Plateau appears to have been exposed but the Victoria Plateau further north was still receiving thin deposits into the Eocene. It is difficult or impossible in these cases to say whether withdrawal of the sea was due to fall in sea level *per se* or to uplift of the land. In either case the practical effect is an uplift above sea level. Withdrawal of the sea at the time and place under discussion would have resulted in a relative uplift by an amount equal to the depth of water offshore when the Poison Hill Greensand was being deposited. As open marine conditions prevailed, a depth of 200 m should be allowed (A E Cockbain, pers comm). The sequence of these events in the Perth Basin is shown diagrammatically in Fig 5. Stage 1 represents the situation during the high sea level of the Cretaceous along a section drawn from the Darling Fault at Midland to the Median Watershed at Corrigin passing through the Darkin Swamp and the Yenyening Lakes which are thought to have lain on the ancestral Avon River. At the epoch of Stage 1 the formation of the Mesozoic surface of the Yilgarn Plateau is held to have been completed (Beard 1998), sloping gently down to the coast from the Median Watershed and drained by sluggish rivers in shallow valleys. The grades and levels were in accord with the high sea level of that time, with the shore line initially along the Darling Fault but gradually moved a few kilometres east of it by marine erosion. At this stage a height of 200 m for the Median Watershed has been assumed as it is in accord with later evidence.

Recession of sea level at the end of the Cretaceous had the effect of raising the river mouths along the Darling Fault, discharging onto a plain below. This level is represented today by the Dandaragan Plateau (after further uplift later). With the river mouths initially > 200 m above sea level and rainfall high in the Late Cretaceous and Early Tertiary, it is likely that the rivers lowered their beds to the new base level and that the valleys were adjusted accordingly throughout the catchments. A period of thirty million years from the Maastrichtian to the Upper Eocene is available for this process, arriving at Stage 2 in Fig 5. Lowering of sea level by 200 m has had the effect of raising the Median Watershed to 400 m, roughly its present height, maximum 385 m near Corrigin. As this watershed is capped by duricrust and sandplain deposits it is thought not to have been disturbed since the Eocene. A tributary of the Avon comes down to join the confluence of the Avon and Yilgarn Rivers at the present site of the Yenyening Lakes where the palaeochannel had been excavated to 140 m asl (Salama 1997). Numerous authors (*e.g.* Mulcahy *et al.* 1972; Salama 1994, 1997) have suggested that the combined Avon-Yilgarn flowed directly west from there passing through the present site of the Darkin Swamp. This swamp today lies in a valley system on the Darling Plateau and at the epoch of Stage 2 the river must have incised a substantial valley about 200 m deep below the plateau level, as is the situation today. The river level is shown on the diagram with the base of the valley at the Darkin Swamp estimated at about 50 m asl.

At this same Late Cretaceous stage, rejuvenation of the rivers with increased vigour of stream flow and volume of sediment, augmented by the reversal of drainage inland and the formation of the Caroline Gap, at first excavated a substantial valley west of the Darling Fault which in late Palaeocene-Early Eocene time became filled with siliciclastics (the King's Park Formation) after a further marine transgression (Cockbain 1990). This implies that the former sea floor exposed by the Late Cretaceous regression stood at a high enough level for the incision, at least near shore. Further offshore, excavation could have been taken deeper by turbidity currents and joined to the pre-existing submarine canyon. This process is known to be possible where only soft sediments are being removed (Kuenen 1953; Conolly 1968). In Late Palaeocene time, some subsidence or transgression is required for the deposition of the King's Park Formation in the near shore part of the canyon as the sediments are 265 m thick in the type section below King's Park and thicker off shore.

The levels involved create some difficulty for this interpretation. The valley in which the King's Park Formation was deposited must have been incised into a southward continuation of the Dandaragan Plateau, a feature now missing from this part of the Perth Basin. The plateau now stands at 250-300 m asl whereas the top of the King's Park Formation is at sea level. It seems evident that after incision of the valley and before its filling with sediment some considerable subsidence of this part of the Perth Basin took place. Absence of the continuation of the Dandaragan Plateau to the south was formerly explained by marine erosion (Playford *et al.* 1976) but is now seen to be due to subsidence of a syncline, the Swan Syncline (Davidson 1995) which carried down the Jurassic and Cretaceous sediments in the Basin south and west of the present Gingin Scarp, leaving the Dandaragan Plateau intact further north. The axis of the syncline trends NNE-SSW, situated some 15 km west of the Darling Fault at Perth, approaching it in a northerly direction. No movement along the Fault itself is implied, the syncline being treated as slumped against the Darling Scarp. The next event to affect the situation (Stage 3 in Fig 5) was epeirogenic uplift of the western margin of the Yilgarn Craton during the later Eocene. Since this was synchronous with down-warp of the Eucla Basin and adjacent land, it might be suggested that there was a general tilt of the Craton. The evidence from the west coast however requires a differential uplift. Salama (1997) reported that the Yilgarn River had been obstructed by an uplift of the Darling Range to the west, causing the formation of a "huge lake" centred on the Yenyening Lakes where up to 70 m of sediment were deposited. The river could not have continued to the west because the base of the palaeochannel at the Darkin Swamp is now 60 m above the base at the Yenyening Lakes, implying uplift by more than that amount. The Yilgarn River could not at first escape to the north down the present course of the Avon since the base of the river channel at Beverley, York and Northam is also higher than the Yenyening Lakes, so that some ponding would have taken place. Since the Darkin Swamp was originally downstream and therefore lower than the Yenyening Lakes palaeochannel, the evidence calls for an uplift of 140 m. Diversion of drainage in the extreme north of the

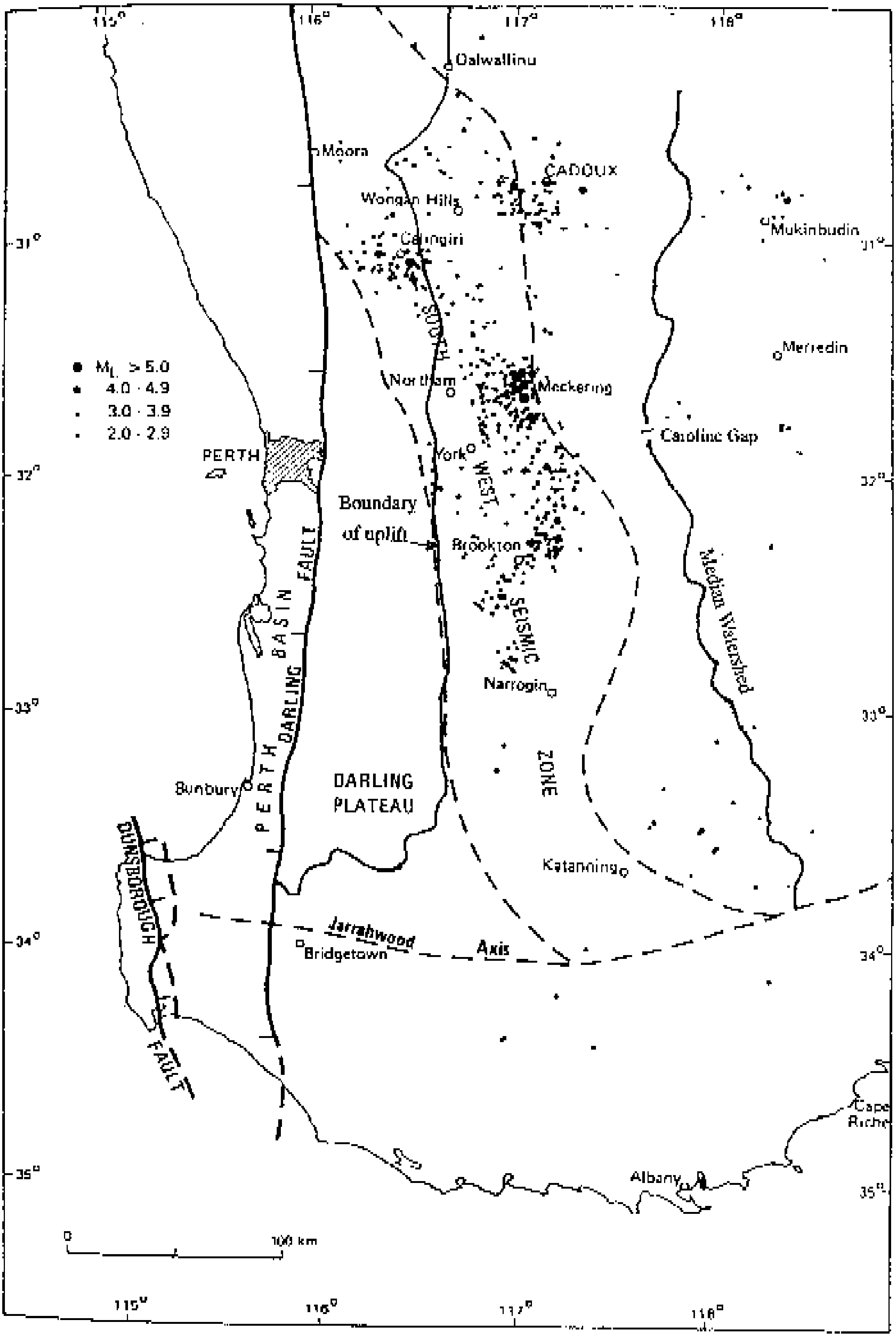


Figure 6. The South-West Seismic Zone (after Lewis *et al.* 1981) contrasted with the Median Watershed and the Darling Plateau uplift.

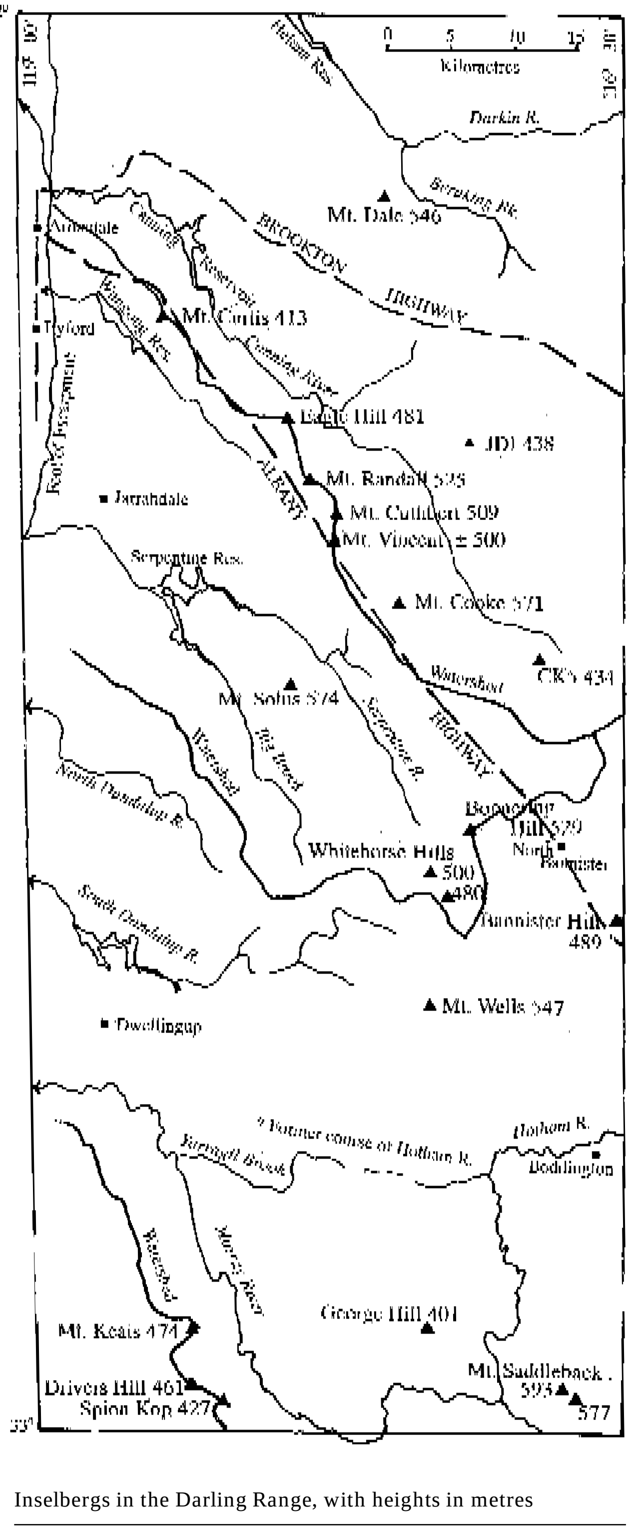
Mortlock catchment indicates uplift of 50-100 m. Palaeochannels in the Beaufort River system indicate uplift to the west of >110 m.

Marginal uplift on the west of the Yilgarn Craton is not a new idea and goes back at least to Jutson (1914) though it seems to have been generally overlooked in recent years. It was taken up by Mulcahy *et al.* (1972) as central to their conclusions on landforms and soils "on an uplifted peneplain in the Darling Range". They showed that the Range is a zone of some 80 km in width of greater elevation than country to the east, which was taken to imply a marginal upwarping of the Craton.

It is not clear how this uplift relates to that postulated by Libby & de Laeter (1979) and de Laeter & Libby (1993) from biotite dates along two traverses across the Darling Range in the central area near Perth, since it is dated as Silurian. The very considerable uplift calculated is likely to have been eroded away by the end of the Cretaceous, especially as the glacial episode of the Early Permian intervened. Effects on evolution of the drainage call for a renewed uplift in the Early Tertiary. For dating of this we can rely on the macrofossil and palynological data derived from fluviatile sediments apparently laid down in the early stages of disruption of drainage by the uplift, These show Late Eocene to Oligocene in one case, Middle Eocene to Oligocene in another (Hill & Merrifield 1993), Eocene (Wilde & Backhouse 1977) and possibly late Middle to Late Eocene (Waterhouse *et al.* 1995). All these agree sufficiently closely to suggest a Late Eocene date. Only the results from Salama (1997) are at variance with this. Material from two boreholes at the Yenyening Lakes was dated as no earlier than Miocene and must have been deposited in a much later stage of valley fill, although found at a considerable depth, 56-57 m and 63-68 m.

It is worth considering, as an alternative explanation, whether the disruptions of drainage may have been due to movements in the South West Seismic Zone (Fig 6). Everingham (1968) and later authors (Gaull *et al.* 1990; Doyle 1971; Lewis *et al.* 1981) identified a seismically active zone in the south-west of Western Australia in which several destructive earthquakes have taken place in recent years. This area has been assumed to "fall largely within a down-warped zone which separates the low-relief, gently warped interior of the Yilgarn Block from the uplifted, marginal plateau" (Gordon & Lewis 1980). In the physiographic context of the present paper, the seismic zone would be expected to lie between the Median Watershed and the Darling Range uplift zone, but a contrasted overlay of the boundaries (Fig 6) shows that this is not entirely the case. While the Median Watershed shows some parallelism with the eastern boundary of the seismic zone, the western uplift continues much further north and transgresses the seismic zone.

The profile of the Yilgarn River (Fig 3) shows that the grade does not steepen west of the Caroline Gap as would be expected if there had been down-warping. While Fig 3 shows the present surface, Salama's (1997) data equally show no steepening of the palaeochannel. However a possible explanation which would account for the Pliocene dates of his samples may be that when the drainage from the interior broke through the Caroline Gap the site of the Yenyening Lakes stood higher and the



Inselbergs in the Darling Range, with heights in metres

Shoulder of Mt Saddleback	593	White Horse Hills	500, 480
Mt Saddleback	577	Eagle Hill	481
Mt Solus	574	Mt Keats	474
Mt Cooke	571	Drivers Hill	461
Mt Wells	547	JDI	438
Mt Dale	546	CK5	434
Boonering Hill	529	Spion Kop	427
Mt Randall	525	Mt Curtis	413
Mt Cuthbert	509	George Hill	401
Mt Vincent	³ 500		

Figure 7. Location of Monadnocks > 400 m in the Darling Range.

river was able to flow directly through into the upper Avon. If later there was a local down-warp affecting the Yenyening Lakes area, the renewed pluvial conditions of the Pliocene, shown *inter alia* by local deposits at Lake Tay (Bint 1981) and nearby Lake Toolibin (Milne 1998), could have caused the accumulation of the substantial valley fill recorded by Salama (1997). It was probably at this stage that Salama's "huge lake" was in existence to absorb the Pliocene sediments which are not in evidence downstream on the coastal plain. The Middle Eocene is the most recent interval during which significant drainage can be demonstrated in the Perth Basin (Quilty 1978).

Reverting to Fig 5, the present situation (Stage 4) is not greatly different from Stage 3. The Yenyening Lakes have filled with sediments surfaced with a chain of playas. The Darkin Swamp has also partly filled with sediment. The plateau level on the Darling Range is thickly duricrusted and seems not to have been modified since Eocene time. Although the fossil evidence of Hill & Merrifield (1993) demonstrates the presence of rain forest with *Nothofagus* and several species of conifers in the Eocene, thereafter rainfall in general together with stream activity appear to have declined materially in an episodic fashion, generally dry in the Miocene, humid in the Pliocene.

King (1962) noted that monadnocks on the Darling Range exceed the height of those further east in the wheatbelt country. A number of impressive inselbergs (mainly granite) of outstanding height are restricted to an area on the Pinjarra map sheet between Lat 32^0 and 33^0 and between Long 116^0 00' and 116^0 30', within 50 km of the Darling Fault (Fig 7). The watersheds range between 300 and 400 m in height except where inselbergs are included and indicate a general plateau level of about 400 m; 21 points exceed this height, 11 of them exceeding 500 m, with a maximum of 593 m on part of Mt Saddleback. Perhaps not all of these are strictly inselbergs with exposures of bare rock, as some will be forested hills capped with duricrust. Mt Wells and Mt Saddleback consist of basalt, not granite. The only other high points in the Darling Range are Russel Top (422 m) and Morangup Hill (477 m), situated north and south of the Avon below Toodyay. All are certainly higher than inselbergs further east such as Mt Caroline (340 m) and Mt Stirling (365 m), and even massive outcrops like Billyacatting Hill (400 m) near Kununopping which covers several square kilometres. They may therefore be held to demonstrate uplift, of up to 200 m, but it must be clear that they already protruded from the general level before uplift took place, and that their exposure is not due to denudation since uplift. The higher ground in the Darling Range is thickly mantled with ferruginous duricrust, and denudation since uplift is held to have been moderate. Concentration of inselbergs in this part of the Range is most likely due to their occurrence in the Pinjarra Orogen (Myers 1990b).

The palaeodrainages as developed during the Eocene, that is to say after retreat of the Cretaceous high sea level and before the Late Eocene uplift, are shown in Fig 8. The uppermost tributaries of the Mortlock River North Branch flowed west to the Moore River. Those of the South Branch continued south-west from present Lake Walyourmouring to join the North Branch. The Brockman River created the Chittering valley by exploitation of the Chittering Metamorphic Belt. The Mortlock River Branches and the proto-Avon similarly exploited the Jimperding Metamorphic Belt. Their valleys were widened and deepened. The ancestral Yilgarn River continued west from the Yenyening Lakes area, uniting with the upper Avon and Dale Rivers, across the present Darling Range. Further south the Arthur and Beaufort Rivers flowed into the Collie catchment. Disappearance of the Dandaragan plateau in the southern Perth Basin led to down-cutting by the lower courses of all these rivers.

After the uplift the rivers adjusted their courses to those of the present day (Fig 1). The headwaters of the Moore Rivers were diverted to the south as were those of the Mortlock North Branch. In its lower course the latter was moved further to the east, joining with a formerly separate Middle Branch (Fig 8). The Avon and Dale Rivers abandoned their course across the Darling Range and developed a new route to the Mortlock which already had its own outlet across the Darling Range. The Murray River seems to show the least evidence of disruption by uplift, probably because the catchment does not extend so far east as the others and was uplifted

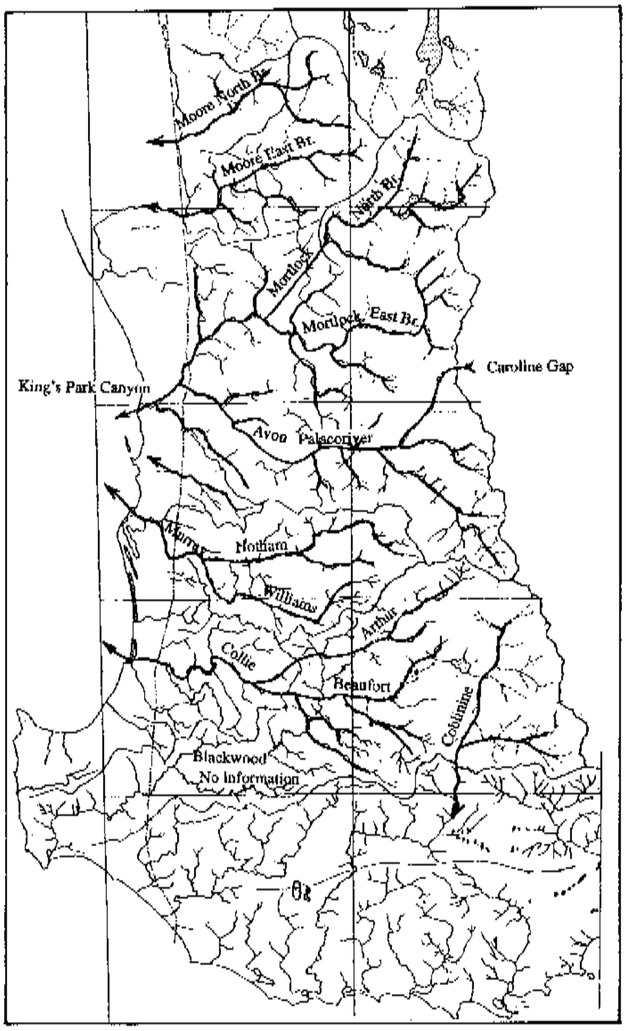


Figure 8. Palaeodrainage of the West Coast Systems, epoch Palaeocene (bold lines). The submarine Perth Canyon is located west of this diagram.

as a whole. There is some indication (Fig 8) of diversion of the Hotham River. The palaeochannels of the Arthur and Beaufort Rivers, having filled with sediment, developed a new outlet through the Blackwood.

Conclusions

1. Drainage of the central Yilgarn System is confined by two north-south watersheds, the Central Watershed of Beard (1998) and the Median Watershed defined here. These constitute a bifurcation of the central watershed of the Western Shield. Drainage of this area which today is mostly intermittent or inactive, is gathered from the north, east and south to escape to the west through a single point, the Caroline Gap, in the Median Watershed and joins the Avon River. The shape of the Yilgarn catchment, prevalence of north-south alignments, and in the south conspicuous alignments with rivers draining to the south coast suggest that drainage of the System originally flowed in a southward direction. The Yilgarn System is bounded on the south by a watershed parallel to the south coast, formerly named the Jarrahwood Axis. This name is now found inappropriate.
2. The South Coast Watershed formed in the middle to late Cretaceous by marginal uplift of the craton during separation from Antarctica causing reversal of former southerly drainage. This reversal appears to have been assisted by a contemporary downwarp across the northern part of the Yilgarn System along a line termed the Chin-Smith Lineament. Prior to the south coast uplift the south-flowing rivers incised canyons into the rifted margin of the continental platform.
3. Subsequent to uplift forming the South Coast Watershed the continental margin sagged towards the rift forming a slope (the Ravensthorpe Ramp) which continues to the edge of the continental shelf and has carried down the canyons to become the submarine canyons of today. This situation is most clearly defined south of the Yilgarn System. Further west there is a secondary axis of uplift, the Stirling Range Axis, about 50 km south of the south coast watershed. Further east there is evidence for an additional south-flowing former palaeoriver, the Woolgangie, which has been truncated by capture by the Lefroy-Cowan system.
4. Drainages to the west coast formed in the Mesozoic bounded inland by the Median Watershed and contributing sediment to the Perth Basin. In the Early Cretaceous there was an uplift associated with continental separation on the west. An extensive canyon (the Perth Canyon) was incised at the edge of the rift and later drowned. High sea level prevailed in the Perth Basin until the late Cretaceous when regression promoted rejuvenation of the rivers. A deep valley was cut by the lower Avon River into sediments of the Perth Basin but was drowned and filled after subsidence of the Swan Syncline. The Brockman River, Mortlock River North Branch and the Avon from Beverley to Toodyay owe their alignments to exploitation of the Chittering and Jimperding Metamorphic Belts.
5. In the Late Eocene a marginal uplift of the craton by 150-200 m took place in a belt 80 km wide east of the Darling Fault creating the Darling Range and causing diversions of drainage. Headwaters of the two Moore Rivers (north and east branches) were cut off and diverted to the south. Headwaters of the Mortlock River (north branch) were similarly diverted and the lower course of the Mortlock was relocated some distance to the east. The combined Avon and Yilgarn Rivers which formerly flowed due west were diverted north to join the Mortlock in a new course through the Darling Range. Similarly the Arthur and Beaufort Rivers were diverted from the Collie System and found a new outlet through the Blackwood River. Depth of the palaeochannel beneath the Avon-Yilgarn affords proof of the uplift of the Darling Range as there would otherwise have been no outlet. It is probable that there was a later local down-warp associated with the South West Seismic Zone in the area of the Yenyening Lakes which then accumulated substantial thickness of sediment during a Pliocene pluvial interval. Monadnocks in the Darling Range which can also be cited as evidence for uplift have been identified and mapped.

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