Natural History of the North East Deserts

Edited by
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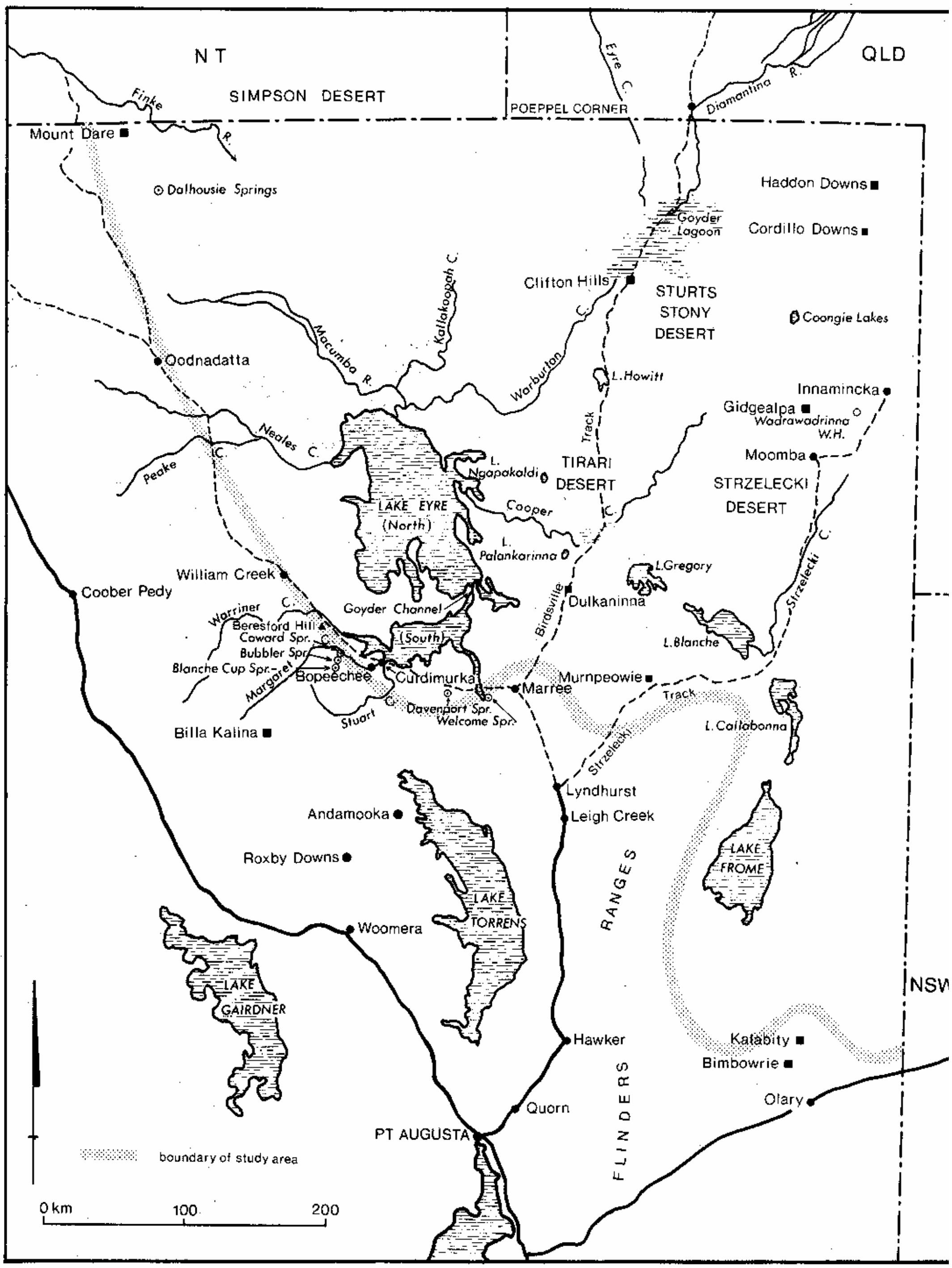

North East Desert region.

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Foreword

This is the fifth publication in a series of regional natural histories of South Australia. The series is intended to bring together widely scattered information on the physical, natural, and human sciences, and to present it in a form that provides an explanatory account of all major components of the environment.

Natural History of the North East Deserts is the most ambitious of the books in the series. It was selected for treatment at this time because of the level of interest in this part of South Australia, and the lack of any previous attempt to synthesise the observations that are available. Accordingly when we invited the authors to contribute to the volume, several commented that to be able to do so would require further research to plug gaps in knowledge. Happily they were prepared to do so, and the volume improved appreciably in consequence.

There remain substantial deficiencies in our understanding of the South Australian environment. This is largely attributable to the centralisation of population in one area of the State, and the limited opportunity for researchers to gain access, collect and observe in remote areas. In fact we suspect that, but for the opening up of portions of the north east to exploit natural gas reserves there, we would have had to seriously consider deferring the publication of a volume of the area until it was better known.

A great deal remains to be known about the north east and we believe that this publication will highlight deficiencies and encourage further investigation. Obviously many of the organisms present there have not been mentioned, but few of the groups involved are known in sufficient detail to permit more than a superficial and unsatisfactory treatment here. We are also constrained by the economics of marketing: the capacity to publish further

volumes in this series is mainly dependent upon proceeds from the sale of existing volumes that have been published. To achieve our objective requires that we respect market demand, and always include topics that are high on the list of those of interest to a broad readership.

We thank the authors for accepting referees' and editorial comments in the constructive manner in which they were offered. We regret the delays in publication inherent in a multiple authored work, and so frustrating to those who met our deadlines.

We also thank our colleagues and others who have contributed to the publication. We thank particularly Santos Pty Ltd for provision of the magnificent aeriel view used on the front cover, Chris Crothers for the Frontispiece map, to Kelly Maurice-Jones and Sherry Proferers who drafted and redrafted several figures, and to Philip Kempster who prepared several of the half-tone figures.

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1: Geology

by G. W. KREIG, R. A. CALLEN, D. I. GRAVESTOCK & C. G. GATEHOUSE

INTRODUCTION

The north east deserts is not a single geological entity, its boundary being a combination of physiographical, geographical and geological features enclosing parts of several geological provinces (Fig. 1). The diverse geology is partly expressed in the various landforms of the region such as the Simpson and Strzelecki dunefields, the great playa lake and river systems of Lake Eyre and Cooper and Diamantina Creeks, the gibber plains and stony plateaux and, along the western and southern margin, a line of artesian springs and associated features. As well as the surface geology, unexposed rocks form an integral part of the geological story. In this chapter the rock succession extending from the oldest and deepest known to thepresent land surface, is described briefly and the processes and events which formed it are explained.

The geological record consists of a thick sequence of sedimentary strata deposited over a period of more than 500 million years. During this span many different environments evolved then disappeared in response to the inexorable changes of global climate and crustal deformation. These environments and their associated earth processes and events are recorded in the rocks which, if interpreted with understandingprovide views extending into antiquity.

At various times, shallow seas covered the area, with volcanic islands erupting and shedding debris onto the surrounding sea floor on one occasion. At other times, global cooling allowed glaciers and ice caps to form, scouring the landscape and then covering it with a blanket of moraine and outwash debris after the ice retreated. There were times also when conditions were warm and wet, and the landscape was forested and contained numerous large rivers, lakes and peaty swamps. These deposits formed coal seams and organic-rich mudstones which are the source of oil and gas in the Cooper Basin. Later, when drier conditions prevailed, huge lakes evaporated leaving extensive limestone sheets, and the land became arid and windy, and vast sandy dunefields developed.

During this span of earth history there were also extended periods of stability that led to a very subdued landscape in which very little sedimentation or erosion took place. Deep chemical alteration then bleached or coloured the near-surface rocks, the results of this process now expressed in the vivid white or multi-hued bluffs of the tableland country.

Of this 500 million year record, only representatives of the younger, upper strata extending back no more than 160 million years, are exposed. The older, deeper strata, are covered, and are known only from drillhole intersections which, to date, have penetrated to depths of about 4 km. The oldest of these strata, dated from their fossil content, were deposited in the Cambrian Period (Fig. 2) about 530 million years ago. Below these Cambrian rocks very little is known of the geology but it is possible that rocks similar to those of the Flinders Ranges (which are up to about 900-950 million years old) are present, and below them again the older, crystalline basement rocks like those of the Willyama and Mt Painter Inliers and the Musgrave Block (Fig. 1). In fact, the older crystalline rocks probably are represented in some drillholes near the margin of the study area where the overlying section is thin, but the extent, distribution and precise nature of these Proterozoic to Archaean rock successions beneath the desert, are unknown (Fig. 2).

Although over 4 km of section have been penetrated, this represents by no means a complete record of the past 500 million years. There are major time intervals for which no rocks are present. These breaks in the record are called unconformities and they represent times when either erosion, or non-deposition and weathering, were taking place (Fig. 2). The strata of the north east deserts region have thus been divided into five, unconformity-bounded sediment 'packets' superposed one above the other. The older three are completely covered by younger rocks - only the upper two are exposed at the surface. Each sediment packet results from a particular set of erosional events related to uplift and/or climatic change. Each is a distinct depositional entity and

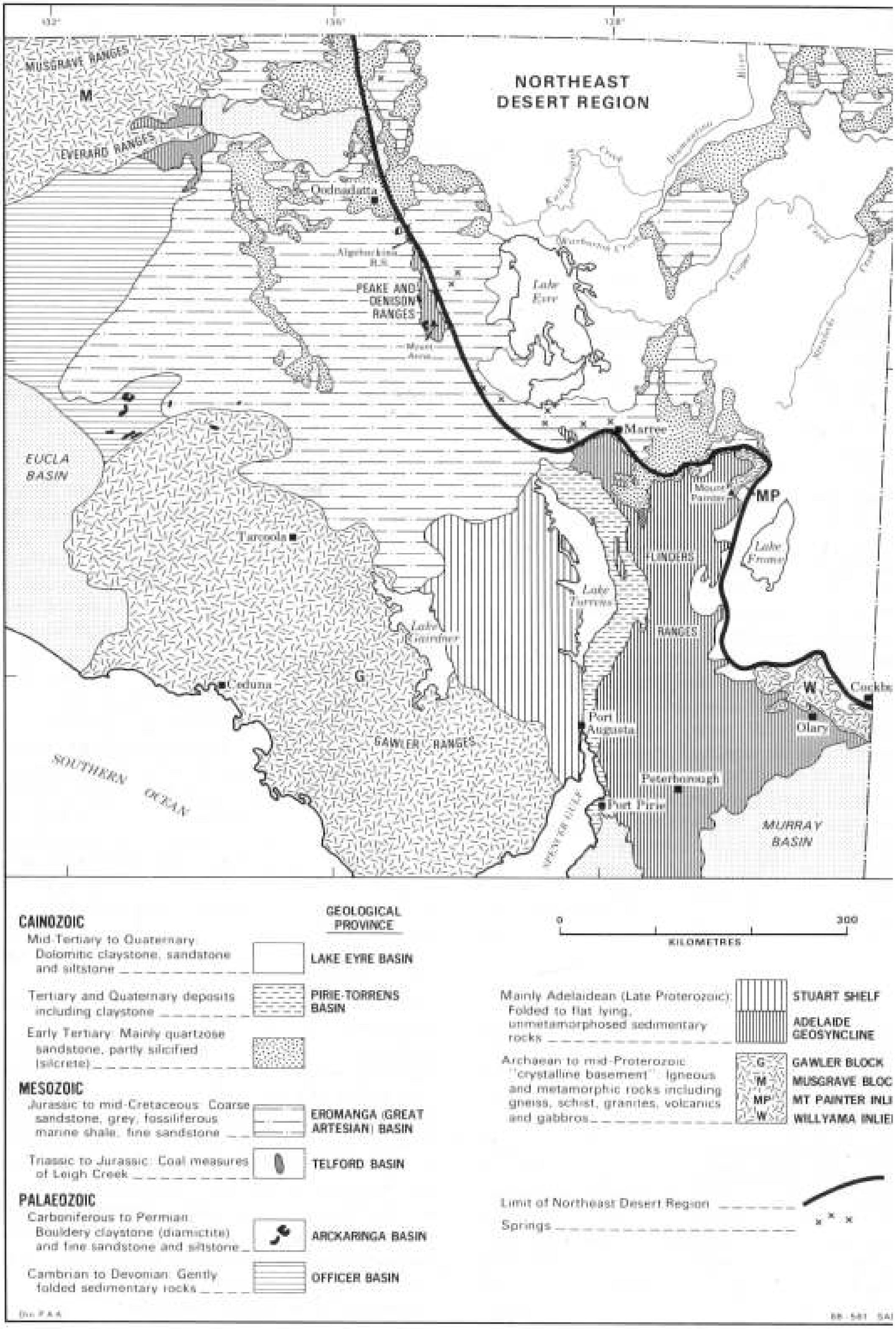


Fig. 1. Geological setting of the north east deserts.

occupies a separate sedimentary basin. Starting from the oldest, these are the Warburton Basin, Cooper and Pedirka Basins, Simpson Desert Basin, Eromanga Basin and the Cainozoic Basins (Fig·3).

WARBURTON BASIN

The Warburton Basin (Wopfner 1969) is one of a number of Early Palaeozoic basins that formed around the margins of an ancient stable landmass centred on the Archaean to Proterozoic Gawler Block (Figs 1, 3). The character of the rocks that form the basin floor reflects the nature of this landmass, which is a northwesterly extension of the Proterozoic terrain of the Willyama Supergroup in New South Wales (Willis *et al.* 1983). Most of the basin lies north and northwest of Cameron Corner (Fig. 4) and extends into the Northern Territory and Queensland. It contains sediments ranging in age from Early Cambrian to possibly Devonian and also volcanics of Cambrian age and granites which are as young as Carboniferous (Fig. 2).

The Early Cambrian is represented by the Mooracoochie Volcanics which form the Gidgealpa Volcanic Arc (Fig. 4). The volcanics comprise rhyolite, trachyte, prophyritic trachyte, welded tuff, and agglomerate in drill hole Gidgealpa-2; dacite and rhyodacite occur elsewhere. An unusually wide range of composition suggests that the original minerals have been altered by chemically active pore fluids. Overlying the volcanics is the Middle to Late Cambrian Kalladeina Formation. This unit comprises shelf and slope carbonates, clastics, and volcaniclastic sediments and occurs mainly west and northwest of the Gidgealpa Volcanic Arc. The Kalladeina Formation is dated and correlated by means of fossils, such as the agnostid and polymerid trilobites common in some drillcores (Fig. 5). Other fossils include phosphatic brachiopods, hyolithids, and algae.

The Ordovician Dullingari Group consists of quartzose sandstone, green and grey shale, siltstone, dolomitic siltstone, and black pyritic shale. The lateral and vertical distribution of these various sediment types is poorly known as most of the drill holes penetrated only a few tens of metres of Dullingari Group and the intersected sequences vary from hole to hole. Near Moomba the sandstone predominates and is interpreted as a shallow water facies. To the east is the grey and green shale facies which is presumed to have been deposited in deeper water. Further east is the black pyritic shale facies which is interpreted as a deep water deposit in which lack of oxygen prevented removal of carbon and allowed the generation of pyrite in the sediments.

The "Innamincka Red-beds" are presumed to be younger than Dullingari Group and may be Devonian, although the evidence is not strong. As its name suggests the unit is predominantly red in colour and is known to be marine because of the presence of glauconite in part of the section; it also contains worm and trilobite tracks.

Unnamed granites are present in several areas in the Moomba-Big Lake area and in McLeod-1 drill hole. Geochronological age dating has shown that at McLeod-1 the granite is of Carboniferous age. This was based on a single zircon crystal which gave an age of 310 ± 17 Ma. At Moomba-1 drill hole a zircon date of 342 ± 28 Ma was obtained.

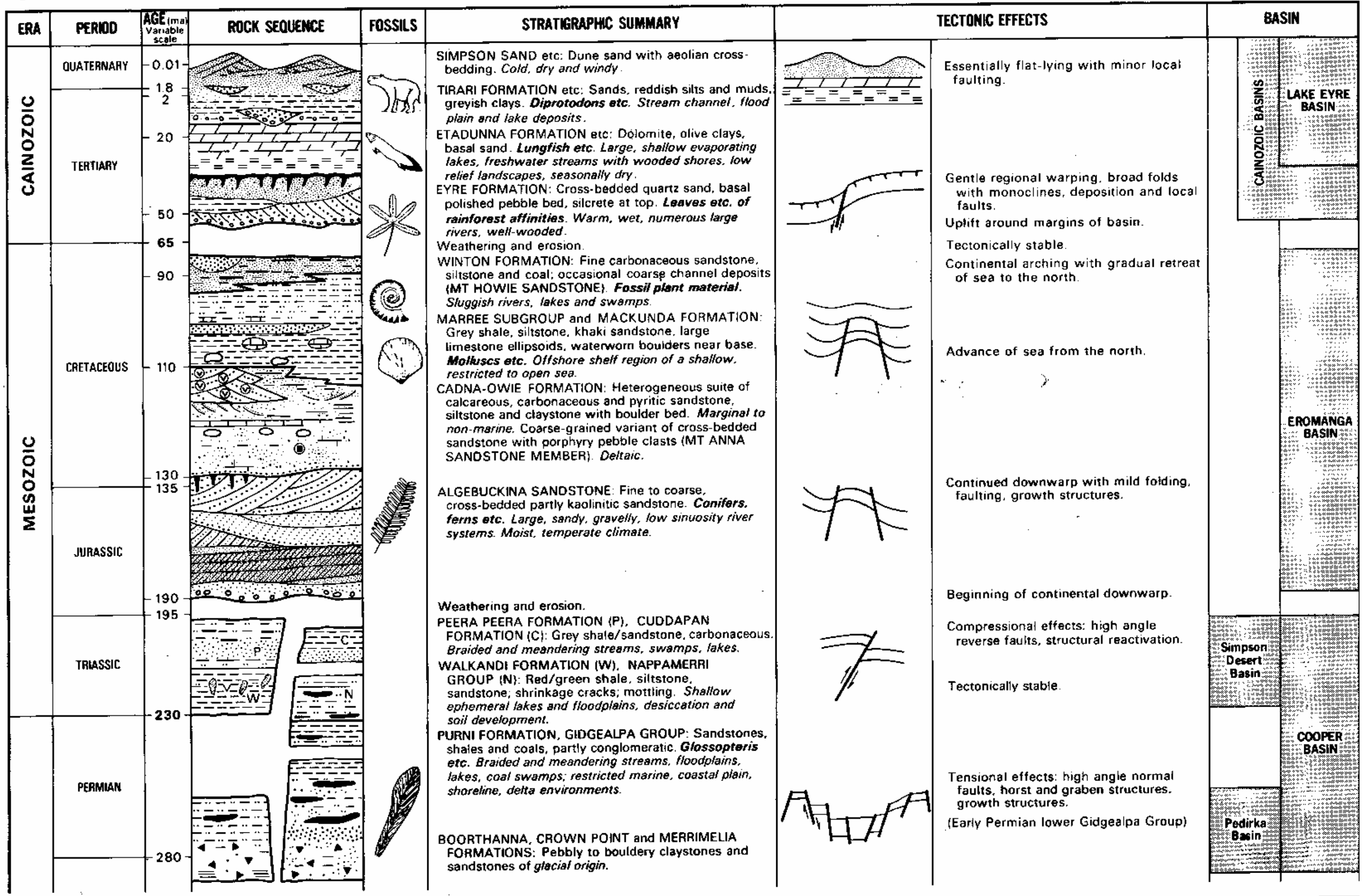
Folding and faulting have strongly affected sediments of the Warburton Basin, most likely during the Alice Springs Orogeny (Wells *et al.* 1970).

COOPER AND PEDIRKA BASINS

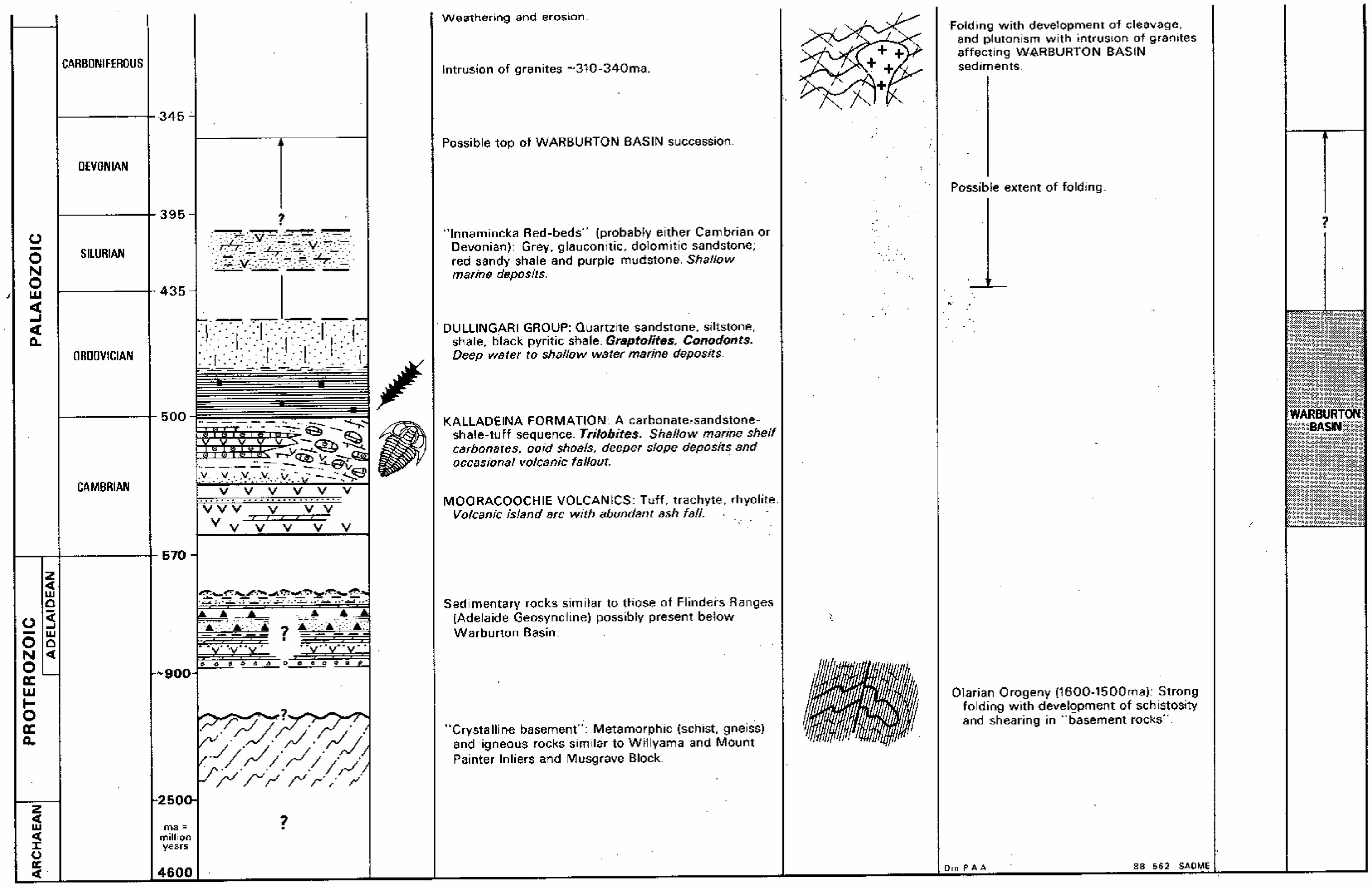
Sedimentary rocks of the Warburton Basin, locally intruded by granites, were effectively 'welded' to the Australian Craton by the mid Carboniferous final phase of the Alice Springs Orogeny. Australia was part of the Gondwana Supercontinent, and at sufficiently high southerly latitudes (66° - 70^0S) to have been partly covered by continental ice. Subsidence of parts of the Warburton Basin along ancient zones of crustal weakness gave rise to the intracratonic depressions that were eventually to become the Cooper and Pedirka Basins. However, deposition did not begin until the Late Carboniferous. Veevers (1984) has suggested that the lack of deposition or 'lacuna' between the Mid and Late Carboniferous occurred because sediments were ice-bound until warmer climatic conditions freed the enormous volume of glacially entombed debris.

The oldest sediments in the Cooper and Pedirka Basins are tillites and polymict conglomerates, frequently with ice-worn cobbles and boulders eroded from the underlying land surface. Glacially scoured valleys and actively subsiding fault-bounded depressions were filled with thinly banded deposits of silt and mud while more sandstone and conglomerate accumulated in more elevated areas (Williams & Wild 1984). Melting and retreat of glacial ice in the Early Permian mobilized huge volumes of sandy sediment which were either rapidly 'dumped' as glacial outwash or supplied bedload to fluvial systems. These glacigene deposits in the Cooper Basin form a depositional continuum mapped as *Merrimelia Formation* and *Tirrawarra Sandstone* to which the *Crown Point Formation* is equivalent in the Pedirka Basin

Fig. 2. Geological summary of the north east deserts.



ERA	PERIOD	AGE (ma) Variable scale	STRATIGRAPHIC SUMMARY	TECTONIC EFFECTS	BASIN
CAINOZOIC	QUATERNARY	0.01	SIMPSON SAND etc: Dune sand with aeolian cross-bedding. *Cold, dry and windy.*	Essentially flat-lying with minor local faulting.	CAINOZOIC BASINS LAKE EYRE BASIN
	TERTIARY	1.8 2	TIRARI FORMATION etc: Sands, reddish silts and muds, greyish clays. ***Diprotodons etc.*** *Stream channel, flood plain and lake deposits.*		
		20	ETADUNNA FORMATION etc: Dolomite, olive clays, basal sand. ***Lungfish etc.*** *Large, shallow evaporating lakes, freshwater streams with wooded shores, low relief landscapes, seasonally dry.*		
		50	EYRE FORMATION: Cross-bedded quartz sand, basal polished pebble bed, silcrete at top. ***Leaves etc. of rainforest affinities.*** *Warm, wet, numerous large rivers, well-wooded.*	Gentle regional warping, broad folds with monoclines, deposition and local faults. Uplift around margins of basin.	
		65	Weathering and erosion.	Tectonically stable.	
MESOZOIC	CRETACEOUS	90	WINTON FORMATION: Fine carbonaceous sandstone, siltstone and coal; occasional coarse channel deposits (MT HOWIE SANDSTONE). ***Fossil plant material.*** *Sluggish rivers, lakes and swamps.*	Continental arching with gradual retreat of sea to the north.	EROMANGA BASIN
			MARREE SUBGROUP and MACKUNDA FORMATION: Grey shale, siltstone, khaki sandstone, large limestone ellipsoids, waterworn boulders near base. ***Molluscs etc.*** *Offshore shelf region of a shallow, restricted to open sea.*	Advance of sea from the north.	
		110	CADNA-OWIE FORMATION: Heterogeneous suite of calcareous, carbonaceous and pyritic sandstone, siltstone and claystone with boulder bed. *Marginal to non-marine.* Coarse-grained variant of cross-bedded sandstone with porphyry pebble clasts (MT ANNA SANDSTONE MEMBER). *Deltaic.*		
	JURASSIC	130 135	ALGEBUCKINA SANDSTONE: Fine to coarse, cross-bedded partly kaolinitic sandstone. ***Conifers, ferns etc.*** *Large, sandy, gravelly, low sinuosity river systems. Moist, temperate climate.*	Continued downwarp with mild folding, faulting, growth structures.	
		190	Weathering and erosion.	Beginning of continental downwarp.	
	TRIASSIC	195	PEERA PEERA FORMATION (P), CUDDAPAN FORMATION (C): Grey shale/sandstone, carbonaceous. *Braided and meandering streams, swamps, lakes.*	Compressional effects: high angle reverse faults, structural reactivation.	Simpson Desert Basin COOPER BASIN
			WALKANDI FORMATION (W), NAPPAMERRI GROUP (N): Red/green shale, siltstone, sandstone; shrinkage cracks; mottling. *Shallow ephemeral lakes and floodplains, desiccation and soil development.*	Tectonically stable.	
	PERMIAN	230	PURNI FORMATION, GIDGEALPA GROUP: Sandstones, shales and coals, partly conglomeratic. ***Glossopteris etc.*** *Braided and meandering streams, floodplains, lakes, coal swamps; restricted marine, coastal plain, shoreline, delta environments.*	Tensional effects: high angle normal faults, horst and graben structures, growth structures. (Early Permian lower Gidgealpa Group)	
		280	BOORTHANNA, CROWN POINT and MERRIMELIA FORMATIONS: Pebbly to bouldery claystones and sandstones of *glacial origin.*		Pedirka Basin



Weathering and erosion.

Intrusion of granites ~310-340ma.

Possible top of WARBURTON BASIN succession.

"Innamincka Red-beds" (probably either Cambrian or Devonian): Grey, glauconitic, dolomitic sandstone; red sandy shale and purple mudstone. *Shallow marine deposits.*

DULLINGARI GROUP: Quartzite sandstone, siltstone, shale, black pyritic shale. ***Graptolites, Conodonts.*** *Deep water to shallow water marine deposits.*

KALLADEINA FORMATION: A carbonate-sandstone-shale-tuff sequence. ***Trilobites.*** *Shallow marine shelf carbonates, ooid shoals, deeper slope deposits and occasional volcanic fallout.*

MOORACOOCHIE VOLCANICS: Tuff, trachyte, rhyolite. *Volcanic island arc with abundant ash fall.*

Sedimentary rocks similar to those of Flinders Ranges (Adelaide Geosyncline) possibly present below Warburton Basin.

"Crystalline basement": Metamorphic (schist, gneiss) and igneous rocks similar to Willyama and Mount Painter Inliers and Musgrave Block.

Folding with development of cleavage, and plutonism with intrusion of granites affecting WARBURTON BASIN sediments.

Possible extent of folding.

Olarian Orogeny (1600-1500ma): Strong folding with development of schistosity and shearing in "basement rocks".

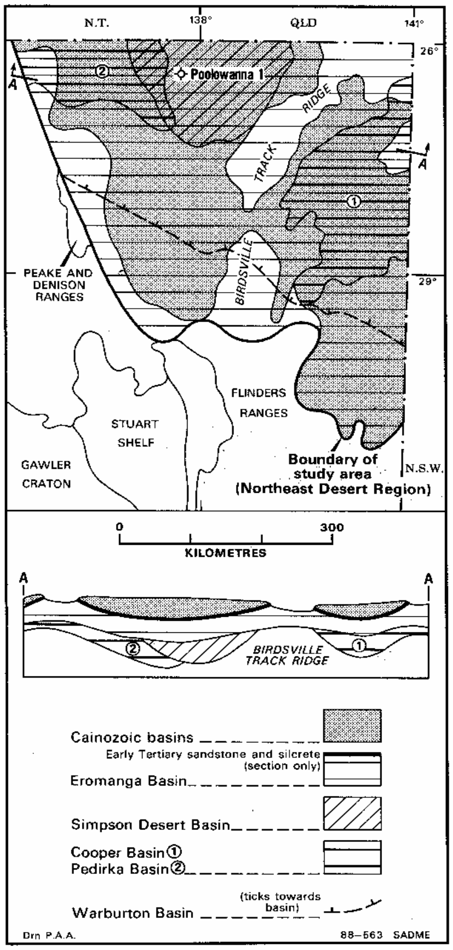


Fig. 3. Basins of the north east deserts.

Cold - to cool - temperate forests dominated by giant ferns were widespread over northern South Australia in the Early Permian. With time, these plants gave rise to thick, locally extensive peat deposits in poorly drained swampy floodplains crossed by meandering streams. Thickest deposits occur in the Patchawarra Trough of the southern Cooper Basin where coal seams derived from peat are up to 30 m thick. The coal measures, with interbedded fluvial sandstones and floodplain mudrocks, are known as *Patchawarra Formation* in the Cooper Basin and *Purni Formation* in the Pedirka Basin (Gatehouse 1972; Battersby 1976; Youngs 1976). Late in the Early Permian, extensive flood basin lake deposits covered parts of the southern Cooper Basin *(Murteree Shale, Roseneath Shale).* These and their interbedded fluvio-deltaic-shoreface sequences *(Epsilon, Daralingie Formations)* formed the last Early Permian deposits in the Cooper Basin. Equivalents have not been found in the Pedirka Basin: they were not formed or have been subsequently eroded.

At the end of the Early Permian, compressional reactivation of thrust and strike-slip faults, formerly active during the Alice Springs Orogeny, led to uplift and erosion along arcuate north east structural trends (Kuang 1985). Locally, erosion was severe enough to cut down and expose Warburton Basin rocks, but away from these highs, deposition may have been continuous (Battersby 1976). The Late Permian was an epoch of relative tectonic quiescence during which meandering river deposits alternated with floodbasin lake sediments. These strata comprise the *Toolachee Formation* and are restricted to the Cooper Basin. Deposition continued into the Early Triassic in this region where redbeds of the *Nappamerri Formation* provide an effective seal over the underlying hydrocarbon reservoirs.

SIMPSON DESERT BASIN

Geophysical surveying in the 1960s led to the belief that Permian sediments may have been deposited beneath the Simpson Desert region (Sprigg 1962; Williams 1973; Youngs 1976). However, drilling of the oil-discovery well Poolowanna-1 (Fig. 3) in 1977 revealed a thick Triassic sequence disconformably overlying the Warburton Basin, with the Permian wholly absent (Wiltshire 1982). More recent exploration has delineated a sedimentary basin bisected by a north-south trending trough, the Poolowanna Trough, which contains a thick Mesozoic sequence. The Triassic portion of this sequence is assigned to the Simpson Desert Basin, with the thickest developments being in the Poolowanna Trough (Moore 1986).

Triassic sediments are assigned to two formations, the lower *Walkandi Formation* which is restricted to the Poolowanna Trough, and the conformably overlying, more widespread *Peera Peera Formation.* The Walkandi Formation of presumed Early to Mid Triassic age is similar lithologically to the Nappamerri Formation in the Cooper Basin although the two are now separated by the 150 km wide Birdsville Track Ridge.

Walkandi Formation consists of silicacemented, variegated red and green shales with fine sandstone interbeds. Shrinkage cracks and

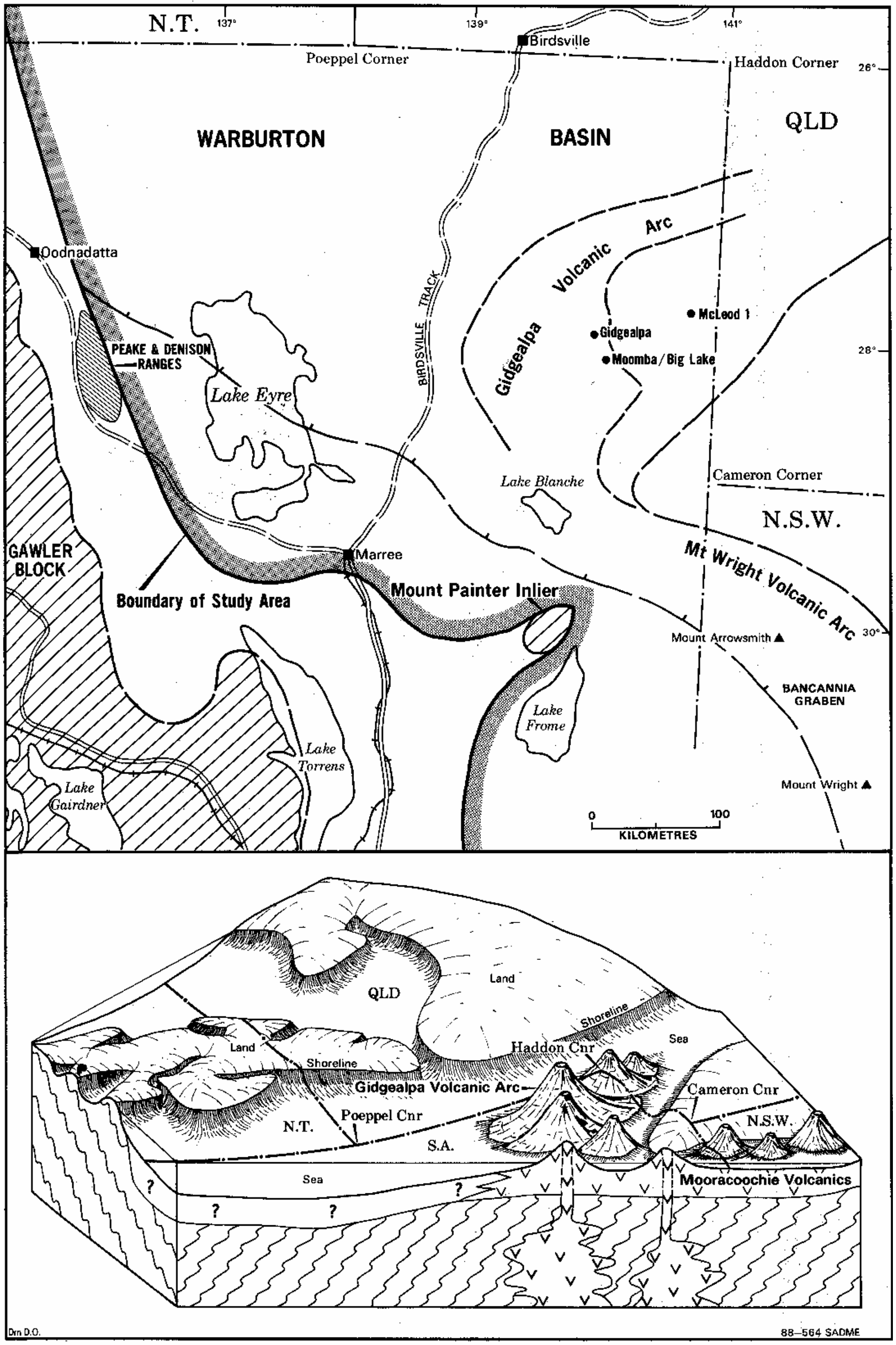
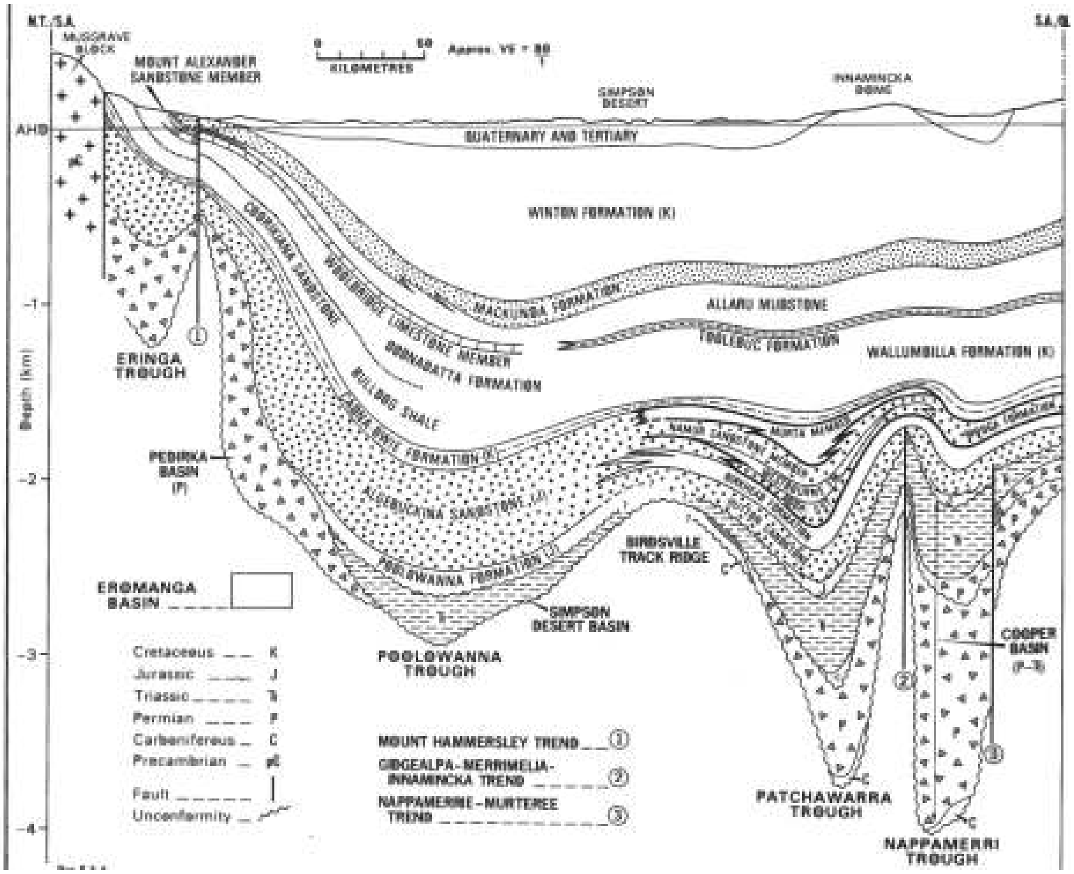


Fig. 4. Distribution of Mooracoochie Volcanics and palaeogeography of the Warburton Basin after their extrusion.

Fig 5 Silicified trilobite fragments from the Kalladina Formation in Gidgealpa 1 drill hole, core 23, depth 3732 m Acetate peel of slabbed core.

colour mottling reminiscent of pedogenic processes suggest a shallow oxidising ephemeral lacustrine environment of deposition. (Moore 1986). Plant microfossil assemblages indicate that the conformably overlying Peera Peera Formation is Mid to Late Triassic in age, thus correlating with the Leigh Creek Coal Measures. *Peera Peera Formation* was widespread in the Simpson Desert Basin and a may have been continuous with unnamed Upper Triassic sediments over parts of the Cooper Basin. Wiltshire (1982) has suggested that the Leigh Creek Coal Measures may be an outlying remnant of formerly very extensive deposits. In the Simpson Desert Basin, Peera Peera Formation consists of carbonaceous sandstone, siltstone shale and coal. Cyclic lithofacies suggests a meandering fluvial system on a broad floodplain, perhaps developed over lacustrine deposits (Moore 1986). The Peera Peera Formation, and Upper Triassic deposits elsewhere in the north east of the State, are unconformably overlain by sediments of the Eromanga Basin.



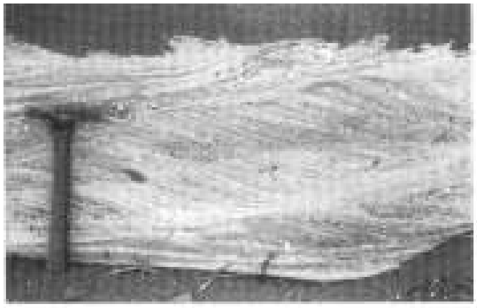
EROMANGA BASIN

Following relatively stable tectonic conditions near the end of the Triassic and beginning of the Jurassic Periods, renewed crustal downwarping over the northeastern part of the Australian landmass initiated development of the Eromanga Basin. At first rivers deposited detritus derived from the erosion of the surrounding uplands around this huge subsiding basin, but as subsidence increased, the sea invaded the region from the north, introducing a marine environment of deposition. Finally, as the basin filled and the region was uplifted, the sea retreated to the north and fresh water, terrestrial conditions returned. Fig. 6 shows the sedimentary sequence that resulted from this cycle of events.

The first-formed units of the Eromanga Basin are *Algebuckina Sandstone and associated formations.* This sedimentary packet, consisting predominantly of sandstones and approaching 1000 m in thickness, was deposited from large river systems approximately 190-130 million years ago. Although mainly of sandstone, significant finer grained units of siltstone, shale and coal occur subsurface in the northeastern part of the study area, representing the more central regions of the Eromanga Basin. Here, at times, rivers were more sluggish and flood plains, swamps and lakes more extensive than nearer the basin margin, where this stratigraphic interval is composed entirely of Algebuckina

Algebuckina Sandstone is essentially a fine to coarse, pebbly sandstone which is kaolinitic in the lower part, clean, with a more uniform grain size in the upper part, and with northerly-directed current-bedding (cross-bedding) throughout. It is exposed extensively along the south and west margins of the study area resting with angular discordance on steeply dipping older rocks of the Willouran, Mt Painter and Peake and Denison ranges. From here the unit dips basinwards and extends subsurface to the northeast where it interfingers with the fine-grained associated formations. Good examples of Algebuckina Sandstone can be seen at the type and reference sections (Wopfner *et al.* 1970) near the former Algebuckina railway siding and near Mt Anna (Fig. 1). The lower, kaolinitic part occurs as conspicuous white cliffs, the current bedding as tabular-planar sets or large 'scour and fill' troughs (Fig. 7), and the upper part as light brown-or-grey weathering, uniformly large scale trough-cross-bedded, porous sandstone. In the top of the unit impressions of fossil leaves and wood are locally preserved where silica and iron-oxides have impregnated the sandstone. Microfossils of plant remains, especially spores and pollen of conifers and ferns, have been recovered from the rare clay lenses in the unit and from drill hole specimens.

Fig 7. Medium scale current bedding of karge ripples in a stream with pebbly scour hollows. Algebuckina sasndstone, Jurassic, Warrina region



Algebuckina Sandstone was deposited in a landscape of large, northerly-flowing, moderately energetic rivers with fluctuating discharge during its earlier stages of deposition and a more uniform, stronger flow later. Conifers and ferns dominated the plant association of the region (Alley 1986) suggesting a moist cool-temperate climate although Wopfner *et al.* (1970) give evidence for aridity in the earliest stages of deposition. Given the cool climate a pronounced seasonal snow-melt from adjacent uplands to the south could possibly explain the variable stream discharge indicated by the various current bedding styles. Conditions in the latter part of deposition were generally wetter, with the ubiquitous, large-scale cross bedding in the upper part of the unit. Eventually, when stream gradients diminished, waterlogged tree trunks and other plant debris accumulated in lakes and sluggish rivers. At this time silica and pyrite (later oxidised to iron oxides) may have entered the saturated sediments, marking the end of active Algebuckina Sandstone deposition.

While Algebuckina Sandstone was being deposited over the western Eromanga Basin, associated formations were being laid down over the northeast region. These thick fluvial and lacustrine deposits comprising four major units are presently nowhere exposed. In ascending order they are the Lower Jurassic *Poolowanna Formation* and *Hutton Sandstone,* Mid to Upper Jurassic *Birkhead Formation* and Upper Jurassic to basal Cretaceous *Namur Sandstone Member* of the *Mooga Formation.* In the northeastern most part of the study area the Namur Sandstone can be further subdivided into the *Adori Sandstone, Westbourne Formation* and *Hooray Sandstone.* An additional unit, the *Murta Member* of the

Mooga Formation, occurs more locally at the top of the sequence. This rather complicated subsurface stratigraphy has arisen chiefly because on passing basinward over the Birdsville Track Ridge, lacustrine siltstones and mudrocks with minor floodplain coals are interposed between sandier fluviatile units. Each formation is a major oil producer, and for this reason each has been separately mapped and studied in some detail.

Poolowanna Formation, the lowermost Eromanga Basin deposit, occurs in the Poolowanna Trough and to the west interfingers with the Algebuckina Sandstone. To the east it extends over the Birdsville Track Ridge into the Patchawarra Trough region of the Cooper Basin. The formation passes laterally and vertically into the Hutton Sandstone in this region and, despite being an oil producer, has not been mapped systematically.

Lithologically the formation consists of sandstone with carbonaceous to coaly shale interbeds. These form fining upward cycles in the Poolowanna Trough (Moore 1986), but in the Patchawarra Trough the sand and mud rock interbeds are thicker and more discrete. Braided to anastomosing moderate to high energy fluvial environments of deposition have been proposed (Barr & Youngs 1981; Moore 1986).

Hutton Sandstone is widely distributed and is composed predominantly of cross-bedded quartzose sandstone with minor mudrock interbeds. The unit intertongues with the Algebuckina Sandstone west of the Birdsville Track Ridge, and overlies or intertongues with the Poolowanna Formation. Hutton Sandstone is considered to represent widespread low sinuosity braided stream deposits with little preservation of overbank and floodplain mudrocks (Bowering 1982). Apart from being a major oil producer, Hutton Sandstone is also a significant aquifer of the hydrogeological Great Artesian Basin (Habermehl 1986). The top of Hutton Sandstone is diachronous, younging westward, and locally there is a thin transitional passage into the overlying Birkhead Formation. Elsewhere the formation boundary may be abrupt. Dipmeter and isopach data suggest that Hutton Sandstone was deposited on a north-northeasterly palaeoslope, with evidence in some areas of a change in palaeocurrent direction towards the east near the top of the formation. This change may reflect a transition from basinward progradation to vertical aggradation as topography became more subdued.

Birkhead Formation is a thin, fine grained unit which conformably overlies Hutton Sandstone east of the Birdsville Track Ridge. Lithologies consist of fine to medium grained sandstone, siltstone, carbonaceous shale and minor coal. Locally, sideritic carbonate horizons occur in the lower part and these provide impermeable seals to Hutton Sandstone reservoirs. Elsewhere Birkhead Formation and Hutton Sandstone are in transitional contact and good reservoir quality sandstones form important targets for oil. Environments of deposition range from meandering fluvial to coal swamp and lacustrine (Paton 1986).

Namur Sandstone Member, since it was defined by Nugent (1969), has not been closely studied in terms of sedimentary facies. In northeastern South Australia and southwest Queensland an additional shaly unit (Westbourne Formation) has been mapped, but elsewhere the Namur Sandstone Member as the name implies consists mainly of sandstone although it contains lesser siltstone and mud rock.

The unit has traditionally been regarded as of braided fluvial provenance comparable with Hutton and Algebuckina Sandstones and, like these, it is a major artesian aquifer. However there is increasing evidence to suggest that the upper Namur Sandstone and Early Cretaceous equivalents were partly subaqueous deposits. This may represent the first marine incursion into the Eromanga Basin (Alley & Lemon 1988) possibly via a narrow seaway through the eastern Eromanga Basin to the Gulf of Carpentaria.

The Murta Member was recognised as a lacustrine unit by Nugent (1969). Because of its significance as an oil reservoir it has been studied in some detail (Mount 1981, 1982; Ambrose *et al.* 1986). As with other fine grained units Murta Member did not extend west much beyond the Birdsville Track Ridge where Algebuckina Sandstone is overlain by Cadna-owie Formation. Various shoreline bar, deltaic, and delta fan facies have been described for the Murta Member which is presumed to have been largely non-marine. The unit is conformably overlain by Cadna-owie Formation.

Cadna-owie Formation, the next unit in the Eromanga Basin sequence, represents the transition from fluvial conditions (Algebuckina Sandstone) to marine (Marree Subgroup), a time interval of 17-18 million years. Like Algebuckina Sandstone the unit is exposed around the southern and western margins of the study area where it is generally less than 20 m thick, and from where it extends northeast as a thin, subsurface blanket, generally less than 70 m thick, over the entire region.

Cadna-owie Formation is an assemblage of sandstone, siltstone and claystone very different in character from Algebuckina Sandstone being finer-grained and lacking the ubiquitous medium and large scale cross-bedding. In subsurface the unit is a single, coarsening-upwards sequence grading from grey siltstone at the base to fine or occasionally medium-grained calcareous sandstone at the top (Moore & Pitt 1985). In outcrop, however, Cadna-owie Formation is surprisingly heterogeneous as illustrated in the type section some 4 km west of Algebuckina railway siding (Wopfner *et al.* 1970). Here the unit contains sandstone beds and lenses that are variably fine to coarse grained, gritty to pebbly, calcareous, pyritic, ferruginous and oolitic, together with carbonaceous claystone, and cross-laminated siltstone and very fine sandstone. Particular features of note are the pebbly ferruginous grit layer with red rhyolite clasts near the top of the section and a sandstone bed nearer the base containing large waterworn boulders up to one metre across. These features may be observed in other outcrops and in particular the interval with rhyolite pebbles is very thick at the Mount Anna reference section where it contains an abundance of these pebbles and occurs as a coarse sandstone with large trough cross-bedding. This distinctive interval has been named the Mount Anna Sandstone Member by Wopfner et al. (1970).

Cadna-owie Formation was deposited in a complex of local environments associated with the advancing marine shoreline and adjacent coastal plain. Quiet backwater lagoons and swamps where chemically reducing conditions prevailed could have produced the pyrite and carbonaceous beds. Oolites suggest shallow agitated water such as a sea or lake shoreline or marine shoal, and fine, current-laminated sand and silt perhaps represents a shallow, near shore environment where gentle currents distributed sediment. The layer of boulders probably came from eroding Permian boulder clays exposed in the hinterland. Later in this depositional period large strongly flowing rivers draining the Gawler Ranges region (Fig. 1) carried erosion products including rhyolite pebbles northwards to the sea and built deltas which became the Mount Anna Sandstone Member. Eventually, however, the sea advanced over the whole region setting the scene for the next cycle of sedimentation.

Marree Subgroup (Bulldog Shale, Coorikiana Sandstone, Oodnadatta Formation) and *Mackunda Formation* together represent the marine-deposited interval of the Eromanga Basin sequence. This interval is widely, though often poorly, exposed around most of the margin and extends basinwards beneath younger deposits reaching a maximum thickness of perhaps 750 m. It was deposited over a time interval of approximately 15 my giving way to terrestrial conditions about 100 my ago.

Fig 8. Shell bed in hard dark grey carbonate (limestone) pod, in Bulldog Shale, Cretaceous, Curdimurka region

Marree Subgroup starts with *Bulldog Shale,* a dark grey shaley mudstone with silty and very finely sandy phases. Small scale constituents include shell fragments, flecks of carbonaceous matter including small pieces of carbonized wood and disseminated patches of sulphide minerals. The basal part of the unit contains large, waterworn boulders and large fossil logs. Higher in the unit dark grey, ellipsoidal limestone pods up to one metre thick and two or three metres long occur in distinct layers which individually extend over a few hundred metres. Occasionally these pods contain abundant shell remains (Fig. 8) and are commonly rich in microfossils. Bulldog Shale is largely an offshore shelf mud deposited from suspension. The lowest part represents restricted, and perhaps locally stagnant, very marginal marine conditions and for the upper part a more open, oxygenated marine environment is indicated by the greater abundance and diversity of fossil remains. The large boulders may have been transported from their Permian source area by seasonal ice flows, as Australia in the Early Cretaceous was much further south than now and presumably had a colder climate.

Coorikiana Sandstone is a khaki brown-weathering very fine-to medium-grained, and occasionally very coarse, calcareous sandstone with locally-developed pebble-conglomerate layers. Small scale trough cross bedding, ripple marks and fossil burrows, trails and wood fragments with *Teredo-type* borings are common. Fossil shells (e.g. bivalves, gastropods) and rare shark and reptilian teeth have been found. The unit is about 10 m thick, restricted to the west and southwesterly regions of the study area and represents a transitory but significant partial marine retreat in the overall marine transgression. It was deposited in the nearshore to shoreface environment where gentle to moderate marine currents prevailed. Locally however the higher energy currents of river channels deposited coarser material at river mouths along the coast.

Oodnadatta Formation is a grey siltstoneclaystone sequence with laminae of very fine sand, and interbeds of fine sand. It is similar to Bulldog Shale but somewhat siltier and sandier. The unit is in places slightly carbonaceous and contains mollusc shells and shell fragments, the large fossil bivalve *Inoceramus* being prominent. Limestone concretions, some richly fossiliferous with microassemblages, are common. Oodnadatta Formation was deposited in a welloxygenated, shallow, open marine environment. As originally defined, Oodnadatta Formation included a sandstone member at the top called Mt Alexander Sandstone Member (Freytag 1966). This interval is now thought to be equivalent to Mackunda Formation (Vine & Day 1965).

Mackunda Formation is a khaki-brown weathering, very fine, thinly bedded and crossbedded sandstone with intervals of fossiliferous, burrowed claystone or siltstone and thin calcareous mudstone and limestone beds. The unit may be carbonaceous and contains fossil wood fragments near the top. In outcrop Mackunda Sandstone looks quite similar to Coorikiana Sandstone, and was deposited under similar marine to marginal marine conditions as the sea made its final retreat to the north.

Winton Formation and Mount Howie Sandstone (Wopfner 1963) represents a return to terrestrial, fresh-water conditions. At first, sluggish meandering streams, shallow lakes and marshes, and extensive forests with ferns and aquatic plants covered the vast low-gradient plain left by the sea. Up to 1200 m of Winton Formation, composed of dark grey, carbonaceous, pyritic claystone interlaminated and cross-laminated with pale grey siltstone and fine sandstone, accumulated in this quiet environment. Coal derived from peat bogs, grey-green coarser sandstones and calcareous sandstones and limestone concretions are also present. A few specimens contain traces of volcanic debris indicating some distant volcanic activity at this time. Deposition in the Eromanga Basin culminated shortly after Winton Formation times when stream gradients increased perhaps in response to regional tilting. Rivers then cut channels into the underlying beds leaving channel-confined, coarse pebbly sands and gravels with large current-bedding features. This deposit, Mount Howie Sandstone, is only locally preserved.

Deposition of Eromanga Basin sedimentation ended about 95 my ago or a little later. There followed a very long period, some 35 million years, for which there is no sedimentary record in the region. Considerable erosion is thought to have occurred during this time as indicated by the erosional contact with the overlying Eyre Formation and by the preservation of only the lower part of Winton Formation around the margins of the region. It is possible, though, that at least some chemical alteration of the near surface strata also took place, although the main weathering event may have been later. In any case, the sequence, where exposed in silcretecapped scarps of the study area, has been intensely bleached white or shades of pale yellow, pale grey or mauve.

THE CAINOZOIC BASINS

The assemblage of landforms constituting the modern northeastern deserts - dunefields, playas, plains, fans and watercourses - results from the last of three major sedimentary phases that developed successively since the beginning of the Cainozoic Era, 65 million years ago. Each phase produced a sedimentary sequence with distinct characteristics, and resulted in particular landforms being associated with a particular sequence of rocks. The regional topography reflects Cainozoic tectonic events superimposed on the earlier Mesozoic basin development. As well as these processes, the Cainozoic palaeoclimate also, has markedly influenced the northeastern landscape including the distribution of flora and fauna, and of Aboriginal man.

Climate during the development of these sediments and soils shows an overall regional temperature decrease. This has been deduced by studying the fossil microfaunas of ocean sediments, terrestrial spores and pollen blown into the sea, and oxygen isotope studies of foraminifera in deep sea cores (Frakes *et al.* 1987). Two major drops in temperature are recorded, one in the late Eocene (c.39 Million years ago) and another in the early to middle Miocene (c.13 Million years ago), each event lasting in the order of several hundreds of thousands to a million or so years. In the Pleistocene (the last 1.8 million years) a series of marked temperature oscillations recurred and produced the ice ages so well documented in many parts of the world. This regional cooling of the Australian continent is thought to have been caused by the development of southern seaways and cold, circum-Antarctic currents as the Gondwana supercontinent broke up, this cooling effect outweighing the warming effect of Australia's drift towards the Equator.

The climate during the first depositional phase, encompassing the Late Palaeocene to Late Eocene, a period of some 23 million years, was warm and wet, probably monsoonal, and the landscape was river-dominated. The second phase was a magnesian lake-dominated environment with much drier periods (perhaps seasonal), thought to span the Early to Middle Miocene boundary, but possibly being as old as latest Oligocene. The third phase, which includes the sediments of the modern desert, involved the deposition of red brown fluvial sands, dunes and saline lake deposits. These sediments span a period of at least 50 000 years and most likely 4-5 million years, with several of the ice-age events being recorded. The soils and surficial cement within the sediments record aspects of near surface conditions during periods of non-deposition.

The overall climatic picture deduced from the sediments themselves comes from three lines of evidence: (1) the nature of the sediments and sedimentary structures (2) the fossils and (3) the soils, and these aspects are described below for each sedimentary phase (Fig. 9).

PHASE 1 LATE PALEOCENE-EOCENE (RIVER AND SWAMP DEPOSITS) (FIG.10).

Sediments

Phase 1 deposits are composed entirely of Eyre Formation (Wopfner *et al.* 1974) and represent an assemblage of complex sandy channel systems, continuous fluvial sand blankets and braidplains, and fine-grained laminated swamp deposits. The unit is made up of fine-to-mediumgrained sands, with well-rounded and subrounded grains, often with polished surfaces on the larger ones. Several gravel horizons occur at the base, containing multicoloured quartz, chert, and fossil wood derived from the underlying Mesozoic rocks. Silcrete pebbles are abundant in some areas and sparsely distributed throughout. In the southern Lake Eyre Basin, thick silts and laminated clays are present. Carbonaceous matter and pyrite are ubiquitous. Thickness is usually 30-70 m, though the swamp deposits may be over 80 m thick around Lake Eyre, suggesting this was the depocentre for much of the fine-grained material that is absent elsewhere. The sands have sometimes been cemented by secondary silica or carbonate which forms thin hard rock layers.

The most prominent bedforms of the unit are those of river channels consisting of complex bars, slightly sinuous large scale sandwaves, smaller scale ripples, and scour hollows, each with characteristic cross bedding structures in cross-section. Individual channels were sinuous to relatively straight being from 15 to 10's of metres wide, and a few to 10's of metres deep. Clay lenses, sapropels and fine laminated silts representing floodplains may be present. Such sediments are common in modern river deposits in humid environments with an abundant sand source and strong stream flows.

During deposition of Phase 1, the basin was sinking quite rapidly, permitting the stripping of the weathered mantle on the southern ranges, which had probably accumulated during the long period of non-deposition during the Late Cretaceous to Paleocene. Deposition appears to have occurred in two distinct episodes, late Paleocene to Early Eocene, and Middle Eocene, as there are no sediments representing Early Eocene time at least in the southern parts of the basins (Sluiter & Alley in prep).

Soils

The sediments contain horizons of deeply kaolinized regolith sometimes developed directly on basement rocks, sometimes transported and often containing rootlet horizons and patches of silica cement. The silica cement usually takes the form of overgrowths on existing transported

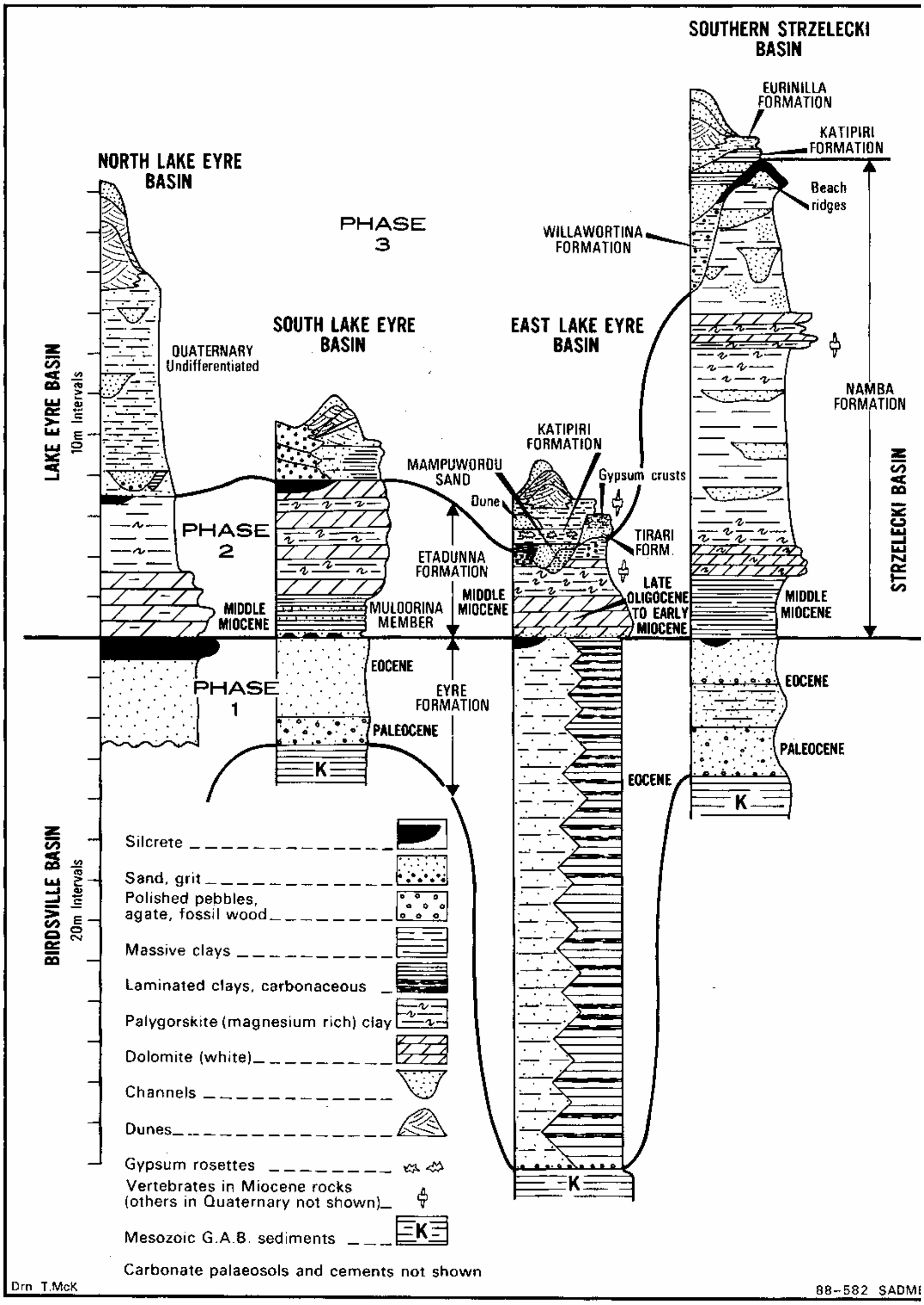


Fig 9. Stratigraphic detail of Phase 1-3 Cainozoic, north east deserts, showing stritigraphic units and relationsips;

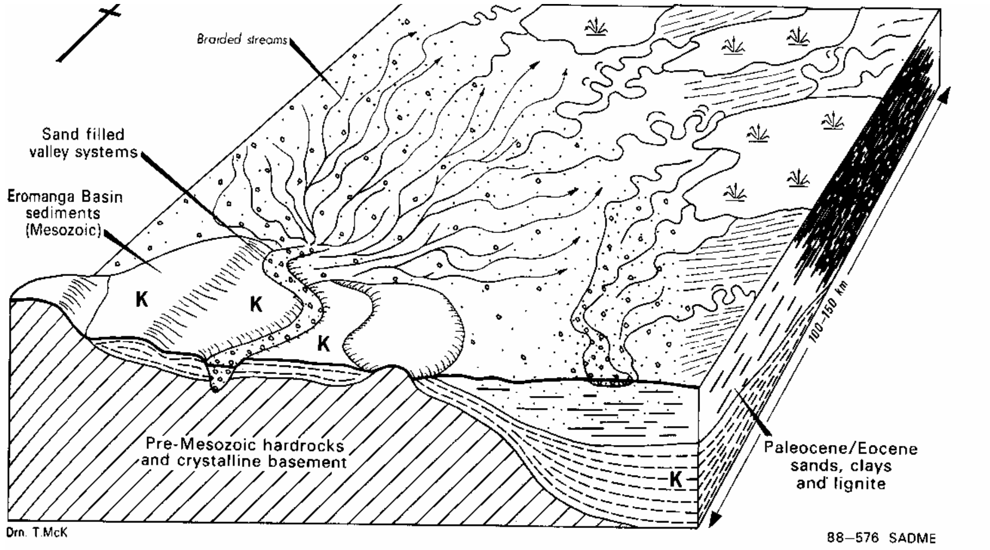


Fig. 10. Palaeogeography during the Late Eocene. Open circles and dots on the surface are alluvial spreads; faint dashed lines are distal fans; plant symbol is swamp facies. Other symbols are as for Fig. 9.

(detrital) quartz grains. Peaty horizons with wood chunks and roots are common in the swamp deposits.

These features are typical of swampy vegetated areas with acid groundwaters.

Fossils

Abundant pollen, spores and plant macrofossils are present wherever the unit is unweathered. Rare carbonaceous clay lenses contain floras of comparable preservation style to that reported from Golden Grove near Adelaide (e.g. Christophel & Greenwood 1987). The more common silcretes contain leaf impressions (Fig. 11) and fruit-casts. The macrofloras contain leaves and fruits typical of Australia's unique modern

Eucalyptus-dominated forests, in addition to leaves of mesophytic species and conifers more like those of modern rainforests. These are summarized by R. T. Lange (in Wells & Callen 1986). His work, and that of C. E. Offler on the coniferous floras of the Woomera area (thought to be of the same age), and more recently Christophel & Greenwood (in press) on the southern floras of southeastern Australia, indicate these forests were similar to those of New Guinea and northeast Queensland. On the other hand, recent leaf discoveries in the Lake Eyre region, indicate this was not exclusively rainforest (N. Alley & D. Greenwood pers. comm. 1988) but probably represented gallery forests along watercourses with more open vegetation between.

Fig 11 *Banksia* leaf impression in silicified Eyre Formation sand of pahse 1, east of Morris Creek Bore, south of Lake Eyre South

Microflora data are summarized by Truswell & Harris (1982), Truswell *et al.* (1985), Martin (1981), Sluiter & Alley (1988 in prep.), Sluiter & Harris (1987) and Christophel & Greenwood (in press), and are in accord with the above. Sluiter & Alley (in prep.) have found the floras of these northern areas are more in harmony with a semi-open canopy forest during the Middle Eocene.

Summary

The time from Late Paleocene to Late Eocene was dominated by a climate similar to that operating across the Queensland monsoonal rainforests and woodlands of today. The combination of abundant vegetation cover and vigorous sand bed streams, together with erosion of deeply weathered hilly terrain, suggests a strongly seasonal, perhaps monsoonal climate. This provides a strong contrast with today's aridity and shrub-steppe and arid herbland vegetation. Deposition terminated with a widespread reedy horizon in the southern Lake Eyre Basin. Direction of transport is thought to be largely to the north and west away from highlands in the Willouran-Flinders Ranges and the Glary-Broken Hill area. Little is known of the northern parts of the basins, although some data have been summarized in Wasson (1983).

PHASE 1 - PHASE 2. SILCRETE AND TECTONICS

Silcrete is a silica cement with intermixed titania, usually of microcrystalline quartz and g quartz overgrowths on detrital grains, and h occasionally with opal. It forms very hard massive grey duricrusts near, or at, old land surfaces, and a contains nodular and columnar structures. The silica cements sediments or regoliths and is more massive in porous rocks which are coarse· a grained. The near surface silcretes are often associated with structures typical of soils. In addition there are several horizons at lower levels which are generally massive quartzites with a sugary texture and no internal structure, and are thought to result from groundwater fluctuations. Silica dissolved from rocks in highland areas by acid groundwaters, was carried to topographically lower positions where it was redeposited in the near surface environment in unconsolidated or weathered sediments or rocks.

Such rocks are common in the Tertiary sequences (Wopfner 1978; Callen 1983a), resulting in the production of tablelands with hard caps. Two main horizons are recorded during Phase 1, the first is only poorly represented in places by rounded gravel up to boulder size in the basal grit beds. The second is a set of

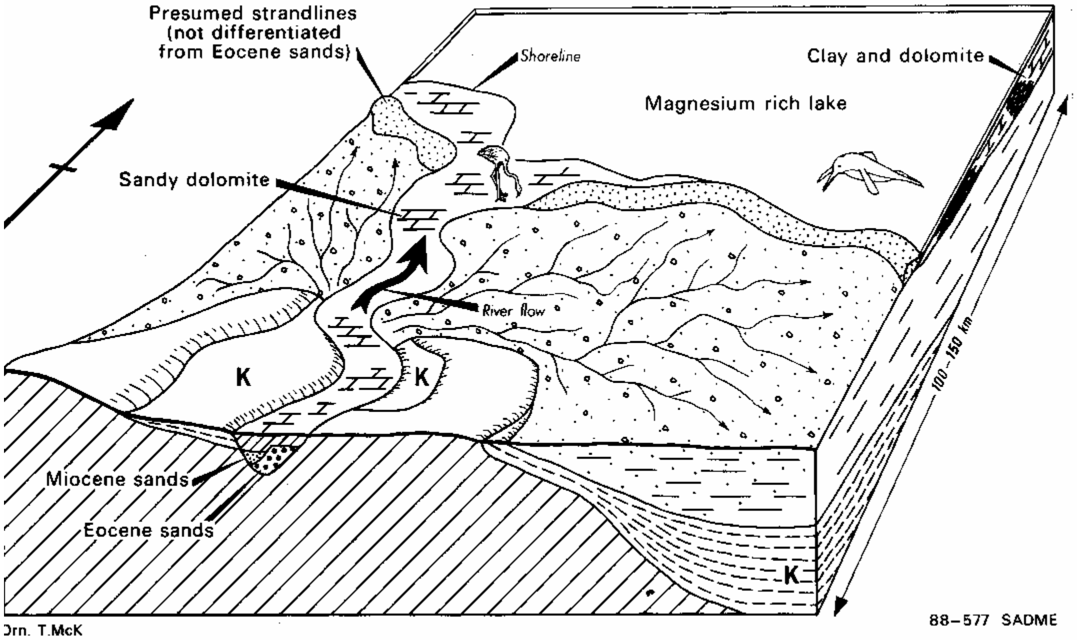


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Fig. 12 Palaeogeography during the mid-Miocene. Symbols are as for Fig. 10.

horizons, at the top of the sequence. It is associated with a widespread fossil reed-bed horizon in the southern Lake Eyre Basin, but is generally massive and columnar elsewhere. This has been extensively eroded, and is now believed by some investigators to be not as widespread as the younger Phase 2 - Phase 3 silcretes.

The silcrete horizons are most prominent in the last stages of deposition of the Eyre Formation, and have thus been caught up in the subsequent tectonics that divided the Birdsville Basin into two. During the Oligocene and Early Miocene, various domes formed (Wopfner 1974) within and around the margins of the northeastern desert region. A major line 'of domes was the Cooryanna (or Kopperamanna) Dome - Birdsville Track Ridge complex which essentially divides the basin in two. The western basin is now called the Lake Eyre Basin, and the eastern, the Callabonna Basin (Wells & Callen 1986; Callen 1988). Uplift of these features was probably taking place to a degree throughout the early Tertiary. Uplift was also taking place on the southern margin of the Lake Eyre Basin.

The Benagerie Ridge in the Lake Frome region, is a rejuvenated Cambro-Ordovician structure now buried under the Curnamona plain and Strzelecki dunefield. It has a thinner sequence of Eyre Formation upon it, though this is partly due to erosion of the Eocene. A number of prominent domes such as Innaminka Dome in the east, exhibit reduced sequences of Eyre Formation in comparison with the subsurface, and also erosion of parts of the section. Plotting subsidence curves, for which sea-level variations have been allowed, reveals that the basin was sinking rapidly during the Eocene.

PHASE 2. MIOCENE - THE GIANT LAKES (FIGS 12, 13)

The Sediments

Phase 2 sediments, representing the 'giant lakes' environment, contain such units as Etadunna Formation (Lake Eyre Basin) and Namba Formation (Callabonna Basin), and possibly Doonbara Formation and Cadelga Limestone (Wopfner 1974). They form a characteristic sequence of fine clastics and carbonates with a very high magnesium content (Callen 1977). Colours of fresh material are grey, bright blue green (in the Lake Eyre Basin), olive, and white, contrasting with the black and grey sands of the Eyre Formation. Channel sands, sometimes coarse and pebbly, are present, especially in the upper part of the sequence.

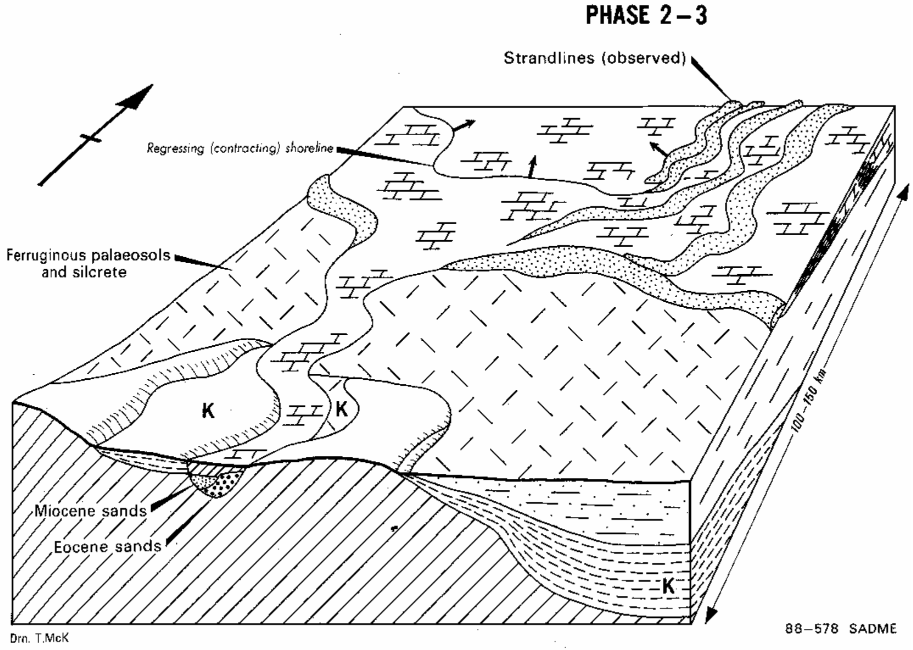


Fig. 13. Palaeogeography towards the end of the mega-lake phase. Symbols are as for Fig. 10. Broken cross hatching is iron-silcrete 'hardpan' or duricrust. K = Cretaceous.

Phase 2 is known to extend throughout the northeastern basins, overlapping the Eyre Formation around the margins. It extends into the Northern Territory (Whitula Formation of Senior 1972) and southwest Queensland (the Marion Formation of Reynolds 1968; Wyatt & Whitaker 1979). However, most information is from the southern basins where bore data are most abundant. In these areas thickness is around 25-30 m, reaching 80 m in the central Lake Eyre Basin. Dolomite is better developed in the thicker sequences, which are located towards the western sides of both the Lake Eyre and Lake Frome regions.

Sandy channels, such as preserved at Pool Creek, contain similar sediments to the Eyre Formation of the previous cycle, but generally indicate lower energy streams with smaller sedimentary structures, and do not have the multicoloured pebble horizons like those in the base of the Eyre Formation.

Deltaic and floodplain facies which developed in the upper marginal facies of Phase 2 sediments, are distinguished by extensively bioturbated (i.e. churned by burrowing animals) dark-coloured clays with disrupted sand beds and iron-mottled soil horizons.

Lacustrine sediments are represented by thin bedded dolomites and silts, also strongly bioturbated in some horizons. Algal mats and stromatolites are common in the south, and pebble intraclasts and rip-up clasts are common everywhere. Laminated lacustrine sediments are present in the southwestern Callabonna Basin, being dark olive laminated tissue clays with ostracods and molluscs.

In the dolomites, there are no features resembling those of the Coorong dolomite lakes in southeast South Australia, such as tepees and multiple phases of mudcracks (Warren 1983; Smoot & Katz 1982). The absence of such structures is surprising, and suggests that the lake rarely dried out. For the final uppermost stages of deposition, their absence may be the result of the high percentage of very expandable clays present. Subsequent wetting and drying of these clays would destroy or disrupt such features, if present. The large surface area of these lakes would have meant that quite limited dry seasons were probably sufficient for the evaporitic environment necessary for dolomite precipitation. Such conditions were more prevalent in the Lake Eyre Basin than the southern Callabonna Basin, as dolomite along with magnesium rich clays like palygorskite (attapulgite), are commoner in the Lake Eyre sequence.

Age

The age of this packet of sediments is probably no older than Late Oligocene and no younger than Middle Miocene. This age is not as welldefined as that of the Eyre Formation in Phase 1 and is based on one palynological determination from a bore in Madigan Gulf of Lake Eyre, and four estimates from the southern Callabonna Basin, together with long distance correlation of vertebrate faunas (M. Plane *in* Wells & Callen 1986; Woodburne *et al.* 1985). The palynology of the Miocene biostratigraphic zones has never been properly documented for these basins, but does suggest an age spanning the Early/Medial Miocene boundary. However, foraminiferal studies (Lindsay 1988) and a single rubidium/strontium isotope age determination of doubtful status of illite (Norrish & Pickering 1983) suggest deposition falls within the Late Oligocene to Early Miocene interval. Deposition occurred over quite a short time-span, perhaps 1-2 million years, according to preliminary palaeomagnetic studies (Barghoorn *in* Woodburne & Clemens 1986).

Fossils

Plant macro and micro fossils, foraminifera, aqueous and terrestrial vertebrates, ostracods, charophytes and shelly faunas (Mollusca and Bivalvia) are all common in Phase 2 sediments. Of these, only the vertebrates (Chapter 17) and microfloras have been studied in any detail.

Pollen and other microflora remains, algae etc., include Myrtaceae with *Eucalyptus, Nothofagidites* (a relative of the 'southern beech'), Gymnosperms including coniferous trees, and many others. The algae *Bottryococcus,* and *Pediastrum* are present in abundance. These species are responsible for oil shale accumulations in Queensland. A sedge-like plant, misidentified as grass (pers. comm. N. Alley 1988), comes from a single drillhole, Wooltana 1, west of Lake Frome. This single sample was responsible for the widespread reporting of grasslands in the Miocene landscape (e.g. Callen & Tedford 1976). The flora has recently been studied in detail by Martin (1989 in prep).

A species of foraminifera recovered from BMR Palankarinna 1 bore on the Birdsville Track in the Lake Eyre Basin (Lindsay 1988) is similar to a species from distant marginal marine environments found in Late Oligocene rocks of New Zealand. It is most likely a form adapted to saline lakes, along with *Ammonia beccarii* (Lloyd 1968; Veevers 1984) which also occurs in these rocks. However, the interesting possibility of a long distance marine connection should not be ruled out. Any such connection would most likely have been via the Murray Basin (Callen & Tedford 1976) or the Gulf of Carpentaria, as the Eucla Basin was closed off to the southwest by the DenisonWillouran Divide (Krieg *et al.* in prep) and the Stuart Range Divide.

Overall, fresh or brackish waters are suggested, becoming saline at times. Both open and closed vegetation were present, with tree species, and a more diverse content of taxa at the Family level than exists today in South Australia.

Soils

Mottled ferruginous horizons of vertisols are preserved in the dark clays of the deltaic/fluvial facies, and calcretes are sometimes present in the carbonates. These indicate waterlogging with seasonal wet and dry conditions.

Summary

This phase of sediments represents deposition in very extensive relatively shallow brackish permanent lakes in a magnesium rich groundwater environment. These lakes may have filled as much as 50% of the catchment or basin area, a situation requiring higher rainfall within the drainage basin itself in addition to more distant highland river sources. Meandering rivers with sandy beds and extensive floodplains supplied these lakes. Presumably extensive sandy beaches formed, but these have been clearly identified only in the Billa Kalina Basin on the southwestern margin of the deserts. No shallow bordering mudflats have been recognized, suggesting permanent watercover most of the time.

The lakes supported an abundant bottom fauna, and contained algal mats and stromatolites. Numerous water-loving vertebrates lived in and around the streams. Tree dwelling species indicate surrounding forest, and the grazing and browsing marsupials are associated with open vegetation. The mineral content of the sediment and soils is suggestive of a periodically dry climate, probably with dry winds increasing the evaporation. Vegetation was open forest or woodland, perhaps concentrated around the waterbodies. Reed-like and sedge-like plants were quite common. Clastic input was very low during this period, and the sediments spread out widely into the basin margins, suggesting low relief.

PHASE 2 - PHASE 3. SILICIFICATION AND DRYING OF THE LAKES (FIG. 13)

Sometime during the Middle Miocene to Pliocene these extensive lakes dried up, leaving a legacy of regressive beach ridges, preserved beneath the dunes in the eastern parts of the basins, either in the form of

beach and lunette deposits or as an imprint. Examples are the aligned chains of claypans approximately parallel to the present lake shores, in areas where the dunefields are superposed on Tertiary sediments without much fluvial cover (e.g. eastern Strzelecki dunefield), and in the silicified ridges superposed on Etadunna Formation dolomite to the southeast of Lake Eyre North. There are also examples in the linear lakes of the southeast of Lake Frome in the Callabonna Basin. Disjunctures in the palaeodrainage systems of the sort produced by successive changes in baselevel are also preserved. Other scattered outcrops of silicified sand throughout the dunefield are probably part of this system.

During these last phases of deposition, patchy silicification took place in strips between the beach ridges. It extends across the lake facies, cementing all lithologies. It is best developed in the sands and weakest in the carbonates. The silicification alternates with development of red iron-ox ide-rich soil horizons which may contain abundant ant or termite galleries and rhizomorphs (root-like casts and molds). Massive carbonate cementation was also common during this time.

These silcreted soils are accompanied by a number of more massive sugary silcrete horizons related to groundwater fluctuations, which do not contain the microfeatures and nodules associated with soil development.

The silicified horizons contain polished and well rounded silcrete pebbles, which show there was reworking of the silicified sands, probably as the lake fluctuated. The best example of this type of deposition is the ridge system of the Billa Kalina Basin (Callen *in* Wells & Callen 1986; Ambrose & Flint 1981), a depositional basin lying on the southwestern margin of the Lake Eyre Basin, just within the northeastern desert area. Here ridges are preserved in long arcuate concentric forms, like the coastal ridges of southeast South Australia, but silicified. These are the remnants of the strips lying between the relict shorelines of Lake Billa Kalina, which once existed between the Stuart Divide and the Denison-Willouran Divide. Sediments of this lake are preserved in the classical 'bullseye' facies distribution found in such lakes, and are of the same type as in the larger basins.

Callen (1983a) has shown the most widespread silcretes around the southern margins of the basins were formed sometime during the late Cainozoic, before Phase 3 sediments accumulated. Work in the Lake Eyre Basin, particularly the Tirari Desert, confirms this and suggests that the Cooryanna (Kopperamanna) and Gason domes, may also be dominated by these silcretes, although other investigators like Wopfner (1978) who named them Cordillo Silcrete believe these to be the Phase 1 Phase 2 silcretes (see also Senior & Mabbutt 1979; Krieg 1985). Not all of this silcrete is associated with regressive shoreline features as much is developed on regoliths or alluvial sand blankets.

The origin of the silcretes is thought to be as follows. Acid groundwaters dissolved silica, iron, and titania (Stephens 1971; Milnes & Twidale 1983), which subseqently precipitated in the evaporative zone of soils either as opal, which later changed to microcrystalline quartz, or more likely as quartz. Precipitation could have been accelerated by organic complexes such as chelates. Zones of groundwater (e.g. the boinkas of the Victorian Sunset Country), (Macumber 1980) in semi-arid low relief landscapes of South Australia are the site of iron and probably silica deposition today, and are regarded as an analogue of conditions at the end of Phase 2 deposition in the Miocene. The indication is of a much higher watertable than present, flooding the areas between the beach ridges.

Palaeomagnetic dating in the Murray Basin (An *et al.* 1986) on similar silica-iron crusts gave an age of 2.4-4 my, and these were previously correlated across the Olary Hills (Callen 1988), This indicates conditions of acidic groundwaters is persisted probably from the Middle Miocene to re Pliocene.

Preservation of the imprint of the regressive P strandline pattern, in spite of subsequent fluvial erosion and deposition is problematic, but a mechanism is suggested from the Billa Kalina S Basin. Here, reversal of topography occurs, with areas between the original ridges which are more 10 intensively silicified being preserved now as a, mesas of silcrete-capped Mesozoic strata, bl Collapse and disintegration of the silcrete to form al gibber, through undercutting of the silcrete caps, ir results in linear clay ridges surrounded by gibberd, plains, as in the Stuart Creek Valley. Burial of Si these sorts of features in various stages of f~ development by later alluvial sediments would d preserve the former 'grain' of the beaches without any Tertiary sediments. However, once the 0 topography was filled, overtopping of the features co means the streams would no longer be confined, te and hence the ridge imprint would become invisible, perhaps to be exhumed by later erosion

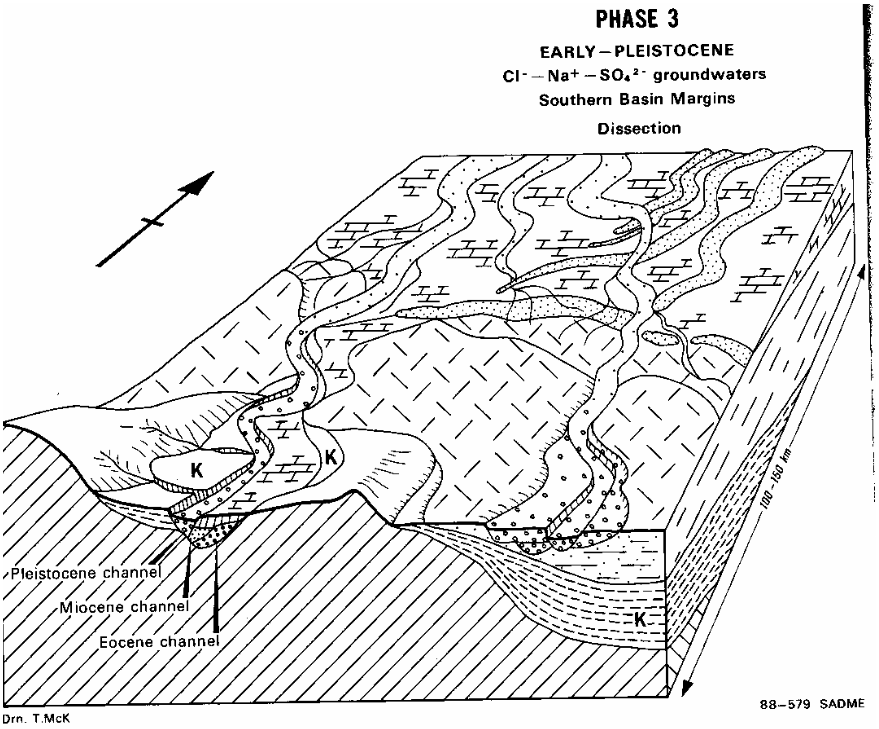


Fig. 14 Palaeogeography in the Early Pleistocene. Symbols are as for Fig. 13.

Shallow, partly buried topography of this sort is preserved in the eastern Strzelecki Desert, related to Lakes Frome and Callabonna.

PHASE 3. ?PLIOCENE - QUATERNARY (FIGS 14, 15)

Sediments

About 6-7 my ago there was a dramatic lowering of sea level around Australia (Frakes *et al.* 1987; An *et at.* 1986), after which conditions became much drier, and the present day playas and dunefields took shape. It was during this drier interval that sediments of Phase 3 were deposited, constituting mainly brown to red-brown sands and conglomerates of fluvial deposits and fans, localized white brown and green lacustrine deposits, and yellow and red brown dune sands.

At this time also, the continued development of folds and faults along the western margin, coupled with erosional downcutting, progressed to the stage of allowing pressure-water from the Great Artesian Basin to escape to the surface. Clastic and chemical deposits from the discharge of water built the line of mound springs that extends from Marree to Dalhousie through the eastern margin of Lake Frome, and beyond (Krieg 1985). These are dealt with in Chapter 9.

Age

The oldest dated material from this packet is from the central Callabonna Basin (Gardner *et at.* 1987, table 1), near Moomba. This thermoluminescence date gave an age of 190-270000 years. In the Simpson Desert, the oldest dates are from radiocarbon methods; c. 38000 years (on *Genyornis* eggshell) from the tops of consolidated dunes (Tedford *et at. in* Wells & Callen 1986) and greater than 38 000 (shell) from beach ridges known to be younger than some of the dunes. A phase of dune formation of c. 48 000 yrs (radiocarbon dates on soil carbonate and thermoluminescence) is known in the southern Strzelecki Desert (Gardner *et at.* 1987, Fig. 7

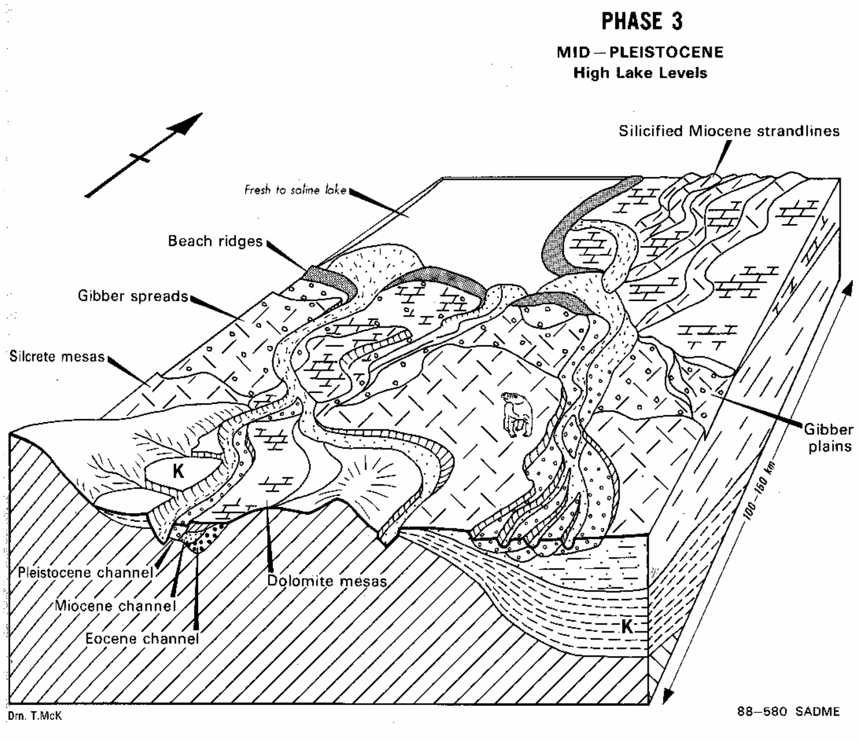


Fig. 15. Palaeogeography in the Mid-Pleistocene. Symbols are as for Fig. 13, stippling is the 10–15m (ASL) shoreline Interglacial times.

Callen 1988, Fig. 4). It is evident from this work and detailed stratigraphic studies that much older dunes are present, and that some of the lacustrine sediment is even older.

From the lake sediment itself, the oldest dates are on radiocarbon from Lake Frome (on disseminated charcoal), and gave ages about 16 000 yrs before present but spores and pollen from a prior phase of Lake Eyre now covered by dunes suggest Pliocene sediments are present. Nanson *et al.* (1987) show alluvial deposition began in the channel country of southwestern Queensland, a continuation of the north east deserts, at least 300 000 yrs ago (from thermoluminescence dating).

The best-dated sequences in South Australia are from the Callabonna Basin, particularly from the last glacial age dunes onwards (Bowler *et al.* 1976; Wasson 1983).

Thus alluvial, aeolian and lacustrine deposition dates back several hundred thousand years, perhaps to the Pliocene, and there is a record of several phases of sedimentation.

The sequence of events and record of climatic change

The earliest sediments are laminated dark lacustrine clays, which were being deposited in Lake Eyre. *Callitris* (Native 'Pine') and *Casuarina* (Sheoak, Bull Oak) vegetation existed further north, the northernmost present day occurrences in the vicinity now being near Olympic Dam. The lake then extended several kilometres further east, but the western shore is thought to have been close to the present shoreline. The red fluvial Tirari Formation of the Tirari Desert was probably deposited, and contains diprotodons, kangaroos and other marsupials.

The sediments indicate dry conditions in the region though not as arid as today, and probably with a greater waterflow in the rivers, keeping the prior Lake Eyre fuller and more permanent than known since European occupation 200 years ago.

Another sequence, probably of Pleistocene age, is the Kutjitara Formation of the Tirari Desert which is a fluvial and aeolian unit, more widespread than the Tirari Formation, but deposited under similar conditions. The landscape at this time is depicted in Fig. 15.

The best documented sequences, recognized in both basins, are the Katipiri Sand and Coomb Spring and Millyera Formations, which are probably around 2-300 000 yrs old i.e. midPleistocene. These are the sediments represented in the meander scrolls of former river tracts of the Cooper, Warburton, and Strzelecki Creek systems. They have also been mapped in the playa area of the Simpson Desert (Krieg & Callen 1980 unpub; unpub data of Callen) where Wasson (1983) reported channels up to 90 m wide. The trends of these drainage systems delineated by claypan chains are probably related , to these sediments. The apparent lower sinuosity of the preserved former river tracts is attributed to obscuration by subsequent dune activity.

Katipiri Sand and associated sediment indicate c a major period of waterflow and alluviation (Fig. 15), though the presence of dune facies and saline sediments show that the local environment was probably arid at times. Runoff probably originated in the monsoonal area of Queensland as it does today, though with more reliable flows. Sediments are yellow and white, cross-bedded sand for the fluvial and beach facies, and green to olive laminated clays with rippled gypsum and algal *Chara* limestone laminae (both stems and minute oval fruiting bodies) for the lacustrine facies. Fluvial channel sands commonly contain locally abundant vertebrate deposits.

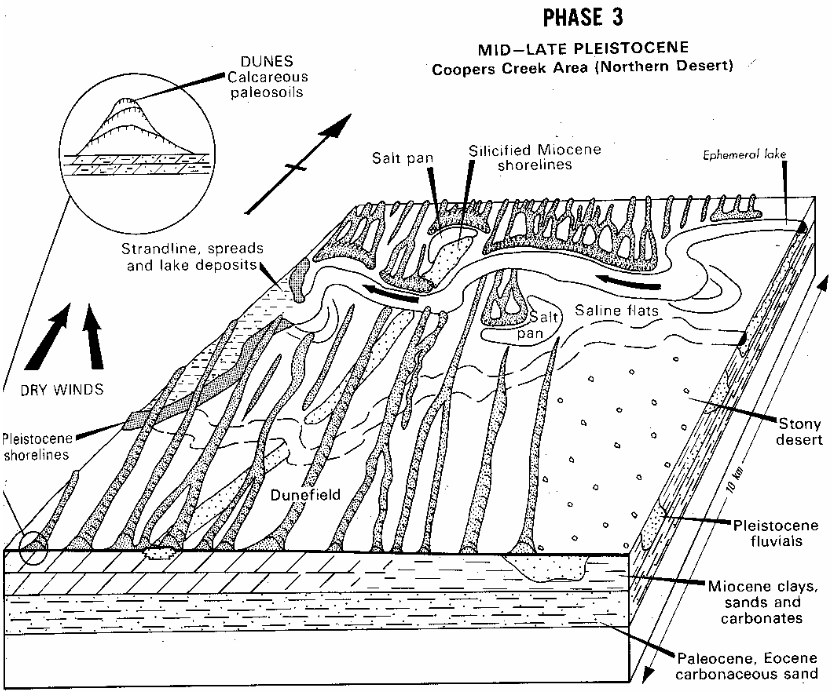
As the watertable dropped during the dry windy episodes associated with the interglacial intervals, (these watercourses were transformed into the chains of playas seen today (e.g. the playa region to the north of Lake Eyre). Some of these were buried by subsequent dune episodes, such as that preserved in BMR Peachawarinna 2, 2a stratigraphic drillholes, where 16 m or more of aeolian and ephemeral playa deposits have accumulated above an old gypsified playa surface. The origin of the present day longitudinal dunefields is believed to date back to this period, about 200 000 yrs ago, immediately after or during the last phases of deposition of the Katipiri Formation, and thus at the start of the second glacial epoch.

Around 25 000 to 40 000 yrs ago major pluvial episodes are recorded (Bowler & Wasson 1983; Gardner *et al.1987)* and would have filled the playas to beyond their present shorelines. The strandline deposits of these episodes (Fig. 16) are preserved as sandy and sometimes pebbly beach.

Fig 16. Pleistocene gravelly beach, see stippled are Fig 15. Former high lake level of Lake Eyre

deposits around the lake margins (Lake Frome - Callen 1983b, 1984, 1988; Lake Eyre - Wells & Callen 1986). Coastal features are especially well-preserved around the southern margin of Lake Eyre South at the ten metre (AHD) level, where such features as islands, headlands, old clifflines, beaches, deltas and sand sheets are recognised. It is possible that these coastal features may extend east to the Birdsville Track as the 10 m contour, where it crosses Cooper Creek, extends this far. The depression in which Cooper Creek flows today may follow a zone where the underlying Etadunna Formation is dominated by expandable clays in which drying out and compaction have caused subsidence. Disjunctures in stream courses associated with prior lake levels can be discerned around Lake Frome (Callen 1988) and Lake Eyre. Lacustrine facies are included in the Millyera Formation at Lake Frome and the fluvial phase is represented by the Eurinilla Formation. Similar units can be distinguished at Lake Eyre.

Whilst these sediments were forming, fanglomerates accumulated around the margins of the southern and western part of the deserts. These included a large proportion of debris flow deposits, suggesting, flash-flooding and erosion of a previously formed thick waste mantle that may have originated during the more vegetated landscapes of pluvial episodes. Wooltana 1 bore in Lake Frome area (Callen & Tedford 1976) records eight phases of sedimentation of this type. The playas developed in the floodout region between these fan edges and the fluvial and aeolian deposits of the dunefields. Their size depended on the interplay between runoff, evaporation and sediment load. At times the playas would have been narrow strips like Lake Callabonna, at others they would have spread out over the fal'l toes and into the dunefields. The present day large playas, Lakes Eyre, Frome, Callabonna, Gregory and Blanche, originated in this way and have moved laterally and changed size in the past.



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. 17. Palaeogeography in the Mid to Late Pleistocene—Glacial times. Symbols are as for Fig. 15, others labelled on diagram. Defunct watercourses form ephemeral salina chains. Several phases of dune building.

The windy period of low lake levels associated with the last glacial around 18 000 yrs ago is well documented in the Callabonna Basin (Bowler *et al.* 1976; Bowler & Wasson 1983; An *et al. 1986;* Callen 1984, 1988; Callen *et al.* 1983). This was the time when lake bed clay and gypsum were deflated from Lake Frome, building transverse dunes up to 30 m high on the downwind (eastern) side of the lakes, and islands on the lake bed itself. Similar features are prominent around most of the playas of the northeastern deserts and are, at least in part, of this age. Features like the huge mound along the northern edge of Lake Eyre South and the Cobbler dune of Lake Callabonna probably contain earlier phases. This was also a period when there was major longitudinal dunebuilding and reactivation of older dunes (Fig. 17). Abundant clay pellets in them testify to higher watertables, a legacy of the last lakefull stage (Bowler & Wasson 1983). This glacial epoch terminated (probably abruptly, e.g. Broecker *et al.* 1988) at about 13 000 yrs before present.

Recent dune activity has been dated over widely separated points in the deserts on the Neales River, and Lake 'Medusa' in the Tirari Desert west of Lake Florence (unpublished data of RAC, F. Leny of CSIRO, Adelaide and R. Wasson of CSIRO Canberra). Substantial modern sand movement has occurred, including building of small longitudinal dunes across lake beds, during the last 100 yrs or so between the older dunes. Today's duneforms and their distribution resulting from these accumulated events, have been described by Wasson *et al. (1988).*

Soil processes, dune colour

Phase 3 sediments show a dramatic change in paleosol types compared with the older deposits, gypsum and carbonate being almosl exclusively developed. Near the ranges gypcrete and calcrete are prominent, becoming patchy and nodular horizons in the distal fans, and soft blotchy materials in the deserts. Carbonate decreases with more northerly latitude, excepl where mound springs are in the vicinity.

Thus there was change in the late Cainozoic from acid groundwaters with a strong flow through, to bicarbonate/sulphate, neutral to alkaline water, reflecting a change in weathering. This is consistent with a change from more vegetated wetter environments to more arid conditions like those of today. Much of the carbonate in the desert is thought to have come from windblown calcareous dust derived from ' continental shelf sediments exposed at the times of low sea level, the glacial maxima.

The origin of the red colour in the dunes is controversial, but Wasson (1982) and Callen & Farrand (1987) have suggested that it is most likely due to inheritance from local red underlying sediments. The abundance of ferruginized Tertiary sands below these dunes, and the red coloured alluvial sediments of the Quaternary are the source.

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2: Subsurface Geology and Hydrocarbon Deposits

by H. WOPFNER

INTRODUCTION

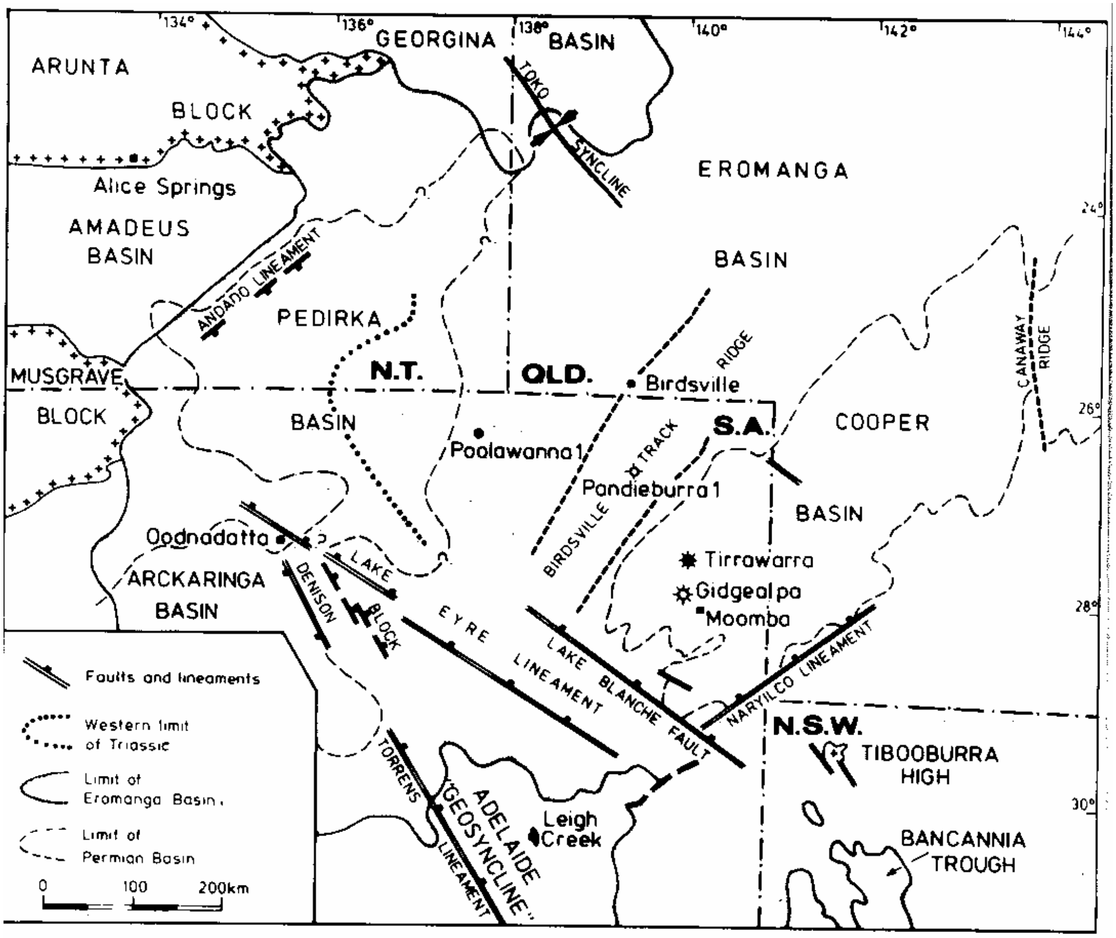
North east South Australia is underlain by the largest and most prolific hydrocarbon provinces on the onshore part of the Australian continent. These are the oil and gas fields of the Permian Cooper Basin province and the oil fields of the Mesozoic of the central Eromanga Basin. These fields not only supply natural gas to the Adelaide and Sydney markets, but also produce about two million kilolitres (13 million barrels) of liquid hydrocarbons annually. These are piped to Port Bonython on Spencer Gulf. A separate pipeline transports oil from the nearby Jackson Field in Queensland to Brisbane. In addition to the established fields, sub-commercial oil accumulations have been discovered in late Triassic - early Jurassic rocks in the well Poolawanna NO.1 in the central Simpson Desert (Fig. 1).

Geologically, the area consists of a basal fold complex comprising late Precambrian to early Palaeozoic strata. This deformed unit is covered by sediments of basin developments of Permo-Triassic, Mesozoic and Cainozoic age respectively. These may reach cumulative thicknesses in excess of 3000 metres. Structural development of the region was strongly influenced by several tectonic features meeting near the centre of the area. In depth, the Tasman line, roughly delineated on Fig. 1 by the trends of the Birdsville Track Ridge and the Lake Blanche Fault, protrudes here to its western-most point. According to Veevers (1984), this line divides Australia into a Precambrian part in the West and a Phanerozoic terrain to the East. This western-most point of the Tasman line is adjoined by the north-west trending central Australian mobile belt, which includes the Amadeus Basin, and which separates the North Australian Craton from the West Australian Shield and its eastward extension in South Australia. These important tectonic sutures were responsible not only for the complex fold structures of the Warburton Basin, created by the early Carboniferous Alice Springs Orogeny (Wopfner 1972), but they also influenced subsequent basin development. Structuring in the Permian Cooper and Pedirka Basins as well as deformations of Mesozoic and Cainozoic deposits of succeeding basins were controlled frequently by movements along these tectonic lines (Wopfner 1960, 1985; Sprigg 1961, 1986). The main structural units of north east South Australia and its surrounding regions are shown in Fig. 1.

Surface expressions range from the uninhabited salina of Lake Eyre and the dune country of the Simpson and Tirari Deserts in the west, to the stony tablelands along the Birdsville Track. Sturt Stony Desert and Strzelecki Desert dominate the morphology of the Cooper Basin, except for the large surface anticlines of Innamincka and Cordillo in the north-eastern corner of South Australia. The remoteness of the area and the difficult terrain are responsible for high exploration costs, requiring comparatively large field reserves before a discovery becomes economically viable.

The first hydrocarbons discovered in commercial quantities were the flows of natural gas and condensate from Permian sandstones in the Delhi-SANTOS well Gidgealpa No. 2 on New Year's Eve 1963. The discovery well was drilled about 95 km south-west of old Innamincka township. The first oil discovery, also in Permian rocks was made in the well Tirrawarra No.2, drilled by Bridge Oil in 1969. The discovery of hydrocarbons in 1963 was preceded by eight years of geological mapping, stratigraphic drilling, geophysical investigations and the drilling of eight deep exploration wells, all of them 'dry' holes (Fig. 2). The author had the good fortune to influence and actively to participate in exploration efforts of these early years, right up to the commercial exploitation of the Cooper Basin gas fields. Subsequently, he was also co-responsible for the selection of the drill site for the well Poolawanna No.1, which discovered the first Mesozoic oil, and which sparked off the string of discoveries in the Eromanga Basin (Sprigg 1986).

Exploration activities, and particularly ensuing field developments, no doubt caused unavoidable changes to the desert. The construction of pipelines, treatment plants and work-force accommodations required the creation of new infrastructures, the building of reliable roads and



ig. 1. **Geologic provinces and major structural lineaments of north east South Australia and adjoining regions. Birdsville Track Ridge and Lake Blanche Fault roughly correspond to the Tasman Line of Veevers (1984). Outlines of the pre-Permian rocks of the Warburton Basin, connecting Amadeus Basin and Bancannia Trough in subsurface have been omitted.**

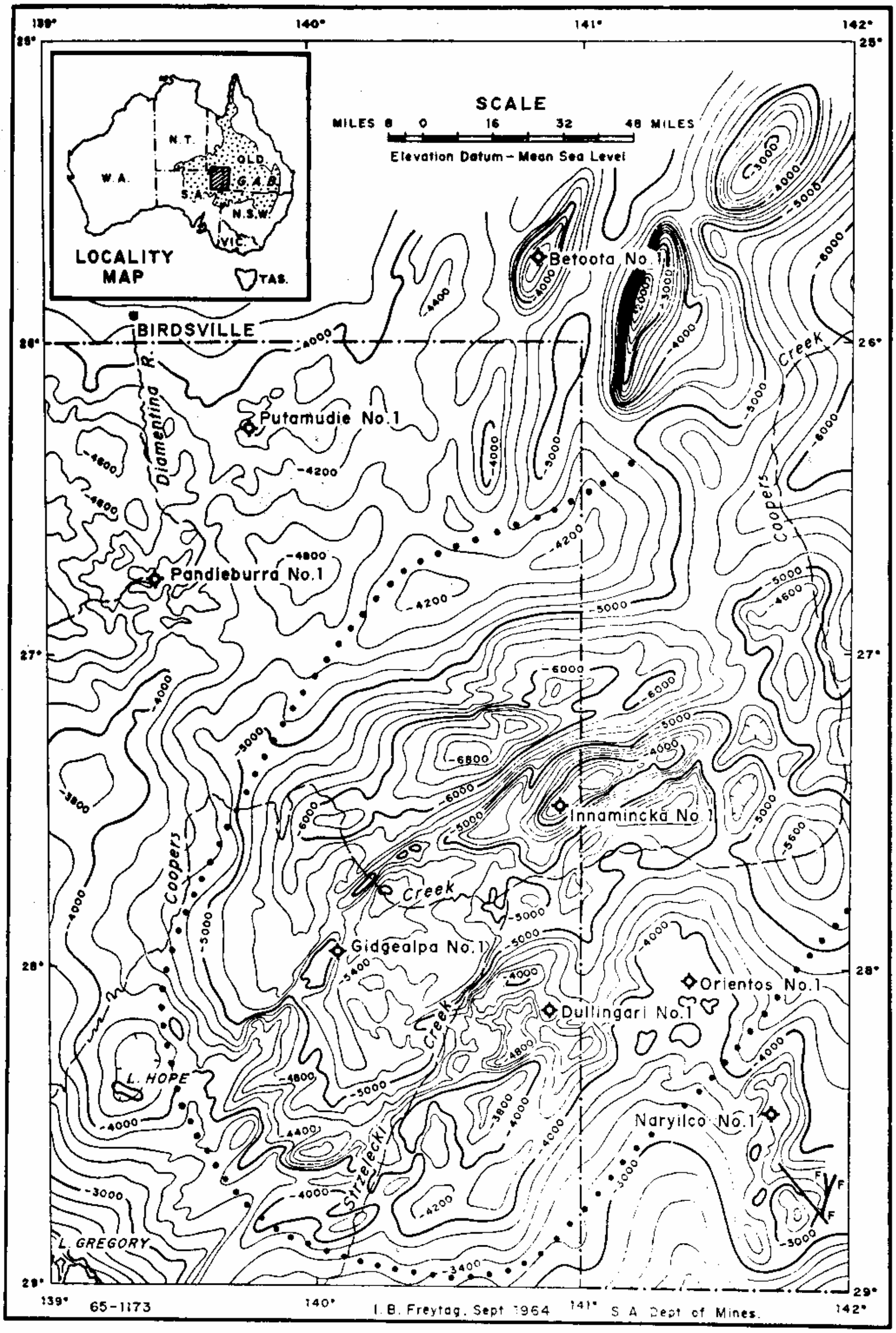
airstrips. But scars heal quickly in the desert and bulldozed seismic tracks would soon be obliterated, were it not for 'nature loving' tourists, discovering the 'Marlboro' freedom in their four wheel drive vehicles. Once, the bottle heap at the old Innamincka pub was acclaimed by all to be the biggest in the outback, but now, a new stratigraphic marker horizon is being formed by empty cans and bottles scattered all over the countryside.

The following account is an attempt to give a broad overview on exploration history, geological background of the hydrocarbon provinces and some thoughts on future exploration targets.

EXPLORATION HISTORY

South Australia can justly claim to have been the first State in Australia in which petroleum exploration was carried out. The first well bore to explore specifically for oil was drilled by the Salt Creek Petroleum Company near Salt Creek on the Coorong Lagoon in South Australia in 1866 (Petroleum Gazette 1986). The early interest in the possibility of finding hydrocarbon deposits in the south-east of South Australia was aroused by the discovery of a rubber-like substance, known as coorongite. This substance, reports of which date back to 1852, was thought to have originated from oil seepages, a reasonable deduction, since coorongite is indeed a hydrocarbon, albeit produced by vast blooms of the alga *Botryococcus braunii.*

Although results of these early efforts were disappointing, exploration remained focussed Fi along a comparatively narrow strip along the coast of South Australia. Only after World War II



65-1173 I.B. Freytag, Sept 1964 S A Dept of Mines.

Fig. 2. Structure contour map of ‘C’ - horizon (*i.e.* top of Cadna-Owie Formation) and locations of oil exploration wells drilled by Delhi-SANTOS prior to the gas discovery in Gidgealpa No. 2 (reproduced from Wopfner 1966).

did petroleum exploration start to spread inland and advance into the far north of the State.

The-Frome-Broken Hill Company, a consortium formed by the Zinc Corporation of Broken Hill, Standard Vacuum of New York and British Petroleum, was the first to carry out-oil-exploration in that area. The group had obtained a licence in South Australia, covering a wide strip of land, extending from the northern Frome Embayment to the northern border of the State. After drilling three dry holes in the southern part of the licence area, and an extensive gravity survey extending as far north as Cordillo Downs, the consortium surrendered the area in 1956 'for lack of any surface structures'. Ironically, the licence covered the whole South Australian portion of the Cooper Basin (Sprigg 1986).

This immediate post-war period, characterised by regional geological investigations and the increased application of geophysical methods, culminated in the discovery of oil in the well Rough Range No.1, drilled by WAPET in Western Australia (Playford & Johnstone 1959). The news of the oil discovery caused a major boom of oil shares on the stock markets all over Australia. Riding the crest of the wave a number of promoters seized the opportunity to float their own oil exploration company - amongst them SANTOS and Woodside, just to mention two of the many.

Although ultimately the oil accumulation in Rough Range No. 1 proved to be noncommercial, the discovery decidedly influenced further exploration thinking. The oil flow from Rough Range NO.1 proved once and for all that Australian sedimentary basins could contain oil. It dispelled the misconceived idea of Australia being far too old a continent to be capable of oil generation.

Yet there was still another prejudice which had to be disproved. Many an expert had condemned the Great Artesian Basin, the largest of all Australian basins, for lack of anticlinal structures, although Jack (1925, 1930) had described some large domal upwarps in the north east of South Australia. It was not until 1956, when the author (as staff member of Geosurveys of Aust. Ltd, acting on behalf of SANTOS Ltd) mapped some large anticlinal structures near Oodnadatta, on the western margin of the Great Artesian Basin (Wopfner 1957; and internal report to SANTOS 1957), that these early observations were recalled.

An aerial and ground reconnaisance of north east South Australia instigated by Sprigg (1958, 1986) and carried out by Wopfner in April 1957, not only confirmed Jack's observations but added a number of other anticlinal structures to the one noted by Jack. The results of this first reconnaisance are shown in Fig. 3. Subsequently, an aerial survey carried out by the author and the late R. O. Brunnschweiler, involving about 130 hours of low level flying in a two seater plywood and fabric aircraft, resulted in the first structure contour map of the Great Artesian Basin. The results of this survey were published by Sprigg (1958). A facsimile copy of the original map has been reproduced in Wopfner (1988) and it also adorns the cover of the Eromanga Basin volume (Gravestock *et al.* 1986). Subsequent surface mapping in the Cordillo Downs region, carried out under the leadership of the author by Greg Swindon, Stan Rowe, Dick Chase and Andy Hess, and supplemented by shallow core drilling (Wopfner 1960), confirmed the aerial observations. Fig. 4 shows the first 'base camp' of the SANTOS team at Haddon Downs in 1957.

The recognition of the large surface structures in north east South Australia and adjacent areas in Queensland (Sprigg 1958; Wopfner 1960) enhanced foreign interest and set the stage for continued exploration efforts. It was the beginning which ultimately led to the discovery of the Permian hydrocarbon province of the Cooper Basin (Wopfner 1966) and the subsequent oil discoveries within the overlying Mesozoic sediments of the Eromanga Basin (Moore 1986a; Sprigg 1986).

When SANTOS and its newly acquired American partner Delhi Taylor Oil Corporation commenced drilling in north east South Australia in 1959, attention was focussed on the large surface anticlines (Figs 2 and 3) and on the Mesozoic succession of the Great Artesian Basin (now Eromanga Basin). As the results of the first two wells were disappointing, attention was diverted to seismically located anticlines and towards the older, early Palaeozoic rocks of the Warburton Basin. Although a thick Permian succession with good gas shows had been encountered in the third well drilled in the area, Dullingari No. 1 (Fig. 2), it required the disappointment of another four wells, before the importance of the Permian, contained within the Cooper Basin, was fully appreciated (Wopfner 1966). The exploration wells drilled up to the discovery of gas in Gidgealpa NO.2 are shown in Fig. 2. In 1962, the French Petroleum Company (Australia) Ply Ltd (referred to as FPC) joined the oil search, taking a large farm-out area from Delhi-SANTOS over the Simpson Desert and the Lake Eyre region.

At that stage, the main targets were considered to be the pre-Permian sedimentary rocks of the Warburton Basin; what Delhi-SANTOS and FPC were looking for were Hassi Messaoud-type oil fields beneath the Great Artesian Basin. Thus it had become customary to punch down the wells.

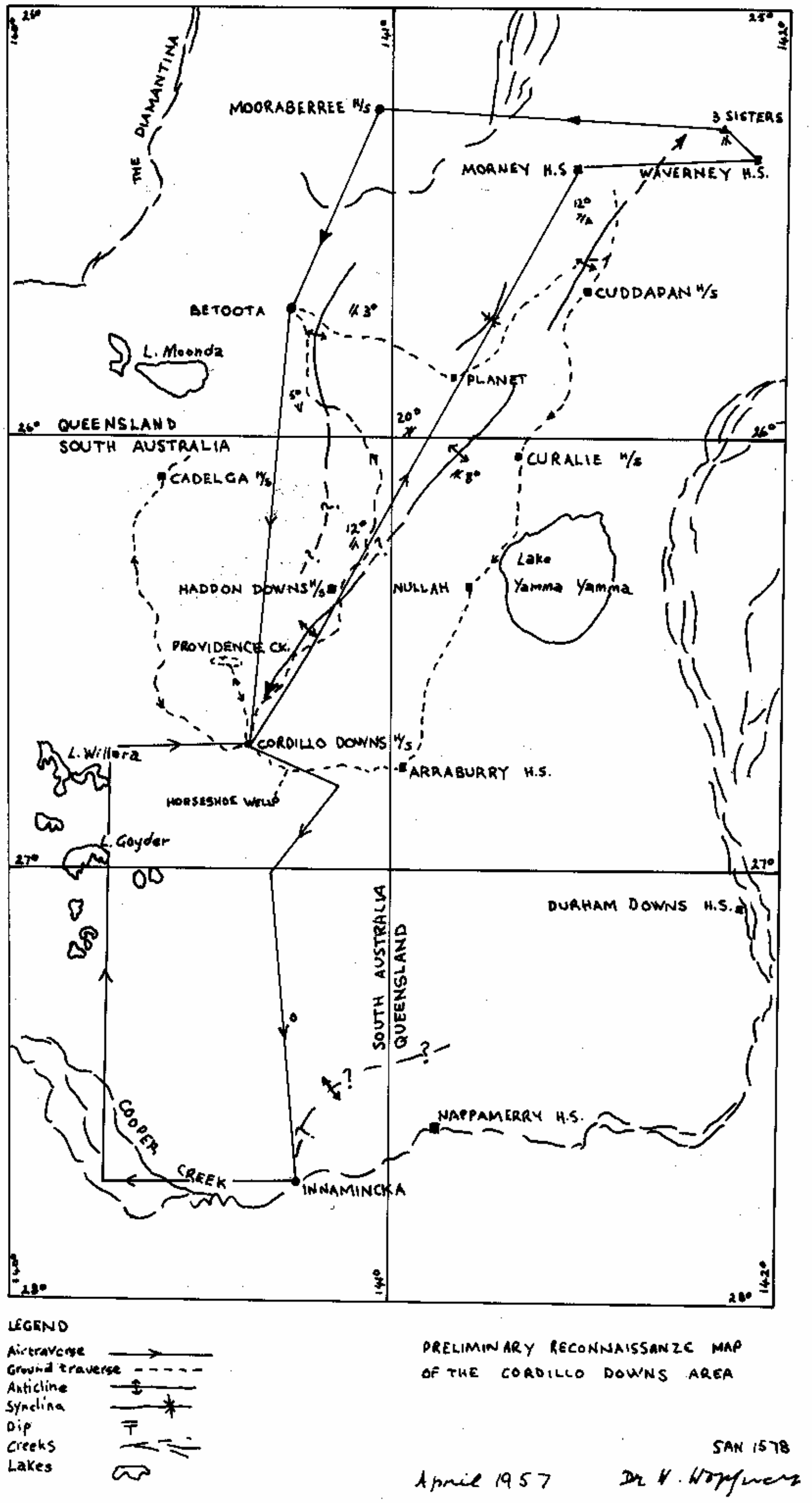


Fig. 3. First structure map of north east South Australia and neighbouring regions in Queensland showing results of the air and ground reconnaissance carried out by the author in April, 1957. The figure is a facsimile reproduction of plan SAN 151.

Fig 4 Old mud hut at Haddon Downs ruins, serving as base camp for geoogosts during the mapping of the Cordillo Downs area on behalf of SANTOS Ltd in 1957. Mesas on eastern skyline are formed by east limb of Mt Howie anticline. Mt Howie is to the right above Landrover (photo H. Wopfner)

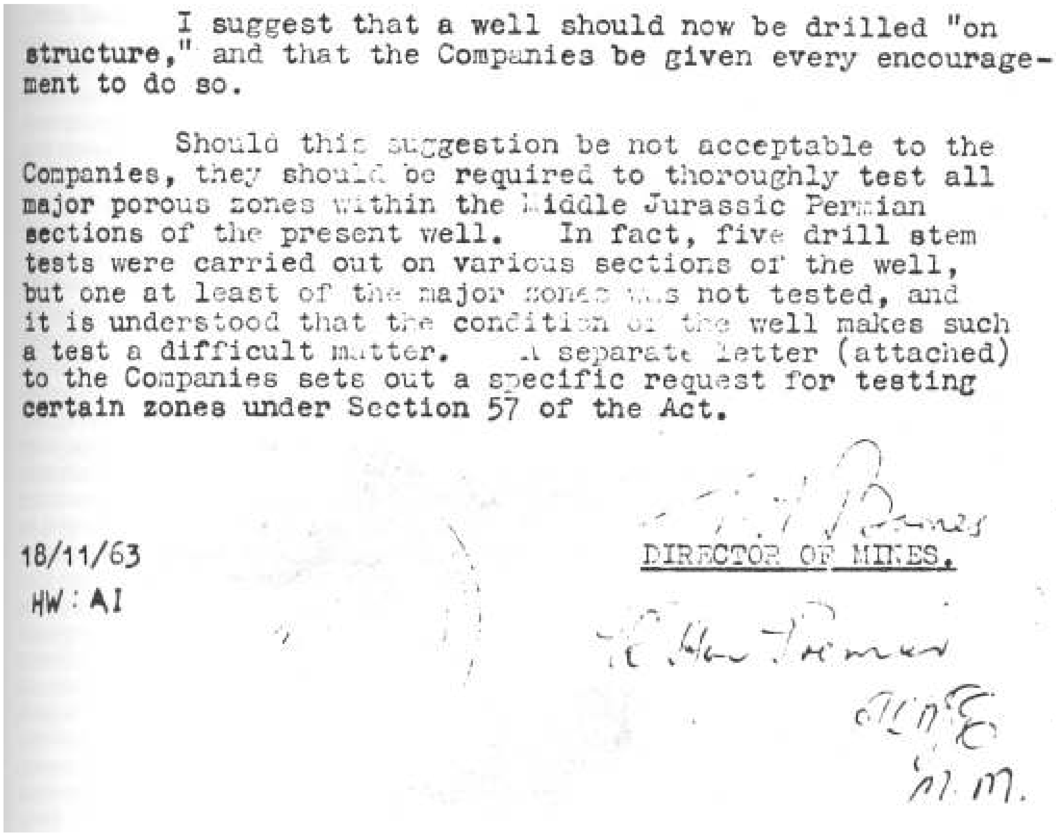
to the pre-Permian unconformity, with little regard for the younger rocks. This resulted in some very untidy, even sloppy, holes.

In Gidgealpa No. 1 the Permian section was so badly washed out and caved that it could not be tested with any open hole test tool available in Australia at that time. Being fully aware of this fact, the author suggested to Sir Lyell McEwin, then Minister of Mines, that the Government should insist that all porous sands of the Permian succession encountered in Gidgealpa No.1, should be tested to the Minister's satisfaction. Alternatively, the companies were given the option to drill another hole near the culmination of the same structure. A facsimile of that minute, forwarded to the Minister under the signature of the late T. A. Barnes, then Director of Mines, is shown in Fig. 5.

A subsequent meeting called at the Rundle Street offices of the Department of Mines, showed the disparity of opinions. SANTOS, represented by Messrs R. C. Sprigg and J. Kluge argued against any additional drilling, as on-structure wells would just prove to be 'bald headed like Betoota'. The company wanted a 12-month moratorium to give it time to reassess its position. SANTOS was supported by C. de Lapparent of FPC, his gallic gestures leaving no doubt of his low opinion of further drilling at that time. Only the representatives of Delhi, Messrs C. Easley and G. Greer were prepared to consider the second well option. The Department of Mines, represented by the Director, Mr T. A. Barnes, the Deputy Director, Mr L. W. Parkin and the author, made it quite clear that the Government would insist on either of the options mentioned above. The meeting was adjourned and the matter reverted to the Premier's Office. It took the well known 'gentle persuasion' of the then Premier, Sir Thomas Playford, to convince Board members of SANTOS that the Government would not be prepared to take no for an answer. Thus, SANIOS reluctantly agreed to the drilling of Gidgealpa No. 2 on structure. It is a fact which many people conveniently overlook, that without government intervention the discovery well Gidgealpa No.2 would not have been drilled.

No other well in the Cooper Basin ever had a more senior crew observing drilling progress. During drilling of the critical Permian interval two senior geologists of Delhi, Messrs R. Freeman and J. Harrison, together with the author performed as well site geologists. At 6 o'clock in the morning of New Year's Eve 1963 an open hole test discovered natural gas at a flow rate of some 2 MMCFD (57000m^3/day). This flow was produced from 11.5 feet (3.5 m) of late Permian sandstone, resting unconformably on Precambrian volcanics (Harrison & Higginbotham 1964; Wopfner 1966).

Several follow-up wells on the Gidgealpa structure showed it to be a potentially commercial reservoir. In 1966 the Moomba Field was discovered, followed by Daralingie late in 1967 and Toolachie early in 1969. In the same year the construction of the gas treatment plant and the natural gas pipeline were completed. In November 1969 gas from the Cooper Basin flowed into Adelaide.



I suggest that a well should now be drilled "on structure," and that the Companies be given every encouragement to do so.

Should this suggestion be not acceptable to the Companies, they should be required to thoroughly test all major porous zones within the Middle Jurassic Permian sections of the present well. In fact, five drill stem tests were carried out on various sections of the well, but one at least of the major zones was not tested, and it is understood that the condition of the well makes such a test a difficult matter. A separate letter (attached) to the Companies sets out a specific request for testing certain zones under Section 57 of the Act.

18/11/63
HW : AI

DIRECTOR OF MINES.

Fig 5 Copy of conclusion of the minute forwarded to Sir Lyell McEwin, then Minister for Mines, in Nov 1963 (Reproduced from SADME file SR 11/5/11

FPC exploring in the westernmost portion of the Great Artesian Basin was less fortunate. They discovered the glacigene and coal bearing Permian sequence of the Pedirka Basin, generally resting on folded sedimentary rocks of the Warburton Basin (Wopfner 1972; Youngs 1975). After drilling six wells in the Simpson Desert and the Lake Eyre region, the company withdrew from active exploration.

On the advice of the author, Western Mining Corporation Lld (WMC) took up a large farm-out area, covering the South Australian portion of the Simpson Desert between 136° 00' and 139° 00' longitude, the Permian of the Pedirka Basin being the main objective. However, the first well, Poolawanna No.1, drilled on a faulted structure some 60 km south of Poeppel Corner tested about 300 bbls (48 kilolitres/day) of oil in late Triassic and early Jurassic sandstones, proving the existence of oil accumulations in the Mesozoic section of the western Eromanga Basin. The discovery stimulated the search for oil elsewhere in the Eromanga Basin (Moore 1986b). Follow-up success in the Lake Eyre region has been lacking so far, but I find it hard to believe that Poolawanna could be a repeat of the Rough Range story.

GEOLOGY

The geological development of north east South Australia is characterized by the formation of various sedimentary basins, commencing in the late Adelaidean. Basin development may be subdivided into a pre- and a post-orogenic phase. The event, separating the two, ensued from the fold movements of the early Carboniferous Alice Springs orogeny, which peaked at around 320 million years B.P. Succeeding basin evolutions were entirely intracratonic and essentially of synecliform nature. However, periods of epeirogenic movements causing changes of stress patterns and periods of non-deposition permit a subdivision of the post-orogenic basin development (Wopfner 1985).

Including the pre-orogenic basin development, four distinctive depositional periods may be recognized:

Phase I: Late Adelaidean to early Carboniferous (pre Hercynian)

Phase II: Late Carboniferous to middle Triassic (pre Kimmerian)

Phase III: Late Triassic to late Cretaceous (post Kimmerian)

Phase IV: Palaeogene to Recent (post Laramian)

This scheme of basin identification was originally introduced by Wopfner in 1969 (1972) for the sedimentary basins of South Australia, but it is also applicable for other parts of Australia (Wopfner 1988).

In north east South Australia Phase I development is represented by the Warburton Basin, Phase II by the formation of the Cooper and Pedirka Basins, Phase III by the development of the Eromanga Basin, previously known as the Great Artesian Basin, and Phase IV by the deposition of the Eyre Formation and younger sediments of the Lake Eyre depocentre.

For the occurrence of petroleum, Phase II and Phase III basins are the most important. They contain the well known oil and gas fields of the Cooper and the Eromanga Basins. A limited potential, particularly for natural gas, must also be ascribed to the Phase I deposits of the Warburton Basin, whereas sedimentary successions of Phase IV are of no direct significance for the formation of hydrocarbon accumulations.

Phase I - Warburton Basin

The Warburton Basin occupied a crucially important position within the tectonic framework of Australia. On the one side it was marginal to the Tasman Geosyncline, but, following Adelaidean trends, it was connected also with the Trans-Australian fold belt of the Amadeus Basin etc. To the south-east it merged with the Bancannia Trough and the Gnalta Shelf. Prior to the Delamerian Orogeny, it also extended south into the Arrowie Basin (Wopfner 1972). This latter connection was severed in earliest Ordovician times, but at the same time a seaway was established between the western Tasman Geosyncline and the Amadeus Basin (Webby 1978).

The Warburton Basin is floored by a variety of phyllites and schists of Precambrian age and occurrences of granite and tonalite below the Big Lake and the Moomba Gas Fields. Radiometric dating of the latter gave an early Carboniferous age, but in the view of the author, this date solely reflects the thermal event of the Alice Springs Orogeny. Similar ages were obtained from rhyolites which are directly overlain by fossiliferous Cambrian limestones in the well Kalladeina No.1 and in Gidgealpa (Wopfner 1966, 1972). These rhyolites and rhyolitic ignimbrites appear to be the oldest rocks covering the Precambrian metamorphics.

The most widespread sediments of the Warburton Basin are Cambrian carbonates and Ordovician siliciclastics. Below the Cooper Basin, the Ordovician deposits consist mainly of dark grey, pyritic, graptolite-bearing pelites, whereas more sandy lithofacies are present beneath the Pedirka Basin. Lithofacies and palaeogeographic reconstructions have been discussed by Devine & Youngs (1975) and Webby (1978). A comprehensive review on stratigraphy and tectonic development of the Warburton Basin was presented by Gatehouse (1986). The dominance of arenaceous Ordovician sediments proximal to the Lake Eyre Lineament apparently resulted from the denudation of the elevated Delamerian fold belt, situated further south. Silurian deposits are generally missing, although some conglomerates encountered below the southern Cooper Basin may be of Silurian age. The Devonian is represented by the Innamincka Redbeds and their equivalents (Tanner 1966) whilst correlatives of the Finke River Beds are present beneath western portions of the Pedirka Basin (Youngs 1975; Devine & Youngs 1975). In the early Carboniferous all these sediments were folded by the movements of the Alice Springs Orogeny. This term is used here in the narrow sense, referring solely to the tectonic events identified by the cluster of isotopic ages in the early and middle Carboniferous (Shaw *et al.* 1984; Schroder & Gorter 1984; Bradshaw & Evans 1988). The extension of the term to include Permian movements within the same tectonic event as suggested by Bradshaw & Evans (1988) is rejected most emphatically.

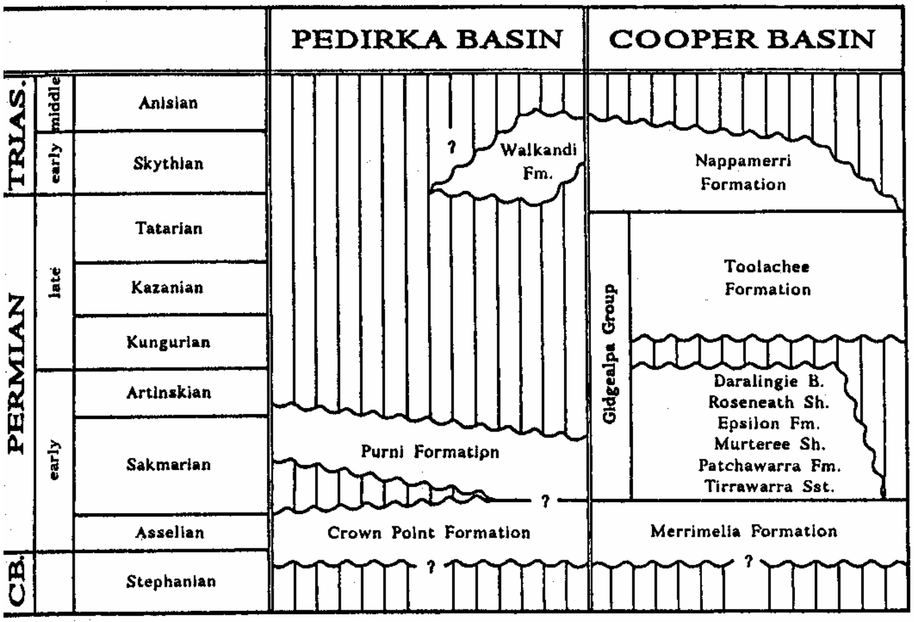
Compressive movements of the Alice Springs Orogeny created a belt of north-east trending folds which parallel the thrust belt of the Pleasant Creek Arch of the Adavale Basin further to the north-east (Remus & Tindale 1988), thus overprinting earlier lithofacies trends. However, a second less pronounced fold pattern with northwesterly axes is indicated in the central and western basin area. It is reflected by residual trends and interference patterns expressed by gravity anomalies, but in some instances it is verified by seismic and dip-meter data. In the western part of the basin these north-westerly trends become more dominant. Thus, the deformational pattern exhibits a similar Y-junction as the Delamerian fold trends of the Painter and Willouran branches further south.

The Warburton Basin is interpreted as a kind of triple junction between a re-entrant of the Tasman Geosyncline and a complex, northwesterly trending aulacogene which transected Australia as a major suture between a northern and a southern cratonic mass. The Alice Springs Orogeny was the final stabilizing event, welding the two cratonic blocks into the Gondwana mosaic.

Phase II - Cooper and Pedirka Basins

Deposition of Phase II was initiated by the Permo-Carboniferous glaciation, which in turn followed tectonic re-adjustments in the late Carboniferous (Ludbrook in Parkin 1969; Wopfner 1980). The glacial event is well documented by the presence of typical glacigene deposits exposed along the western margin of the Pedirka Basin and the Peake and Denison Ranges, but also by widespread occurrences in subsurface. Structurally, the basins of Phase II are essentially intracratonic basins. Their formation was controlled by the partial stabilisation of the Tasman Geosyncline in the east and the formation of a taphrogene system along the western margin of the continent. The basins situated in between were thus controlled by strikeslip movements, caused by an overall compressive state of the crust (Wopfner 1980, 1985; Kuang 1985).

The termination of the glaciation in the early Permian caused a major eustatic rise in sea level in most Australian Permian basins (Ludbrook, *in* Parkin 1969). In northern South Australia, the Samarkian sea invaded the Arckaringa Basin but did not progress beyond the Lake Eyre Lineament (Wopfner 1980) (Fig. 1). Thus post-Samarkian deposition in both Cooper and Pedirka Basins was governed by fluviatile, lacustrine and paludal conditions, leading repeatedly to the formation of thick and extensive coal formations. Within the Cooper Basin, deposition was almost continuous, except for short and local interruptions prior to the commencement of the Gidgealpa Group and again before deposition of the Toolachie Formation (Kapel 1972). Sedimentation continued without interruption into the early Triassic, but under more arid conditions. The intermittent tectonism led to the formation of north-east trending troughs (Patchawarra, Nappamerrie) and ridges (Gidgealpa, Merrimelia, Innamincka) (see Fig. 1) but syndepositional structural growth is also evident (Thornton 1979). Fold development essentially followed trends established during the Alice Springs movements, but the pronounced en echelon pattern of the fold structures indicates deep seated transcurrent displacements as cause for the deformation (Wopfner 1980). Northwesterly trending interference structures are still prevalent and are exemplified, for instance, by the



ig. 6. Stratigraphic units of the Permo-Triassic depositional phase in north east South Australia.

configuration of the Moomba, Kidman and Della fields, just to mention the more obvious. In the Della field late early Permian faulting along these trends, leading to north-west striking isopachs of the Toolachie Formation, have been described by Gravestock & Morton (1984). Stratigraphy and basin development have been discussed extensively, amongst others by Gatehouse (1972), Kapel (1972), Devine & Youngs (1975) and Thornton (1979). An overview of the lithostratigraphy of the Cooper Basin is shown in Fig. 6.

In the Pedirka Basin, the Phase II cycle was also initiated by deposition of glacigene sediments. These are well exposed along the western basin margin, whence they extend eastward into the subsurface (Youngs 1975). Northernmost outliers occur in the Huckita region, at the northern margin of the Simpson Desert (Wopfner 1980). The succeeding Purni Formation is essentially a fluviatile succession with interbedded coal seams of up to 5 m thickness. In contrast to the Cooper Basin, the Permian sequence of the Pedirka Basin does not extend beyond the Artinskian (Fig. 6). However, the widespread presence of Permian remanie palynomorph associations, roughly corresponding to the level of the Daralingie Beds (Fig. 6) in late Triassic and basal Jurassic rocks of the Phase III cycle, suggests that sediments of late Permian age had also been deposited in parts of the Pedirka Basin, but were subsequently removed by erosion.

Syndepositional structuring within the Pedirka Basin was less severe than in the Cooper Basin, reflecting the greater distance from the orogenic front in eastern Australia (Wopfner 1980, 1985). The original fold pattern was extensively modified by Neogene to Recent faulting along northerly and north-easterly faults (Youngs 1975; Wopfner 1985).

The Phase II depositional period was terminated by tectonic movements during the middle Triassic, roughly around Ladinian/Carnian times and broadly related to the Kimmerian disturbance. Tectonic readjustments were expressed by further structuring due to strike-slip movements and finally, by regional tilting to the north-west (Wopfner 1985).

Phase III - Eromanga Basin

Originally, the Eromanga Basin was known as the Great Artesian Basin and this term is still used by investigators concerned with the hydrogeology of that region. Indeed, it would have been more appropriate to retain the classical name for the whole of the basin area.

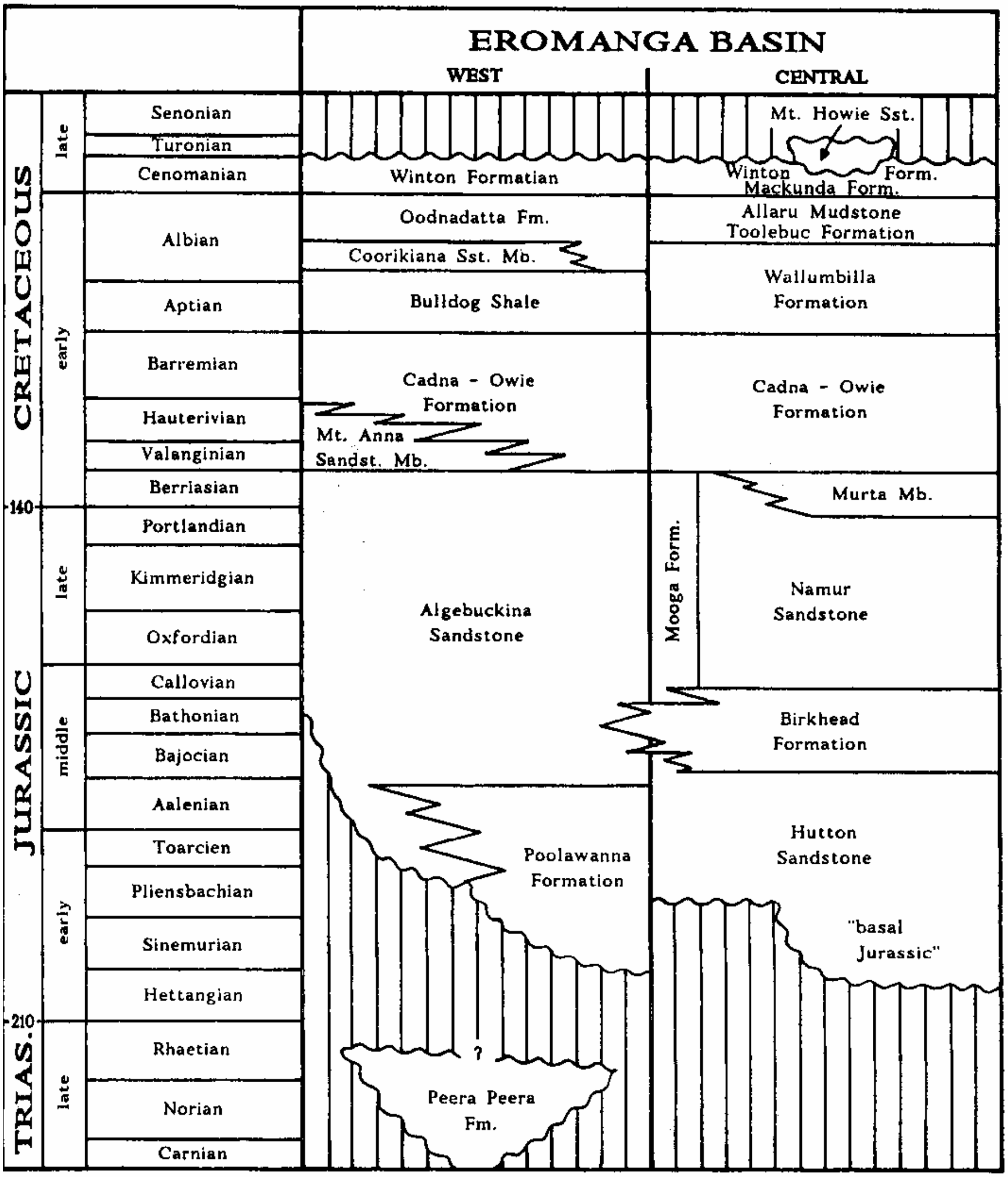
The break between depositional Phase II and III was essentially caused by movements of the Kimmerian tectonic event. These made themselves felt strongest along the eastern margin of Australia, where movements of the Hunter-Bowen orogeny were accompanied by crustal shortening and granite intrusions. Central Australia was upwarped, thus providing the large amounts of siliciclastic material which formed the ensuing fluvio-lacustrine deposits of the late Triassic and Jurassic. The terrain along the south-eastern margin of the Cooper Basin was uplifted, leading to partial erosion of early Triassic and Permian deposits. The ensuing tilting caused a shift of depocentres to the west and north-west. The varicoloured Walkandi Formation of the Poolawanna depression west of the Birdsville Track Ridge (Moore 1986b) may possibly represent a north-western extension of the early Triassic Nappamerrie Formation, deposited during the early stages of these tilt movements. This would entail a hiatus between the Walkandi Formation and the middle to late Triassic Peera Peera Formation and not a continuous sequence as suggested by Wopfner (1982) and Moore (1986b). A hiatus between these two formations is also indicated by the marked difference in climatic conditions (Fig. 7).

Initial sedimentation of the Phase III cycle is thus represented by the Peera Peera Formation and related deposits, such as the Leigh Creek Coal Measures. Sedimentation took place in broad depressions extending from the Leigh Creek and Springfield coal basins in the south to the Huckita region near the eastern end of the Arunta Block (see Fig. 1). In the Poolawanna region deposition was controlled by low energy fluviatile conditions but occasionally tending towards paludal environments, as indicated by the presence of coal and carbonaceous shale.

This depositional style continued into the early Jurassic (Poolawanna Sandstone) but higher energy fluviatile deposits prevailed during the middle and late Jurassic. Towards the western margin of the Eromanga Basin, the braided stream facies of the Algebuckina Sandstone dominated the entire span of the Jurassic (Moore 1986a) (Fig. 7).

Towards the Birdsville Track Ridge and east thereof, fluviatile conditions were interspersed by lacustrine to fluvio-deltaic deposition, leading to a more differentiated succession (Fig. 7). The interbedded, finer grained units are crucial in the formation of hydrocarbon traps in the central Eromanga Basin (Moore 1986a).

The terrestrial deposition of the Jurassic was succeeded by the early Cretaceous marine transgression, commencing around the Berriasian-Valanginian boundary in Neocomian time. Apart from the transgressive Cadna-Owie Formation, deposition was dominated by dark bluish grey shales and siltstones, except for some



ig. 7. Stratigraphic units of the western and central Eromanga Basins (depositional Phase III).

interbeds of glauconitic sandstones and bituminous marls and limestones in the middle Albian and early late Albian respectively (Moore & Pitt 1985; McMinn & Burger 1986) (see Fig. 7). At the beginning of the Cenomanian, regression commenced in the west and the south-west and the sea gradually withdrew from the Eromanga Basin.

The final event of Phase III was the deposition of the Mt Howie Sandstone and its equivalents (Wopfner, *in* Parkin 1969) in the late Cenomanian or (?)Turonian in large, apparently northward draining channels.

Phase IV

Deposition of this phase commenced in the Paleocene. It was initiated by the movements which uplifted the southern region of the

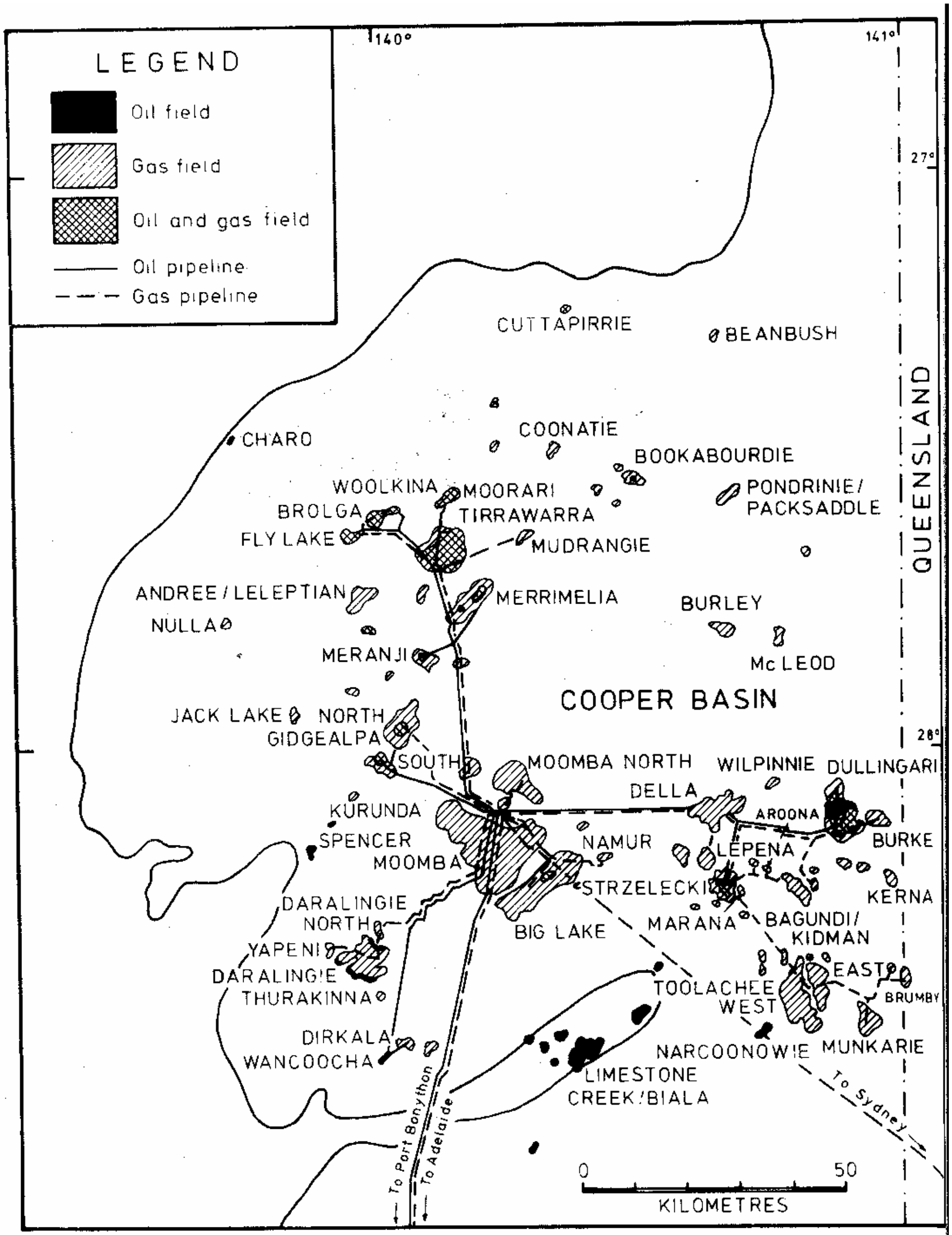


Fig. 8. Oil and gas fields and pipeline system of the Cooper-Eromanga Basin (redrawn after SADME 198

Eromanga Basin and changed the north-easterly palaeoslope of the late Cretaceous to a more westerly and south-westerly transport direction (Wopfner 1972). The basin fill comprises the fluviatile Eyre Formation (Wopfner, *et al.* 1974) which, after termination of deposition in the late Eocene, was capped by the silcrete of the Cordillo Surface.

Maximum thickness of the Eyre Formation barely exceeds 90 m, but its thickness distribution relates to the structuring event which affected the Eromanga Basin in the mid-Tertiary. These movements formed the large surface anticlines on both sides of the Lake Eyre depression which triggered the oil search in northern South Australia in the late 1950s.

Deposition subsequent to the fold movements was restricted to the newly formed local depressions. It includes the dolomitic marls of the Miocene Etadunna Formation and various Plio-Pleistocene formations, some of which contain abundant remnants of marsupials and other vertebrates (Chapter 17). Neotectonism which has partly modified basin geometry is still active today, as witnessed by recent earthquakes in the Simpson Desert.

OIL AND GAS FIELDS

In South Australia commercial production of oil and gas has been established in the Cooper Basin oil and gas province and in the Mesozoic deposits overlying it. Taken together, this is the largest onshore hydrocarbon development in Australia, currently contributing about 35% of Australia's requirements of natural gas, about 25% of its LPG output and 11% of its crude and condensate production (SADME 1988). These oil and gas accumulations have been located in sedimentary deposits of Phase II cycle of the Cooper Basin and within the Mesozoic succession (Phase III) of the central Eromanga Basin. The various oil and gas fields of that region and the gathering and distribution systems are shown in Fig. 8.

Cooper Basin

The basin is characterized by a marked structural differentiation into troughs and ridges with a north-easterly axial trend. Maximum sediment accumulation and retention occurred in the troughs, whereas the ridges experienced considerable reduction of sediment thicknesses, caused either by non-deposition or by erosion (Fig. 9). The structural differentiation was caused largely by syn-depositional movements during the Permian. Major tectonic pulses took place after deposition of the Merrimelia Formation and prior to deposition of the Toolachee (Kapel 1972; Wopfner 1966; Gatehouse 1972). The structuring which occurred during these periods was the main factor responsible for the formation of the hydrocarbon traps. Anticlines and faulted anticlines are by far the most common trap types of the basin. However, the potential of both intrabasin and basin edge stratigraphic traps, which exists at least in some parts of the basin (Stanmore & Johnstone 1988) has not been tested adequately so far.

Reservoir rocks are provided by sandstones of fluviatile or fluvio-deltaic origin which are interbedded with thick coal seams, carbonaceous shales and siltstones of paludal to overbank environments (Thornton 1979). A periglacial, aeolian origin is envisaged for the oil reservoir of the lower Tirrawarra Sandstone (Williams *et al.* 1985). Locally, reservoir properties have been affected adversely by diagenetic modifications, such as dolomite cementation or quartz overgrowth. Such effects may be quite local, as in Moomba No.3 or of more regional extent, as towards the north-eastern parts of the Cooper Basin. There, quartz overgrowth induced by acid ground waters of conditions specific to swamp environments, have caused severe reduction of pora-perm values. In some areas, reservoir quality was reduced further by subsequent pressure solution effects.

The gas is generally a sweet gas with only very low additions of H_2S. Admixture of CO_2 varies between about 7-18%, but higher values are encountered occasionally. The condensate content is generally low in the central trough of the Moomba region. It increases towards both the eastern and the north-western margins, where 40 barrels of condensate per 1 MMCF of gas (2.26 kilolitres/10 000 m^3) are not uncommon.

Most of the oils of the Cooper Basin are paraffin based, waxy, low sulphur crudes with gravity values in the average range between 43° and 56° API. Higher gravity crudes (up to 31.5° API) with high pour points are observed only occasionally, as for instance in Gidgealpa No.4.

Both the oils and the wet gas were sourced from the coal bearing fresh water deposits of the Permian. The hydrocarbons were generated primarily from interseam shales, rich in exinite and vitrinite (Kantsler *et al.* 1983). The extensive coal deposits of the basin are thought to have contributed large amounts of dry gas.

The regional distribution of liquids and gas accumulations was strongly controlled by geothermal gradient. High heat input, experienced in the central depression (Fig. 9) was essentially responsible for the dry gas accumulation of the Moomba fields. Decreasing gradients led to fields with increased condensate contents. Depending on geothermal gradients, the passage of the Permian deposits through the

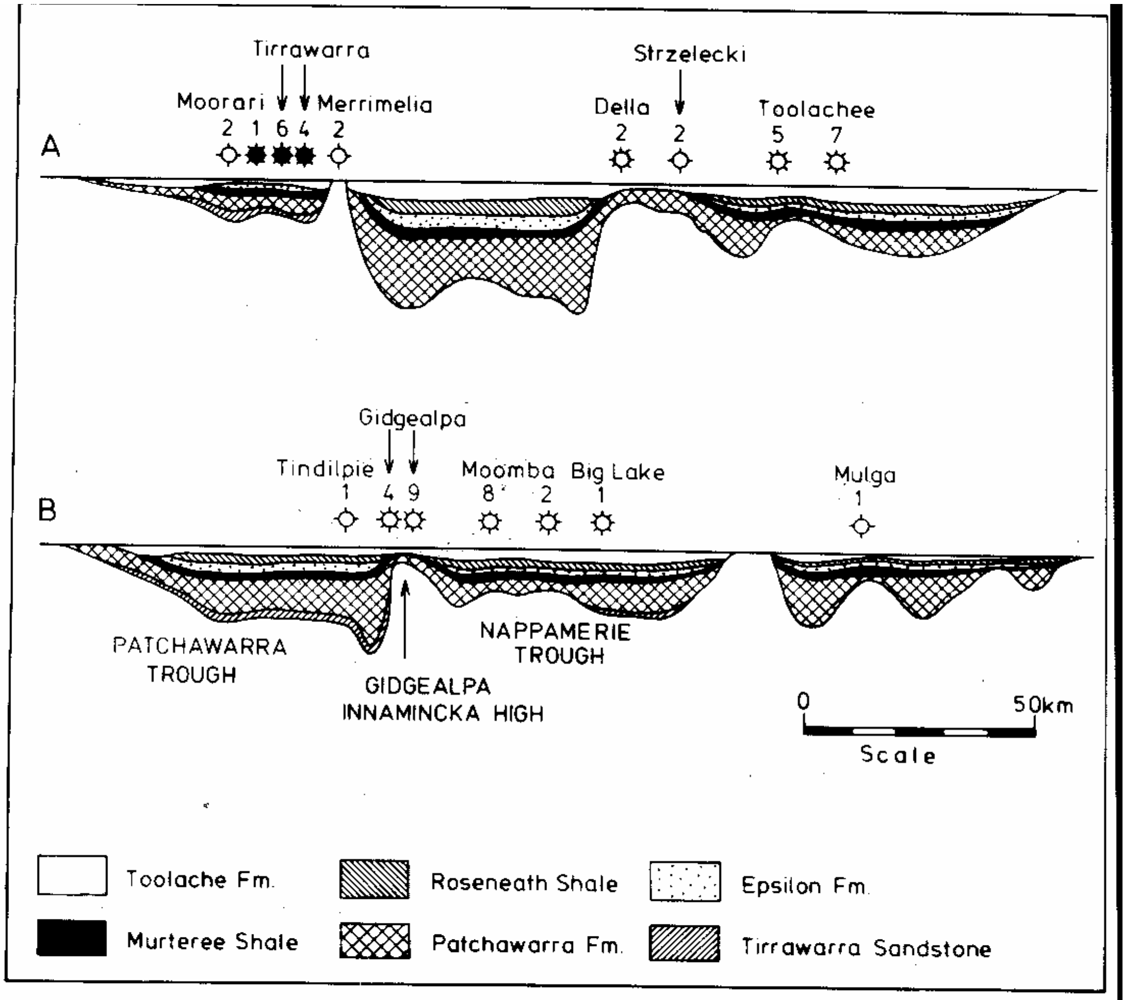


Fig. 9. Schematic cross sections across South Australian portion of Cooper Basin, showing structural differentiation and sediment distribution, caused by syn-Permian movements. Control horizon is base of early Triassic Nappamerrie Formation.

oil generating temperature occurred from the Cemanian onwards into the latest Cretaceous (Kantsler *et al. 1983).*

Eromanga Basin

Lack of success in the early exploration wells has led to the notion that hydrocarbons contained in Jurassic and early Cretaceous sandstones of the Eromanga Basin had been flushed by artesian waters. Thus, the Cretaceous/Jurassic section was generally drilled through at great speed, in order to reach the more desired objectives below (see pp. 30-32).

The discovery of oil in the lower Jurassic of the well Poolawanna No.1 in 1977, reverted attention to the succession of the Eromanga Basin.

Subsequent drilling of the Mesozoic section overlying the Cooper Basin led to the discovery of oil in the Birkhead Formation in Strzelecki No. 3, in the Murta Member in Dullingari North No. 1 and in the basal Hutton Sandstone in Cuttapirrie No.1. The discovery in the latter well was of particular interest, as the oil was obtained from the same stratigraphic level as in Poolawanna No. 1, thus permitting a tie between western and central Eromanga Basin across the Birdsville Track Ridge. The Cuttapirrie accumulation occurs in a gentle dome structure draped across a northeast trending horst block formed in the later Permian (Barr & Youngs 1981).

The first commercial oil discovery in the central Eromanga Basin was achieved in 1981, when the well Strzelecki No.3 flowed oil from the Hutton Sandstone at a rate of 382 kilolitres per day

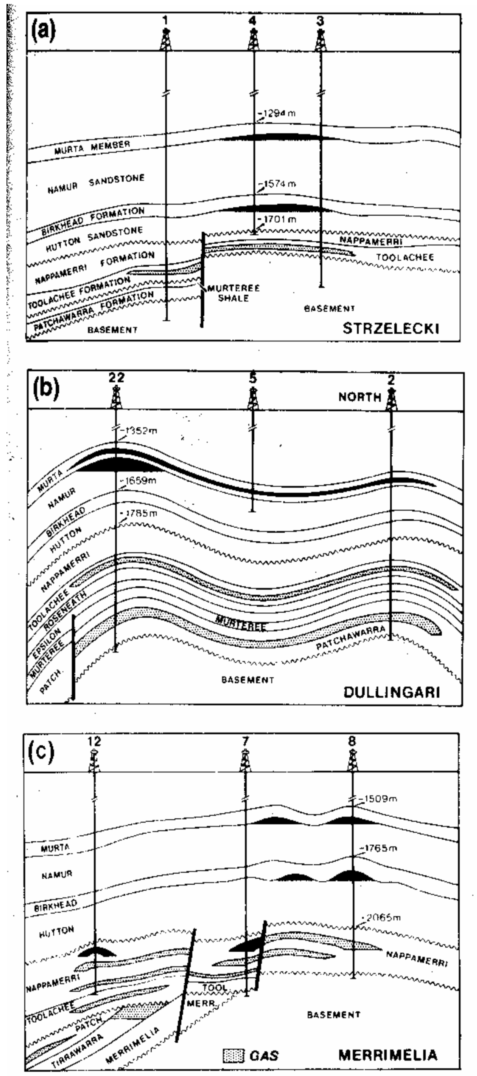


Fig. 10. Cross sections of representative oil and gas accumulations of the central Eromanga Basin. [Reproduced from Moore (1986a) with permission of the Geological Society of Australia Inc.]

(2400 bbls/d; Moore 1986a). Additional discoveries in South Australia and in adjoining parts of Queensland followed in quick succession. In addition to the Hutton Sandstone and the Murta Member, pools were also discovered in the Namur Sandstone, the Birkhead Formation and in the early Triassic Nappamerri Formation (Fig. 10; see also Figs 8 & 9).

Most of the oil fields in the Eromanga Basin are contained in broad anticlinal structures, as shown in Fig. 10. Frequently, two or more levels of oil pools are found within one anticline. Clearly stratigraphically controlled is the accumulation within the Murta Member of the Dullingari Field, where oil saturation extends across the syncline between the anticlinal culminations of Dullingari and Dullingari North (Fig. 10b). The trapping mechanism is provided apparently by the restriction of the isolated sand lens enclosed within the Murta Member.

Opinions about the origin of the crude oils of the central Eromanga Basin are diverging. Some workers view the accumulations along the northeastern flank and also the southern edge of the Nappamerrie Trough as products of Permian source rocks or possibly of mixed origin. According to these opinions, the hydrocarbon fluids were generated in the trough, whence they migrated up into the overlying Jurassic sandstones (Kantsler *et al.* 1983). Although both Permian and Jurassic source rocks are of freshwater origin, there appear to be sufficient differences to suggest a Jurassic/Triassic source for at least a number of the oils of the Eromanga Basin. Certain crudes, like that encountered in Cuttapirrie No.1 show slight signs of immaturity which suggests a derivation from Jurassic sources, like the Birkhead Formation (Barr & Youngs 1981). Kantsler *et al.* (1983) suggest that lower Jurassic source rocks did not reach the threshold of oil generation before the latest Tertiary but Passmore & Boreham (1986 p. 233) maintain that in the central Eromanga Basin 'source rocks as young as Early Cretaceous have reached initial stages of hydrocarbon generation, and peak oil generation is occurring now'. These conditions partly supported by the occurrence of oil in the Cadna-owie Formation and gas in the Cooribiana Sandstone would enhance the prospectivity of the Mesozoic section beyond the influence of the underlying Cooper Basin

CONCLUSION AND OUTLOOK

Thirty years of petroleum exploration in northern South Australia have established large reserves of natural gas and considerable amounts of oil within the hydrocarbon province of the Cooper Basin and the overlying Eromanga Basin. Up to July 1988 the South Australian portion of this province produced 72526 x 10^6 m^3 of natural gas (raw gas) and 6640 x 10^3 kilolitres of oil. During the financial year 1987-88 gas production involving 30 different pools amounted to 7021 x 10^6 m^3. During the same interval 25 oil fields were on production in South Australia, yielding 1.36 million kilolitres of oil plus 0.7 million kilolitres of condensate and 500 000 t of LPG. This annual production represented a value in excess of 700 million dollars (SADME 1988).

Since commencement of the oil search in the 1950s, emphasis on exploration targets has almost gone full circle. As outlined in the historical review, that emphasis had changed from initial targets within the Mesozoic of the Great Artesian Basin to the early Palaeozoic succession of the Warburton Basin, and then to the Permian deposits of the Cooper Basin. After discovery of oil in Poolawanna No. 1 well, attention reverted to the Jurassic and early Cretaceous.

Significantly, most Mesozoic discoveries were made within the densely drilled area overlying the Cooper Basin. This appears to be primarily a question of information density, but some explorationists connected the high success ratio of that area with a hypothetical migration of oil from underlying Permian. This notion of a deep, oil generating 'kitchen' unnecessarily restricts exploration thinking. It is to be hoped, that the oil discovery within the Triassic in James No. 1 well (pers. comm. R. Woodall 1988) situated within the WMC farm-out near the northern margin of the Cooper Basin, will stimulate the search for oil not only within the Mesozoic of that region but also further afield.

So far, no follow-up to the Poolawanna discovery has been achieved in the western Eromanga Basin, and neither has the Permian of the Pedirka Basin given much encouragement. In part this may be due to insufficient information density, but partly it is also due to insufficient attention having been given to hydrodynamic influences. Poolawanna No. 1 is situated on the upstream side of a major fault. The oil accumulation there appears to be governed as much by the pressure shadow, caused by that fault, as by structural geometry. Although Williams & Moriarty (1986 p. 377) concluded that 'consideration of basic hydrodynamic principles precludes flushing of hydrocarbons' it is difficult to conceive that hot artesian waters, not uncommonly exceeding 100°C, should have no influence on hydrocarbon migration and redistribution. Indeed, evidence of flushing like retention of 'live' oil in zones of low permeability and tar residues within highly permeable sections has been observed in a number of Jurassic sandstones penetrated by the drill.

In addition to the direct influence of the hot, artesian waters they also influence temperature distribution within the Mesozoic succession. Transmission of heat is not only affected by rock - specific conductivity but also 5y Interspersed connective systems (Robert 1988). The efficiency of heat transfer by such convection systems is much greater than by conduction. The various artesian aquifers of the Eromanga Basin are exactly such convective systems and are probably responsible for apparent reversals of vitrinite reflectance values near the Permian-Jurassic boundary of the Pedirka Basin.

The pre-Permian sedimentary rocks of the Warburton Basin, once prime exploration targets, have fallen completely into abeyance. Admittedly, in areas of deep burial nothing but gas may be expected, but in 'cooler' regions, such as the Birdsville Track Ridge, the temperature range may still be within the oil window. A sample of Precambrian volcanics, for instance, was found to contain 624 p.p.m. of residual oil 10 m below the Permian unconformity, whilst gas too small to measure flowed to the surface from prePermian unconformity in Toolachee No. 1 (Gatehouse 1986). Reservoir potential can be provided by fracture porosity, as for instance in the Cambrian carbonates encountered in Gidgealpa No.1. Wherever carbonates were exposed to weathering prior to reburial, the formation of unconformity traps and especially the formation of palaeokarst reservoirs could provide attractive targets.

There are still large tracts of north east South Australia which are virtually *terra incognita* in a geological sense. The whole area of Lake Eyre south of the Warburton and north of the interesting hinge line of the Lake Eyre Lineament (Fig. 1) has seen neither seismic nor drilling activities. Its potential is virtually unknown, but both, Mesozoic and early Palaeozoic rocks may provide reasonable targets. No doubt, such ventures carry a high risk factor, but they appear attractive enough to warrant investigating. However, considering the difficult access arising both, from natural hazards and legislative obstacles, it may be a long time yet before this potential will be tested.

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3: Dune Fields

by C. R. TWIDALE and H WOPFNER

INTRODUCTION

North east South Australia is part of a desert complex that occupies central, and much of western, Australia. State boundaries cut through. this arid region in arbitrary fashion, but the South Australian section is not only representative of the desert as a whole, it also includes evidence vital to the understanding of the dune forms that occupy perhaps 70% of the world's deserts.

The popular image of a desert is of endless fields of sand dunes. And dunes loom large in most hot deserts (as opposed to the high latitude regions of snow and ice that are also arid), but they are but one component of the landform assemblages developed in aridity. In addition to uplands of various types (plateaux, fold mountains, volcanic plugs, granitic domes, depending on the local geology) that stand above the desert plains, the plains themselves vary both in their detailed morphology and in their origin. The region under discussion for example is dominated by dunes that though essentially similar in form nevertheless vary in precise morphology, in height and spacing from region to region within the desert. In addition there is the well-known Sturt Stony Desert with its expanse of gibber plains. Regions of stony pavements also fringe the various uplands and the silcrete-capped plateaux and ridges. The plains of the southwestern extremity are underlain by gypcrete, or by opaline silcrete. The region is well known for its major salinas and the myriads of small saltpans and claypans, and, perhaps surprisingly in the desert, there are several major and minor river channels, alluvial valleys and associated floodouts. These morphological elements appear very different and so they are; yet they are parts of a cohesive whole, and the dunes that dominate the region cannot be understood without reference to this entity. Crucial to the evolution of the dune fields are the depositional centres (or depocentres) of the region, and particularly Lake Eyre and other major playas extending from Lake Eyre along a southeast trending lineament to Lake Frome. These depocentres cannot be understood without reference to the structure of the region.

PHYSICAL SETTING

Lake Eyre and its adjacent desert regions (Fig. 1) are situated in the western part of the Great Artesian Basin, a vast complex of structural basins occupied by up to 2500 m of Mesozoic and early Tertiary deposits (Wopfner 1972; Youngs 1975). Lake Eyre and other major salinas such as lakes Gregory and Blanche are located on major lineaments. Certainly the bed of Lake Eyre is downfaulted and is on that account the lowest part of the Australian continent. In detail, because of contemporary compression and warping of the salt crust, the precise location of the lowest part changes in time, as does its exact value, but the southern bays of Lake Eyre North consistently include areas about 15 m below sealevel (Dulhunty 1987).

Lake Eyre is the focal point and terminus of a vast system of internal drainage (Fig. 1). Some 1.3 million km2 in area (Johns & Ludbrook 1963), it occupies much of the eastern interior of Australia and includes not only the region around Lake Eyre which, with an annual average rainfall in the range 120-180 mm, is the driest part of the continent, but also large areas in the Northern Territory and Queensland that receive quite heavy and regular monsoonal rains. Occasional heavy local rains in central Australia cause flooding there. More significantly, rivers like the Georgina, Diamantina and Barcoo that originate in the northern monsoon belt carry water towards Lake Eyre each summer. Usually these waters are dispersed in and over the vast distributary channels and overflow receptacles (or 'f1oodouts') located east and northeast of Lake Eyre, whence they proceed towards Lake Eyre as shallow saline groundwater flows (Wopfner & Twidale 1967). Several times a century, however, heavy rains and flows occur in successive years. Then the floodwaters reach Lake Eyre (Bonython & Mason 1953), and the beds of Lake Eyre and other salinas are wholly or partially covered by water.

Wopfner & Twidale (1967) and Wasson (1983) have pointed to the varied sources of material from which the dune sands ultimately derive. To the south and west the deserts are flanked by the folded Proterozoic rocks of the Flinders, Willouran,

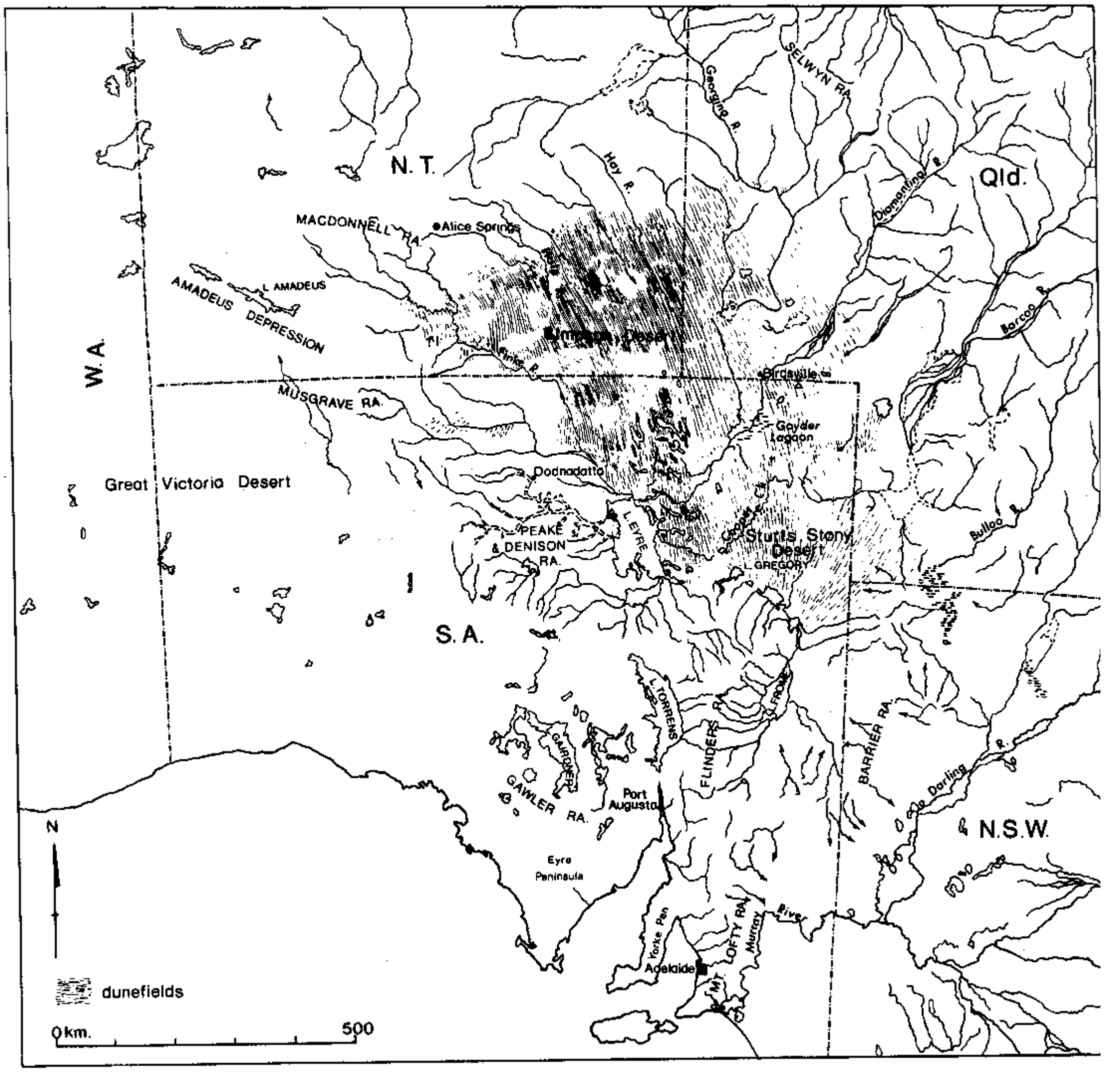


Fig. 1. Locality map also showing the Lake Eyre endoreic drainage system and its dune fields.

and Peake and Davenport (Denison) ranges. These, like the granites of the Musgrave Block, situated on the westernmost margin of the Lake Eyre drainage system, are important sources of sand for the rivers draining into the terminal lakes of the Lake Eyre system. To the north, the sandy deserts are bounded by the latitudinally trending late Precambrian and early Palaeozoic fold belt of the MacDonnell Ranges and the metamorphic complex of the Harts Ranges. These too are prolific sources of sand. The late Jurassic Algebuckina Sandstone and sandstones of the early Cretaceous Cadna-owie Formation which abut all these ranges provide an additional abundance of sand. To the east the sand deserts gradually merge into the stony 'downs' (rolling plains), or gibber plains of the Channel Country of southwestern Queensland where the disintegrating silcrete and the early Tertiary Eyre Formation (Wopfner et al. 1974) also shed quartz sand.

These primary source areas contribute sediment, and particularly sand, to the various rivers that carry it to or toward the focus of the drainage basin: Lake Eyre, or to one of many local centres. It is from these river channels, sand spreads and floodplains, from lagoons and playas, that the sediment is carried by the wind and shaped into dunes.

Early Tertiary epeirogenic movements led to the formation of large domal upwarps {Sprigg et al. 1958; Wopfner 1960, 1985; Wopfner & Twidale

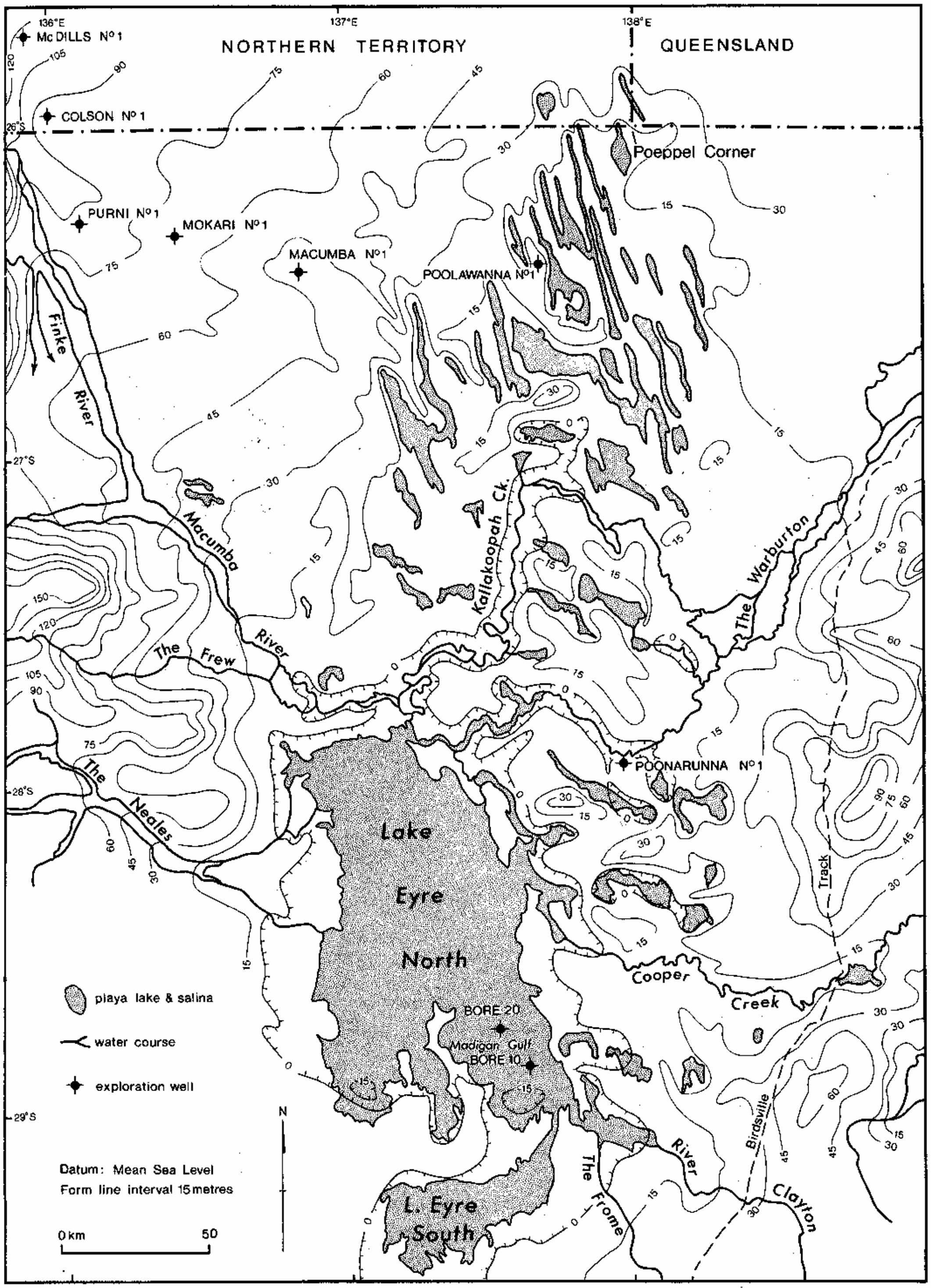


Fig. 2. Topographic contours of Lake Eyre, southern Simpson Desert and the western Tirari Desert. Some localities discussed in the text are also shown. The map is based on elevation data from helicopter gravity surveys carried out by the French Petroleum Company (Australia) Pty Ltd and supplemented with seismic survey data and elevations from oil well localities.

1967; Wopfner et al. 1974) and broad intervening synclines affecting plains that were silcreted during early Cainozoic times. The sand covered synclinal areas contrast with the dissected anticlinal upwarps which feature extensive cuestas and plateau landscapes, capped by silcrete and separated, yet connected, by the gibber deserts (Twidale 1972a). These stony plains formed mostly by deflation of the finegrained materials, leaving a protective carapace of cobbles and pebbles, primarily derived from the breakdown of the silcrete. In addition wetting and drying of clays produces a vertical churning action that results in gilgai and a surface layer of stones (Springer 1958).

The dune fields discussed here are essentially related to the Lake Eyre depression, and are therefore considered regardless of State borders (Fig. 1).

DESERT FLOORS AND AGE OF DUNES

The development of dunes in the Lake Eyre depression is but the last phase of a climatic deterioration which led from the warm humid climate of the Early Tertiary (Wopfner et al. 1974) to the arid conditions which prevail today (McGowran 1979). The stages of that deterioration are marked by the deposition of minerals of increasing solubility, viz. the dolomite deposits of the Miocene Etadunna Formation, the sulphate accumulations of the Plio-Pleistocene Warrina Surface (Wopfner & Twidale 1967; Twidale 1972a; Wopfner 1974). Although the curve of climatic deterioration was not linear and exhibits considerable fluctuations, the sequence of mineral solubility from dolomite to sulphite to halite clearly reflects the mean trend of climatic development from the Miocene to the Present.

The development of the dune fields of the Simpson Desert, the Tirari Desert and the Sturt Stony Desert is thus the most recent depositional event of a late Cainozoic sedimentation cycle which followed the epeirogenic differentiation of the area in Oligocene times (Wopfner 1960, 1974, 1985). The surface beneath the dunefield is of depositional origin. It is formed by desiccated lacustrine and fluviatile sediments of Pleistocene and older age. It resembles a tilted, irregular, indented, and hence asymmetrical, dish.

In some areas abandoned valleys of older drainage systems are discernible in the morphology of the desert floor. For example the pronounced embayed contour lines between the exploration wells Macumba No.1 and Colson No. 1 indicate the course of the ancient Finke River before it was deflected by the growing dunes. A similar deflection at Poeppel Corner probably indicates a channel of the Plenty River drainage which entered the ancestral Lake Eyre (Lake Dieri) near this point.

Further north, information on the composition of the desert floor is scanty. West and WSW 01 Poeppel Corner, low escarpments that rarely exceed 3 m elevation, flank the northern rim 01 some of the interdune claypans. These low bluffs are built of grey gypsiferous and clayey sands, capped by about 30 cm of gypcrete, a succession that is correlated with the gypcrete capped exposures elsewhere in the Lake Eyre basin. The low cliffs are remnants of the northern shoreline of Lake Dieri, the original extent of which is indicated by the 15 m contour of Fig. 2. Red, green and white mottled gypsiferous sands and sandy clays with interbeds of gypsum are known from many seismic shot holes in the vicinity of the South Australian and Northern Territory border. These gypsiferous beds vary in thickness between 3 and 10 metres. They extend for at least 140 km WSW of Poeppel Corner, and for at least 50 km northeast and east of Poeppel Corner into Queensland.

Sequences identical, or very similar, to those observed in the Simpson Desert underlie the sand-covered parts of the Tirari and Sturt Stony deserts, but the depositional sequences are much reduced where they approach the flanks of the large anticlinal structures (Wopfner & Twidale 1967; Wopfner et al. 1974). Thin algal limestones which form part of the desert floor at the southern flank of Cordillo Dome gave an ESR date of 220,000 ± 38,000 years. These carbonates, which apparently underlie the gypcrete in that region, are roughly equivalent to the green foraminiferal clays located beneath the bone bed at the Poonarunna cliff section (Wopfner & Gruen 1984).

The presence of Pleistocene Foraminifera, pelecypods and gastropods at an elevation several metres higher than the adjacent floor of Lake Eyre as well as the algal carbonates from Cordillo, demonstrate the existence of extensive water bodies during the later Pleistocene (see King 1956; Wopfner & Twidale 1967; Twidale 1972a, b, 1981; Loeffler & Sullivan 1979; d'Addario & Jones 1979). This evidence surely precludes an entirely Pleistocene age for the dune fields (cf. Sprigg 1961, 1963; Galloway 1965; Brookfield 1970; Bowler 1976; Breed & Breed 1979; Wasson 1983; Krieg et al. Chapter 1). But whether a pluvial period directly affected the present desert region is not yet clear. The increased run-off in evidence could equally reflect higher rainfall in the northern areas of the Lake Eyre catchment as suggested by Hills (1955) and demonstrated by Hutton et al. (1984) at Lake Woods in the Northern Territory. The possibility of lower temperatures, reduced evaporation and greater effectiveness of rainfall must also be considered.

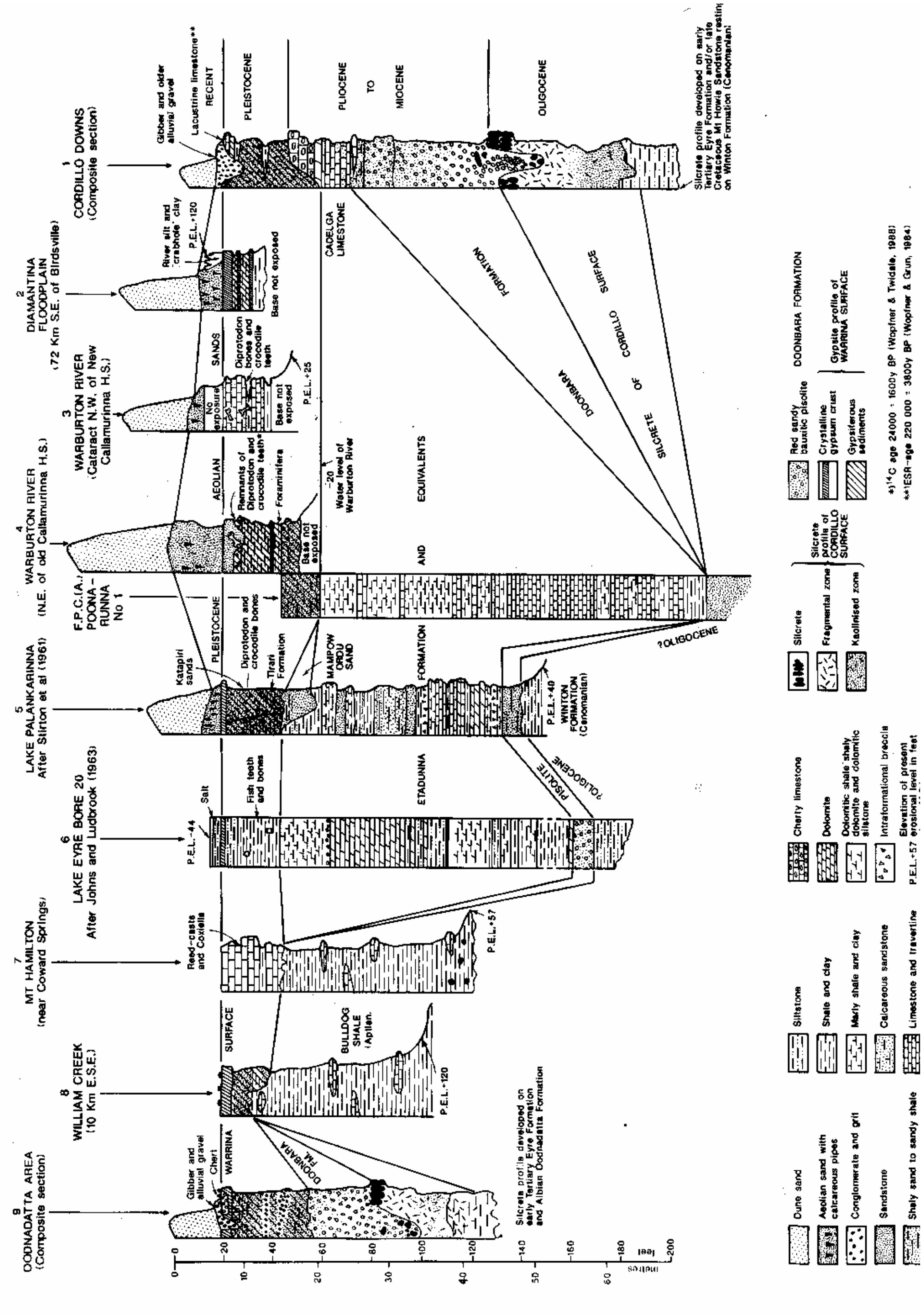


Fig. 3. Stratigraphic section across Lake Eyre basin showing correlation of mid Tertiary-Holocene stratigraphic and morphological units.

The most recent phase of aridity began during the last glacial. This led to an evaporational lowering of the lake level subsequent to the precipitation of gypsum. Further lowering increased erosional gradients inducing incision of the inflowing rivers and the deposition of the bone-bearing conglomerates.

The age of the substrate of the desert floor gives a lower limit to age of the sand ridges. A stratigraphic section across the southern portion of the Simpson Desert is presented in Fig. 3. The desert dunes rest on a substrate that consists of gypsite surface, limestones overlying the gypsum horizon, or lacustrine or riverine sand and clay. Each is fossiliferous and all are of Late Pleistocene age. For instance Diprotodon bones occur in association with gypsiferous sediment. Again, shells of the freshwater gastropod Coxiella are found in the dolomite limestones and in lacustrine clays; 14C dates obtained on Diprotodon fragments from Lake Callabonna gave ages greater than 40,000 years and 6700 ± 250 years (Daily 1960; Grant-Taylor & Rafter 1962).

A 14C date obtained on a Diprotodon bone from the cliff section at the Poonarunna locality on the Warburton gave an age of 24,000 ± 1600 14C years B.P. (Geochron 1970). At least 1.5 m,of current bedded sand and laminated clay and about 0.3 m of sandy gypcrete separate the bone bed from the lower windblown sand, placing the onset of aeolian activity at this location in the latest Pleistocene or early Holocene. Again, radiocarbon dates taken on charcoal preserved in dunes in the Dalhousie area of the western margin of the Simpson Desert yielded ages between 2500 and 2800 years BP (Krieg 1985}.

Additional evidence is provided by tektites (Australites). Evidently tektites fell on a surface of well consolidated red sand, usually with carbonate nodules (as for instance the Lake Torrens Formation, 16,000-20,000 14C years old of Williams & Polach 1971). This consolidated layer is in many areas overlain by 'unconsolidated red sand, usually in the form of seif dunes' (Chalmers et a/. 1976, p. 41).

Thus several lines of evidence indicate that the lithologically varied desert floor is of late Pleistocene age. The dunes of the Simpson and adjacent deserts rest upon these sediments and despite the opposed views of such workers as Folk (1971), Bowler (1978) and Wasson (1983) it is difficult to avoid the conclusion that the sand formations called the Simpson, Tirari and Strzelecki deserts are intrinsically of Holocene age. There is evidence of older dune fields in the form of older aeolian sands and of remnants of seits of an orientation slightly different from those active today. But the stratigraphic evidence cannot be gainsaid. The dunes rest on an alluvial floor that includes dated late Pleistocene and possibly earlier Holocene sediments. The dune fields are therefore intrinsically of Holocene age.

That the dunes are not relic Pleistocene features is also indicated by evidence of historically recent, even contemporary, advances of the dunes. Movement is spasmodic in the sense that weeks may pass without sensible forward motion, but a few days of strong winds produce advances that are readily detectable. Eyewitness accounts recorded by Ratcliffe (1936, 1937) and by the authors clearly show that the dunes are advancing.

The advancing dunes migrate across already deflated gibber plains or other stabilised surfaces such as flood plains that form the desert floor. In Sturt Stony Desert and on the southern floodout of Eyre Creek, about 90 km southwest of Birdsville, dunes have been observed over periods of five to ten years and measured at irregular intervals. During this time advances of dune heads of up to 5 m were noted. From September 1968 to September 1969 the tip of a dune selected for long term observation on Eyre Creek advanced 0.75 m across the substrate. In each of these areas the dune corridors may be followed upwind (south) for 50 to more than 100 km, without any noticeable changes in elevation of the desert floor, apart from the regional gradient. Similar examples have been observed in the eastern and northern Tirari Desert, in the floodout of Cooper Creek, in the Strzelecki Desert and on the playa lakes south of Poeppel Corner in the Simpson Desert.

Other evidence of contemporary dune movement includes the observation that river channels have been choked by sand distributed by dunes advancing on the channels from the south or SSE. Also, local tracks or dirt roads that 30 years ago ran directly between two points located essentially west or east of each other have been gradually diverted northwards by the advance of the dunes.

Nevertheless, and despite the compelling stratigraphic and historical evidence, an older, Pleistocene, age for the dunefields continues to be urged by some workers (e.g. Krieg et aI, Chapter 1; Callen & Hanson pers. comm.). And for good reason, for thermoluminescence dating of sand grains from the dunes gives ages not of a few thousands of years but a few tens of thousands of years! Yet the Law of Superposition cannot be overturned, and the various dates obtained for the substrate beneath the dunes cannot all be wildly incorrect. The problem is 'discussed in some detail elsewhere but briefly it is pointed out that the TL energy accumulated in the lattices of quartz grains may not be entirely cleared during saltation or wind transport.

Whereas it was at one time thought that exposure to UV light could 'clean' a lattice in seconds, it is now realised that many hours are required for the task (Spooner et al. 1988). Thus even though exposed to light during saltation, when again buried the quartz grains may retain energy from previous burials and this when again exposed indicates an age that is too great. The TL dates cited by Callen & Hanson may not give the age of dune building, but a complex, too-old, age of quartz grains.

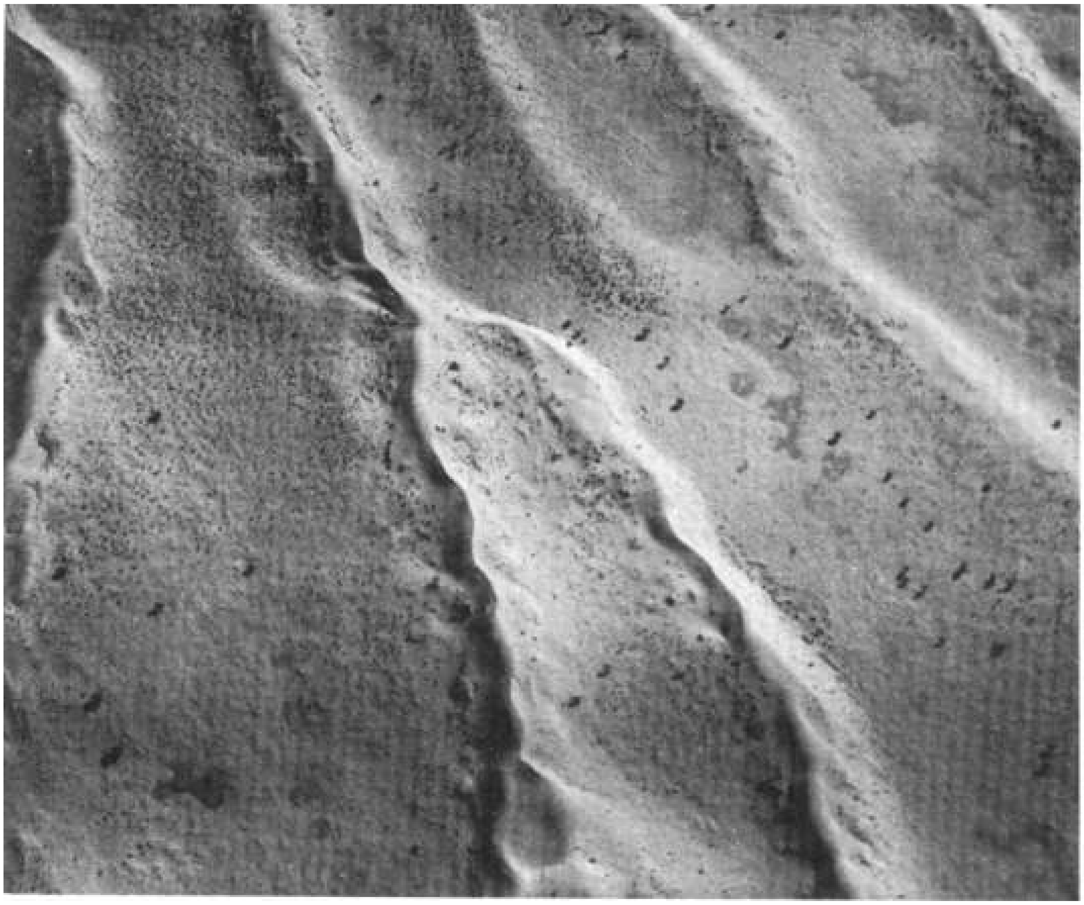
THE DUNE FIELDS

The Simpson Desert is by far the largest of four dune deserts of central Australia. Here and in the co-extensive Tirari, Sturt Stony and Strzelecki deserts, the dominant dune form is the linear, seif or longitudinal sand ridge.

Regional distribution

The dune fields of the Lake Eyre Depression are distributionally and genetically related to the depocentres of the large endoreic drainage system focussed in Lake Eyre North (Fig. 1). Each field is linked to a major depositional area such as a lake or the flood plain of a major ephemeral stream. Thus, the Simpson Desert is associated with Lake Eyre itself and the large floodout area of the Diamantina River southwest of Birdsville (Goyder Lagoon and Kallakoopah Creek). The Tirari Desert is related to the flood plains of the Frome River and Cooper Creek and the Strzelecki Desert adjoins the chain of terminal lakes between Lake Gregory and Lake Callabonna. Sturt Stony Desert originates to the north of the large flood area of Cooper and Strzelecki creeks west and southwest of Innamincka. All these terminal lakes and floodout areas, large and small are primary sources of sand for the individual dune fields.

The distribution of depocentres is ultimately controlled by the regional structural pattern. Anticlinal areas are essentially devoid of aeolian sand accumulations, for any sand blown onto these high areas is washed off by the episodic rains and transported, together with eroded bedrock material, back to the depocentres,



whence the material is blown out again by the wind. This interplay between rivers carrying debris into the depocentres of Lake Eyre and the relocation of the material by aeolian transport has been stressed before (Wopfner & Twidale 1967) and is one of the keys to the understanding of dune-forming processes. It was recognised by Madigan who, after his epic crossing of the Simpson Desert in 1939, noted: 'The desert is thus a great alluvial basin which is still receiving sediment, coarser round the margins, finer toward the lake. This is surely the origin of the aeolian deposits' (Madigan 1946, p. 56).

Dune form and structure

Several types of dune occur in and around the Lake Eyre depocentres: the single crested linear sand ridge or seif dune (Fig. 4); barchanoid ridges and transverse ridges the orientation of which, relative to the main dune trend varies in time; composite linear dunes with complex crest morphology (Fig. 5), including whaleback shaped swales with superimposed single crested linear dunes; reticulate dunes; barchans and sand ramparts or lunettes bordering the downwind sides of playas and flood plains.

Dunes bordering playas and flood plains frequently display cliffed basal slopes due to slumping in periods of flooding.

Fig. 5. Looking north along composite dune with multiple serrated active crests and intervening gibber plain close to the eastern flank of the Mt Gason Dome (southwestern margin of Sturts Stony Desert). The picture was taken in April 1961 after five years of drought. (H. Wopfner).

Of these the single crested linear sand ridge is by far the most common. It represents the equilibrium form related to contemporary climatic conditions, especially wind regimes. Individual dunes commonly extend without break for several hundreds of kilometres. Convergences are common, giving rise to tuning-fork or 'Y' junctions, most, though not all, of which are open to the south. The development of the V-junctions has given rise to some discussion. King (1960) believed them to be erosional but the internal structure of the dunes (Wopfner & Twidale 1967) and the principle of mass conservation (Mabbutt & Sullivan 1968; Tseo 1986) suggest otherwise. Sections through the dunes reveal normal aeolian cross-bedding with no suggestion of massive marginal erosional truncation of the sets. It is also difficult to suggest why the crest of a single large dune should be scoured to create a swale separating two minor sand ridges. Turning to the conservation principle, as Tseo (1986) has pointed out, if erosion were responsible for the V-junction, the cross-sectional area of the original single dune should have been greater than the sum of the cross-section areas of the two dunes resulting from the erosion. Measured sections of dunes that have not been so eroded, i.e. single dunes downwind from the junctions suggests that there is little difference between them and the sums of the dunes constituting the tuning-forks. It seems more likely, therefore, that the junctions are due to a coalescence or a convergence of dunes (Tseo 1986).

The cause of such convergence, however, is not clear. Tseo (1986) considers it may be due to pressure decrease related to the increase in wind velocity as it is funnelled between parallel dunes - in simple terms the Venturi effect, an application of Bernouilli's theorem. Ships on parallel courses converge for this reason, when only a certain distance apart (see e.g. Tuck & Newman 1974). If this were the explanation, however, then there surely ought to be more Vjunctions per dune frequency in those areas of closely spaced dunes, and this does not appear to be so. On the other hand, the presence of odd diverging bars in areas of widely spaced dunes, of low ridges aligned at an angle to the main dune trend, and of transverse bars on the crests of dunes all suggest that the junctions are related to oblique strong winds.

Although ridge crests are generally slightly sinuous, dune trends are unerringly constant for any given part of the desert area. The dunes trend northeast in the southern Strzelecki Desert backing to almost 10° west of north in the Simpson, Sturt Stony and Tirari deserts (Fig. 1). In cross section they are asymmetrical, usually with a gentle west facing slope and a steep eastern flank, commonly reaching an angle of repose of about 36°. During periods of strong (i.e. sand moving) easterly winds, however, westfacing avalanche slopes develop. Such changes may be pronounced and rapid (Wopfner & Twidale 1967, Plates XVa and b) and commonly lead to the development of a saw-tooth crest of the dune.

The internal structure of these dunes has been observed on eroded faces (Wopfner & Twidale 1967) and in numerous bulldozer-cut seismic lines. Almost without exception, the longitudinal dunes are built up by low to intermediate angle (10°-30°) foreset beds, alternating in direction on either side of the long axis of the dune (Twidale 1972b, 1981). Sets of steeper foresets are cut by low-angle erosional surfaces. These structures are typical of dunes built and shaped from bidirectional wind regimes (Bagnold 1941; McKee & Tibbits 1964; McKee 1966; Glennie 1970; Bigarella 1971).

Composition and colour of dune sands

The sands of the Simpson Desert dunes are primarily composed of quartz grains, which constitute about 98% of the material. The quartz grains are generally subangular to subrounded and frequently display hollows and other concave surfaces. The grain sizes range from about 0.05 mm to 1.2 mm (Wopfner & Twidale 1967; Folk 1971; Breed & Breed 1979). Taking all the dune fields under consideration the median grain size shows values between 0.2 mm and 0.3 mm. All sands of active dunes exhibit excellent sorting. Heavy materials normally constitute only 0.5 to 1.5%, consisting in decreasing order of frequency of maghemite, goethite, magnetite, titanomagnetite, zircon, garnet, epidote and tourmaline. In areas proximal to heavy mineral sources, however, thin layers composed entirely of opaque minerals such as maghemite and goethite form within the quartz dunes (Wopfner & Townend 1968).

In the lee of some playa lakes, as for example to the north of Lake Blanche and northeast of Lake Callabonna, gypsum constitutes up to 20% of the dune material. But the gypsum content diminishes rapidly away from the source area and after 20 km hardly any trace remains. The same comment applies to carbonate minerals, which occur in only small amounts. Clay constitutes up to five per cent of some dunes. It is derived from dried-Up, cracked and curled clay films, formed in adjoining claypans after rains, whence tablets and pellets of clay are blown on to the dunes. Iliuviation quickly removes the clay from the surface and concentrates it in the cores of the dunes (Wopfner & Twidale 1967).

The dunes vary in colour from brilliant white to dark orange-red. The lighter coloured sands are always found in the immediate lee of source areas, whereas the dunes distant from a primary source invariably exhibit red to dark red colours. Similarly, where dune systems cross centres of re-distribution, as for instance the floodout areas of Cooper Creek, the Strzelecki Creek, the Warburton or the Finke River, sudden and striking colour changes are observed. Dark red, well-defined seif dunes advance on to the flood plains like fingers from the upwind side, but the dune swarms emerging on the lee-side of the flats are white or of a very pale fawn colour. This feature, which can be readily observed on satellite imagery of all the deserts discussed in this paper, demonstrates the relationship between dune formation and specific source. The reason for the sudden change in colour at re-distribution areas is primarily a dilution effect as the clean, waterworn sand grains, derived from the flood plains, dominate coloured grains from the ingressing aeolian system.

The intensity of coloration of the sand grain is dependent on the time it remains in the aeolian environment: the longer the more intense its red colour. Hence, the dunes farthest away from the source exhibit the most intense reddening

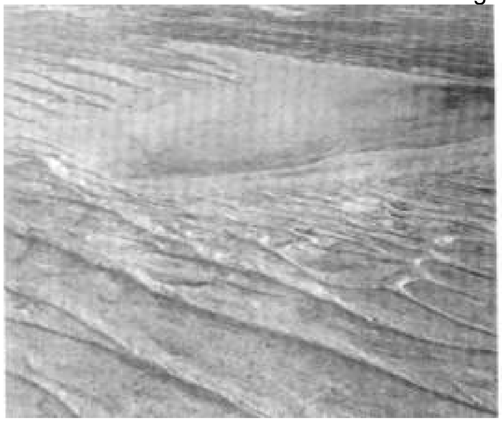


Fig 6 Longitudinal dunes developed in the lee of a play, about 120 km south of Poeppel Corner. Note the increase in spacing in the lee of the playa and the barchanoid shape of the connecting mlunds in the centre and right jand side of the picture. Note the smaller dunes being absorbed by the large dune in foreground, and also the oblique lineaoins on the dune (H Wopfner)

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DUNE DEVELOPMENT

Initiation

Invariably, the areas of linear sand dunes originate in the lee of sand accumulations bordering playa lakes or flood plains. These source-bordering ramparts are congeners of lunettes (e.g. Hills 1940; Campbell 1968; Bowler 1978; Dulhunty 1983), and are derived from detritus that is transported to the lee-shore beaches by wind-driven waves when the depressions hold water. During these periods when the lake is full such constructional shoreline features as beaches, bars and spits (including cuspate forms) are rapidly developed. Some are as quickly degraded when the waters recede, but shingle forms of some antiquity persist (Dulhunty 1975). Sand from the beach is blown downwind (i.e. to the NNW in the Simpson-Lake Eyre system) where it is trapped by vegetation to form source-bordering ramparts. These consist of apparently chaotic accumulations of windblown sand, attaining a height of up to 50 m. Their active surfaces exhibit streamlined ridges, barchans and scalloped forms, often with deep blowouts in between. The ramparts compress the streamlines, thereby increasing wind velocity. The airflow is also deflected and rendered more turbulent.

Downwind the sand is deposited in barchanoid accumulations and streamlined tails of sand which, finally, evolve into low longitudinal dunes (Twidale 1972b). In the process the dune frequency decreases rapidly, and the spacing increases within a few kilometres of the rampart (Fig. 6). In some counts made in the field the dunes are decimated. The lee-sides of the sand ramparts show clear signs of aeolian erosion. This is particularly evident along the northern shores of both Lake Blanche and Lake Eyre North. Thus a belt of eroded sand ramparts extends from the mouth of the Kallakoopah Creek and Nardibuckina, near the junction of the Macumba and the Frew creeks. In addition to wind erosion, water erosion during occasional rains causes the ramparts to be deeply scoured by gullying in which aeolian cross-bedding is exposed.

Topographic depressions, as well as rises, act as obstacles that interfere with the airflow, and dunes are propagated in the lee of latitudinaltrending river channels and even in the lee of dry lagoons. Deflection is evidenced by the offsetting of sand ridges on opposite sides of east-west running channels (Fig. 7). Both playas and channels are repositories for sand and both cause increased turbulence and deflection of the wind. Goyder Lagoon has a well developed lee-side mound with dunes to the north, but sand ridges are also generated on the dry bed of the lagoon in the lee of small arcuate channel remnants (Fig. 8).

Fig 7 These sand ridges north east of Birdsville are migrating north (toward the camera) but have been laterally offset because of defelction of the wind as it passes ovr an obstaclw, in this instance the river channel (C R Twidale)

These particular dunes of white sand stand in stark contrast with the grey-black of the algal mat that covered most of the exposed lake bed.

Sand movement and dune growth

Because the dunefields are Holocene and still spasmodically active, dune formation in the Lake Eyre Basin can be related to the modern wind regime. Analyses of data from stations within the region (cf. Brookfield 1970) show that sand moving winds from the southeast and southwest are dominant and that the seif dunes are aligned along the resultant of these dominant directions and indeed determine the vector of their growth (also Tsoar 1978). At Colson, located in the western Simpson Desert, some 230 km north of Lake Eyre, Sprigg (1980) recorded south-southeast winds dominant for all months except June and September (and possibly July - for which the record is lost). Strong winds (25 km per hour) from these directions were dominant in the period October through November. Brookfield (1970) claims that summer cyclones playa major role in dune development, but other observations show that equinoctial winds from the southern quadrants achieve greatest sand movement and dune construction. This is borne out by the bipolar, NW-NE foresets of the dune structures, which are indicative of the governing forces of southerly winds in dune construction in this area. A similar wind regime exists in the Tirari and Sturt Stony deserts, whereas westerly winds are prevalent in the Strzelecki Desert.

These winds may blow with fairly even strength for days. The persistent plumes of sand at the dune crests caused by them is ample evidence for effectiveness of the winds in sand transport. Sand is transported in a fashion comparable to snow-drift in so-called whiteouts. The dominant

Fig 8 Sand ridges developed in the lee of depressions in creek channels, Goyders Lagoon. (C. R. Twidale)

part of wind-driven sand is moved in a streamer like fashion just ,a few centimetres above the ground. That most sand is transported close to the ground surface has been demonstrated by abrasion studies carried out by Sharp (1964), These showed that the highest impact frequency, causing maximum abrasion by wind-driven sand occurred at 22.5 cm above ground level.

Once a sand ridge has been established it is self-maintaining as long as a sufficient supply of sand is available, It is an example of reinforcement or positive feedback mechanism. In the Simpson Desert for instance, southwesterly winds, moving across the dune fields at an acute angle shift the sand, taking it from the lesser dunes onto bigger ones, where the sand is trapped on the upwind side and on the lee shore of the obstacle formed by the large dunes (see also Madigan 1946). Southeasterly winds achieve similar results (see Wopfner & Twidale 1967, Pls XVa and XVb). The larger dunes grow at the expense of the smaller ones, giving the observed height to spacing ratio (see below). Also, the dune is extended along its axis, the direction of the movement being the resultant of the dominant (strength x frequency) wind direction. The intensification of the dune colour away from the source area also bears out this mode of dune formation and sand transport over long distances.

The genesis of the reticulate dunes can be interpreted as the result of an extensive development of source-bordering dunes. Their distribution in areas of comparatively frequent inundations suggests that their growth is directly related to episodic flooding. It is suggested that irregular recession of flood waters leads to the formation of lee-side mounds around each remnant water body. As the mounds grew into ramparts they merged and so became interconnected.

This model of dune formation finds support in the work of Mabbutt & Sullivan (1968), Mabbutt (1977, p. 237 et seq.) and Wasson (1983). It is at odds with the interpretations of the linear dunes as wind-rift dunes in the sense of Melton (1940). King (1956) was the first to suggest the action of wind-rifting for dunes around Lake Eyre South. There windrifting may indeed have been a contributing factor, although the case is complicated by river and wave erosion. Based on a study of aerial photographs, King (1960) suggested windrift mechanism also for other desert areas in Australia. Similarly, Folk (1971) proposed dune formation by accumulation of material deflated from the substrate of the interdune corridors by vortex rolls, a concept followed by Breed & Breed (1979).

The action of deflation as an important factor affecting desert morphology is not denied, but to credit the formation of dunes entirely to helicoidal flow, is surely untenable. All our observations are incompatible with a wind-rift mechanism. That dune base and the surface of adjacent interdune corridors are essentially at the same niveau is demonstrated by numerous seismic shot holes drilled in all of the desert regions. Layers of pebbles and cobbles within aeolian sands, sometimes quoted as evidence for a dune core of residual substrate must be assessed with considerable caution.

Such coarse materials have been placed commonly by anthropogenic actions, partly collected by aborigines for tool making and cooking but, more often, they are collections of stomach and gullet-stones from lizards and birds, which accumulated at camping or resting places of aboriginal hunters.

Dune spacing

Dune spacing or frequency varies from more than 15 dunes per kilometre to about three dunes or less per kilometre (Figs 9, 10). Source-bearing ramparts were excluded from this evaluation. The map shows a distinctive belt of dune distribution in the western Strzelecki Desert, the Tirari Desert and along the south-western Simpson Desert. Generally, this belt is proximal to the major source areas of the terminal playas and the Finke River, though additional dense areas are observed around the floodout areas of the Plenty River and the confluence of the Georgina River and the Gnallon-O-Gee Creek. An area of very dense dune distribution is associated with the floodout area of the Hale River. Originating either in Palaeozoic sandstones or in granitic terrains, these rivers transport abundant sand into the desert thus providing an additional sand source. The central Simpson Desert and most of Sturt Stony Desert exhibit moderate dune density, whereas the easternmost Simpson and the area of the north of Birdsville show only a low dune frequency. The source here is the sand brought in by the Diamantina River. Clearly, there are some distinctive relationships between the availability of sand-sized material, distance of aeolian transport, and dune frequency.

Dune height, taken as its elevation above the surrounding desert floor, varies with dune frequency. In the deserts surrounding Lake Eyre, this height varies from a mere 10 to 12 m to more than 50 m. Dune profiles compiled from accurately surveyed seismic traverses, provided by Western Mining Corporation Limited, are depicted for areas of different dune densities in the central Simpson Desert, south of 26° latitude (Fig. 11). In areas of low density (line WDG in Fig. 11), the dunes reach their greatest height, whereas in areas of high dune frequency (line WDW in Fig. 11) the sand ridges are lowest (Wopfner & Twidale 1967; Twidale 1981).

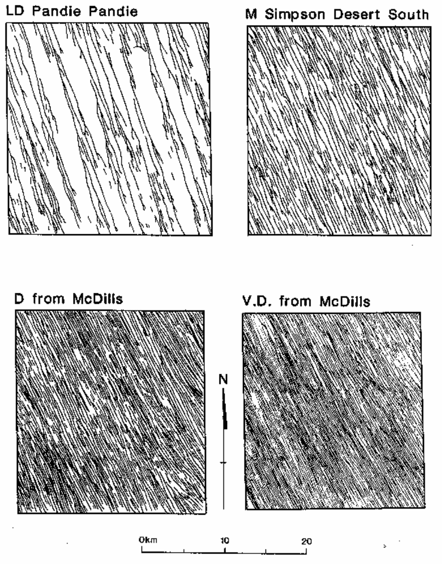

Fig. 9. Examples of dune density classes used in the compilation of the distribution map, Fig. 10. (1) LD — low density; (2) M — moderate density; (3) D — dense; (4) VD — very dense.

The reason for this reciprocal relationship between dune height and dune frequency is not related to differences in mineralogy or granulometry of the dune sands for no consistent regular variations have been detected. It is, however, arguably the same as the downwind ordering effect on source-bordering ramparts. It is inherent to the bidirectional wind system, which continually advances the head of the dunes downwind. As the sand is swept diagonally across the dunes, the larger ones trap more sand than the small ones. As the available mass of sand for any given area is finite, the smaller dunes become starved and gradually peter out as their sediment is transferred to the larger ones which consequently increase in height and volume. Thus, with increased distance downwind from the source, dune frequency will decrease and dune height and volume increase. This suggestion finds support in the downwind changes in dune density observed in the lee of the source bordering ramparts located on the downwind side

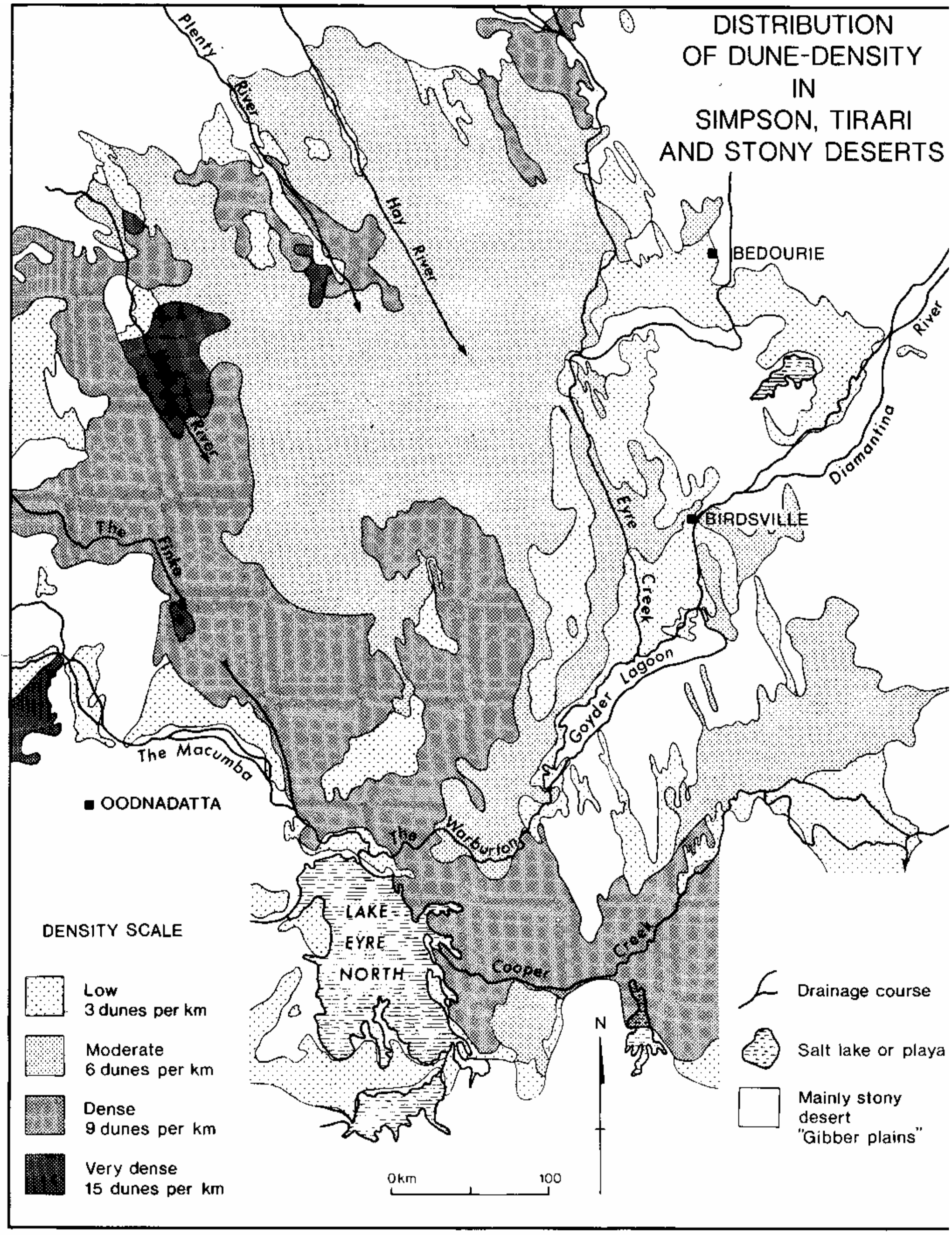

Fig. 10. Distribution of dune frequency in Simpson, Tirari and Sturt Stony deserts.

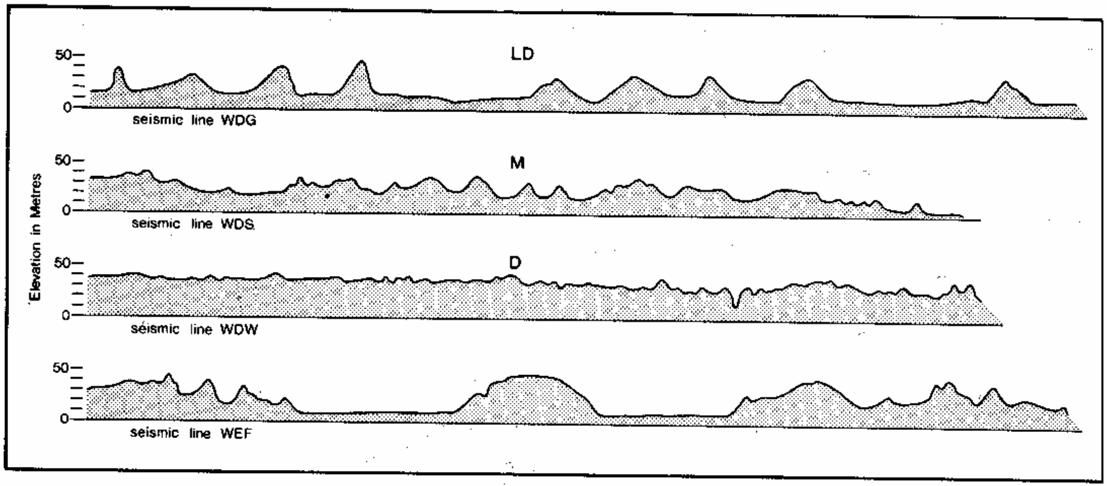

Fig. 11. Elevation profiles from the central Simpson Desert obtained from seismograph survey lines carried out on behalf of Western Mining Corporation Ltd.

of salinas and flood plains. Immediately downwind from the mounds there are many small fingers of sand that coalesce to form dunes. These in turn rapidly merge to form many fewer dunes. At some sites the dunes population is literally decimated within 10 km of the dune generating mound.

Put another way, dune density is a function of time, of the age or maturity of the dune field, with the many, low dunes representing a youthful stage of development, the areas of few but high dunes one of maturity or even senility.

CONCLUSIONS

The dune fields of central Australia are genetically related to topographic depressions such as playas and flood plains, which are the major sources of sand for later dune formation.

Sand from the source areas is heaped up on the downwind side of the playas or flood plains into source bordering ramparts or lunettes. Generation of longitudinal dunes commences in the lee of source bordering ramparts. Multitudes of small dunes initiated near a rampart rapidly coalesce downwind into fewer and fewer individual dunes. As dune frequency decreases, dune height increases.

Internal dune structure and reversing dune crests show that dunes are constructed by an essentially bidirectional wind regime. Dune heads advance across the substrate in the direction of the resultant of the governing wind regime. The present rate of movement averages about 74 cm to 100 cm per year. During long-distance transport sand grains acquire a thin crust of iron oxide. This causes a colour change of the dunes from while to cream near the source to a deep orange-red in the distant downwind parts of the field. Although relics of older fields of sand ridges are present, the dune fields are essentially Holocene in age. They are still active today.

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4: Soils

by M. J. WRIGHT, R. W. FITZPATRICK & C. B. WELLS

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INTRODUCTION

Early informal observations of soils of the north east deserts were made by a number of explorers. Notable was Sturt (1849) who made specific observations about surface soils and subsola.. Others had their attention focused on various goals and their remarks were understandably concerned primarily with surface features related to ease of passage or to stock feed and surface water.

Serious scientific exploration started 80 years later; it began, incredibly, with an aerial reconnaissance by Madigan (1929), and continued with his studies of Lake Eyre (1930) and of the Australian sandridge deserts (1936). Madigan (1937) expanded these studies into a review of the Australian arid regions and then focused on the Simpson Desert portion (Madigan 1938 which he had named in 1929. Colson successfully crossed the Simpson Desert by camel in 1936 from west to east along' the 26th parallel (Colson 1940). This feat demonstrated that camels were essential to the success of scientific expeditions in such sandy deserts, and in 1939 he organised a scientific expedition that crossed the Simpson Desert (Madigan 1945) and on which Crocker (1946a) ws soil surveyor and botanist. Crocker also studied soils in the region at Mutooroo and samples taken in 1937 were included with others from the Australian arid zone, detailed analyses of which were published by Prescott & Skewes

Prescott (1931, 1944) was the founder in Australia of formal soil classification and continental soil maps (1:20,000,000 then 10,000 scale) and his efforts were later greatly expanded upon by Stephens who firmly established the great soil group concept (1953, 1956, 1962) and produced a continental soil map based on them at a scale of 1 :5,000,000 (1961). For the most detailed presentation of soil distribution in the region, however, it remained to Northcote *et a/.* (1960-68) to map soil landscapes of the continent at a scale of 1 :2,000,000. Shortly afterwards Jessup & Norris (1971) proposed an explanation of the Cainozoic stratigraphy of the Lake Eyre Basin and part of the arid region to the south. Similar work by geologists and others (e.g. Wopfner & Twidale 1967; Wasson 1982b, 1983, 1984; Callen & Farrand 1987) has included discussions of soils but was most often primarily concerned with geological units.

Other soils work of a more site specific nature includes a traverse of the Strzelecki and Birdsville tracks in Jackson & Wright (1960); ecological mapping in the southern Simpson Desert by Graetz *et a/.* (1982); soil salinity investigations on Kalabity and Bimbowrie stations at the southern margin (Jessup 1969); and unpublished soil descriptions by N. A. McLaren (pers. comm.) as part of ecological assessments she and her associates made for oilfield developments in the Cooper Basin.

The region was also covered in the environment mapping, using Landsat imagery, by Laut *et a/.* (1977) which draws heavily on the Atlas mapping of Northcote *et al.* (1960-68) for soils information, as this present compilation also, of necessity, must. A deposit of almost pure illitic clay on the shores of Lake Eyre in the vicinity of Muloorina Station has been researched by soil mineralogists (Norrish & Pickering 1983).

SOIL LANDSCAPES OF THE REGION

The north east deserts (Fig. 1) is essentially that part of the Lake Eyre Basin that lies within South Australia and, as such, receives the water and sediment transported from most of the major endoreic streams of the interior of eastern Australia. It lies, however, in the driest part of the continent.

In order to best describe the soil-landscape characteristics of the north east deserts region five sub-regions (Fig. 1) have been delineated, each with distinctive soil and landscape features.

1. Simpson/Strzelecki deserts sub-region
2. Floodplains/braided channels/lakes sub-region
3. Stony tablelands and downs sub-region
4. Gently sloping alluvial plains sub-region
5. Innamincka low hills and plains sub-region

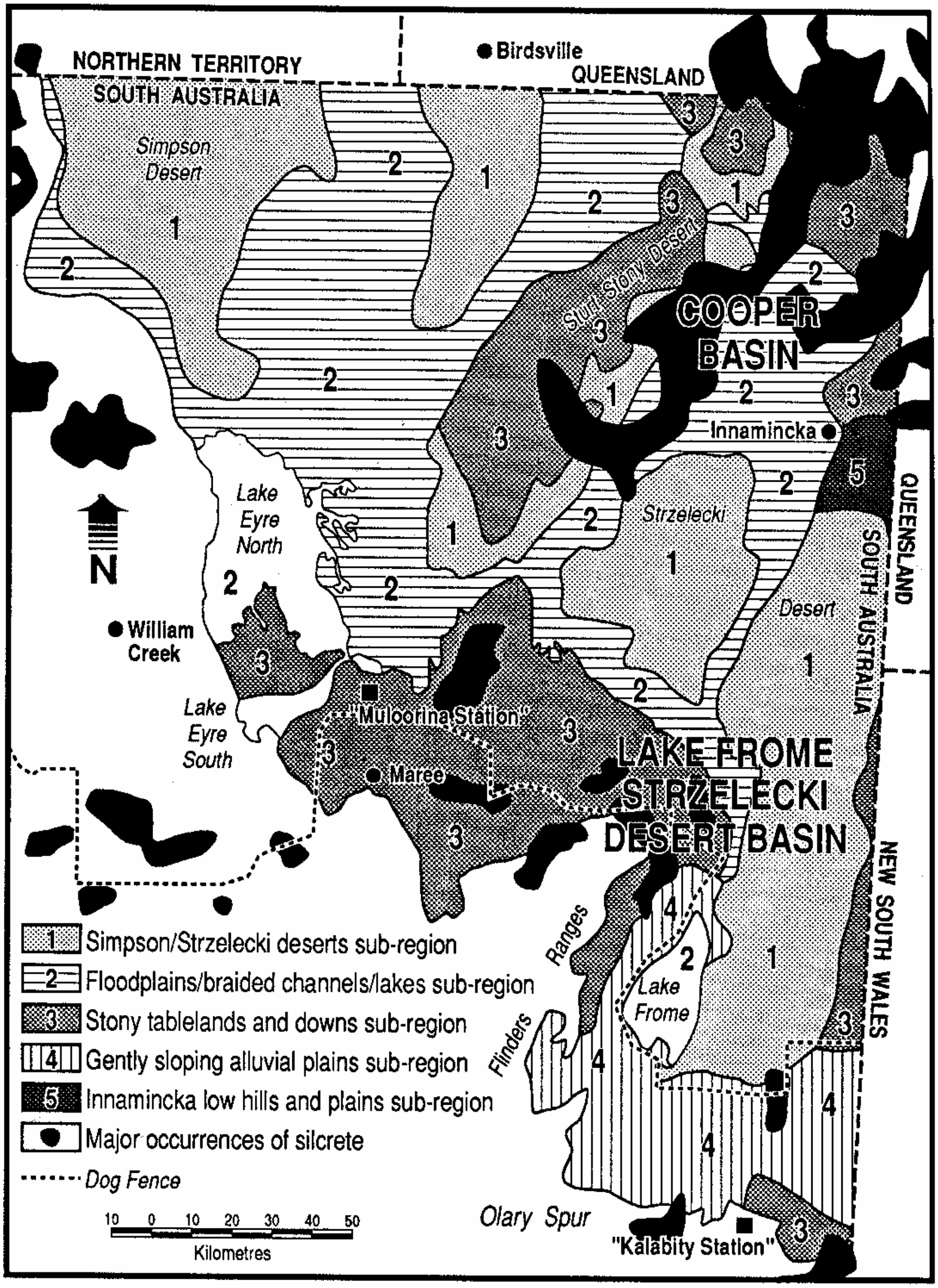

Fig. 1. Generalised soil landscape sub-regions and distribution of silcrete in the north east deserts region.

Legend for Fig 1*

Unit	Landscapes	Dominant Soil
1. Simpson/Strzelecki deserts sub-region		
B43	Dunefields with NW/SE dunes	UC1.23, Uc1.22 or Uc1.21
B50	Small seif dunefields	Uc1.22 and Uc1.23
B51,60	Dunefields with variable plains	UC1.22, UC1.23, UC1.21, Uc5.1
B58	Dunefields of irregular, short dunes	Uc1.2
B59	Dunefields with distributary channels	Uc1.2 dunes, Ug5.2 and Ug5.5
2. Floodplains/braidedchannels/lakes sub-region		
CC92	Clayplains with many dunes	Ug5.2, Ug5.5 and Ug5.3
CC98	Clayplains with claypans and dunes	Ug5.2 and Ug5.5
CC99, 109, 110	Floodplains with channels	Ug5.2 and some with Ug5.3
CC103	Clayplains with widely spaced dunes	Ug5.2, sometimes saline
CC105, 107, 108	Clayplains with channels, some dunes	Ug5.2 and Ug5.3, weak gilgai
CC112, 114	Plains with floodouts or channels	Ug5.2
CC118, 119, 120	Basin plains, plains and floodplains	Ug5.2, Ug5.3 and Ug5.5
OO11, 12	Claypans, saltpans or lake floors	Ug5.5,sometimes saline
3. Stony tablelands and downs sub-region		
Fz48	Scarp ridges, mesas and buttes with stone lags	Um1.43, shallow stony
Mx38	Plains with low sandy rises, some dunes	Gn2.13
My144	Sandy plains with few longitudinal dunes	Gn2.12 with Uc5.21 & Uc1.23
Na4	Undulating plains with tableland remnants	Dr1.12, Dr1.33 & Dr1.43
Nd5, 6 Nb16, 17	Pediments and plains, stony downs	Dr1.32 and Dr1.33 in complex with Ug 5.3
Nb35, 36, 37	Stony downs, plains and pediments	Dr1.33 and Dr1.13 with Ug5.3 in gilgai
Nb39	High, dissected stony tablelands	Dr1.33 and Dr1.13 with Ug5.3 in gilgai
4. Gently sloping alluvial plains sub-region		
DD2, 23	Plains with claypans or dunes	Gc1.12 with calcrete, Dr1.33 and Ug5
DD4	Piedmont alluvial plains	Gc1.12 and Gc1.22 with stony lag
DD22	Dissected plains with floodplains	Gc1.12 with Dr4.73 on floodplains
DD24	Plains with some through drainage	Gc1.22 with Dr1.33 and Ug5.3
DD25	Plains with some dunes, flats and pans	Gc1.12 and Gc1.22 with GnU9
5. Innamincka low hills and plains sub-region		
Fa47	Undulating to low hilly terrain with lags	Um5.51, with Um5.3 on hardpan
Mx34	Plains with seif dunes and claypans	Gn2.13 and Gn2.12 with Uc1.23 and Ug 5.2
Mx38	Plains with low sandy rises and dunes	Gn2.13

* See Northcote *et a*l (1968) for more detailed descriptions of landscapes and soils

1. *Simpson/Strzelecki deserts sub-region*

Red siliceous sand soils[1] (Uc1.23)[2] of the dunes dominate this sub-region but pale (Uc1.21) and yellow (Uc1.22) sands occur too, particularly in those parts of the deserts where playas and distributary channels occur in the interdune corridors. Here the soils between the dunes are dominantly grey and brown clays (Ug5.2, Ug5.5 and Uf6.12). Elsewhere in the deserts the common interdune soils are solonized brown soils (Gc1.1), calcareous red earths (GnU) and earthy sands (Uc5).

2. *Floodplains/braidedchannels/lakes sub-region*

This sub-region occurs very largely in intimate association with the dunefields of sub-region 1. They form a system that, while not perhaps unique, is certainly incredible in its scale, with floodwaters derived hundreds of kilometres away wending a tortuous path through sand dunes fashioned out of sediments formerly laid down by the streams. Thus there is an enormous system of clay-floored swales, swamps and lakes that is slowly filled as the waters progress toward their terminus in Lake Eyre. Such waters, because of their slow progress, drop further fine sediment load along the way.

This enormous system, which supports fine stands of coolibah *(Eucalyptus microtheca),* in particular, drains most of that part of Australia in which Mesozoic sediments were deposited. Much of the sediment is clayey and forms the parent material for the complex of grey, brown and red clays (Ug5.1, Ug5.3, Ug5.5) that dominates the sub-region. Around the saline margins and on floors of major playas such as Lakes Eyre North and South, and Frome, solonchaks (Um, Uf) and rudimentary solonchaks are common too.

3. *Stony tablelands and downs sub-region*

This sub-region is part of an extraordinarily extensive set of complex landscapes in the Australian arid zone, largely related to the enormous Mesozoic sedimentary basin. Such areas often have thin lithosolic soils, particularly where associated with a red-brown hardpan (duripan)[3].

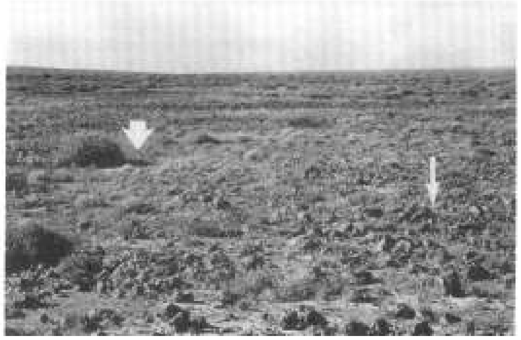

Fig 2. Surface of typical stony tableland (sub-region 3) showing gilgai microreleif expressed as flat (shelf) areas with silcrete-rich stone pavements and integravel vesicyualr crusts, almost devoid of vegetation (long arrow), interspersed with depresson areas higher concentration of vegetation (short arrow) but almost deoid of stone.

Other extensive areas (Jessup 1960a, Jessup & Norris 1971) have moderately deep clayrich soils of aeolian origin. In both landscapes a fine crystalline gypsum-rich horizon is common.

The stony tablelands and downs are typified by a complex arrangement of gilgai depressions and intervening shelves (or relatively flat areas) where desert loam (Dr1.1) and red clay (Ug5.3) soils dominate. The desert loams (sometimes also Uf1) occupy the shelf position in these landscapes, mostly with a complete stone cover (Fig. 2) and often almost devoid of vegetative cover other than low, hardy *Bassia* spp., partly due to a surface seal that prevents infiltration of rainwater. Thus water can be observed lying in pools days after rain on these shelves, but the soil immediately beneath is dry. Because of such efficient sealing, high concentrations of soluble salts are retained just below the surface crust. The presence of both sodium chloride and gypsum give the B horizon the appearance of strong blocky structure in the dry state.

The red clays that occur in this complex crack widely at the surface and consequently accept run-off water rapidly until the clays (which are dominated by 2:1 layer silicates) begin to swell. Salts, including gypsum, are therefore leached to a significant depth. With the added advantage of better water-holding capacity these gilgai depressions are the most productive part of the landscape, but nonetheless support mainly grasses and low shrubs such as *Atriplex* spp.

In these landscapes, with the exception of occasional specimens of *Pittosporum phylliraeoides* in larger gilgai depressions, the only tall shrubs and trees occur in streamlines or where there is some sand cover associated with dunes or sand sheets. Here the red earth soils (Gn2.1) occur.

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[1] The great soil group names according to the Australian soil classification system of Stace *et al.* (1968).

[2] Principal profile form notation of the Australian soil classification system of Northcote (1979).

[3] Terminology used by the soil classification system, Soil Taxonomy, of the USDA, Soil Survey Staff (1975).

4. Gently sloping alluvial plains sub-region

This unit occurs in the southern part of the region where it occupies the slopes from the Flinders Ranges and Glary Spur into the Lake Frome/Strzelecki Desert Basin. This is a subregion of dominantly calcareous soils but no work has been done to establish the source of their parent material. Further south, in the Murray Basin, Crocker (1946b) postulated aeolian reworking and transport of marine sediments to provide the parent material for extensive calcareous soils, although there are local sedimentary deposits of both' marine and lacustrine limestones that could have contributed parent material. In this sub-region, apart from the possibility of aeolian input, there are several calcareous source rocks in the Adelaidean systems of the Flinders Ranges and Glary Spur but, more importantly, Miocene freshwater dolomites of the Etadunna Formation flank Lake Frome and extend along the eastern margin of the Flinders Ranges.

The dominant soils on these calcareous parent materials are the solonized brown soils (Gc1.12, Gc1.22). Others are desert loams (Dr1.3) on areas of stony tablelands or downs, and brown and red clay soils (Ug5.3) and red solodic soils (Dr4.73) on associated minor clay plains and floodplains. The solonized brown soils, in particular, support extensive low shrublands of bluebushes *(Maireana* spp.) and saltbushes *(Atriplex* spp.).

5. Innamincka low hills and plains sub-region

This is a minor area on the eastern edge of the region that extends eastward into Queensland. It consists of low hills and associated slopes interspersed either with plains, seif dunes with claypans in the swales (Fig. 3), or with low sandy rises and dunes. The low hills and slopes are a form of stony tableland but here the soils are generally shallow loamy lithosols on bedrock (Um5.5) or on red-brown hardpan (Um5.3). The plains consist of dominantly red earths (Gn2.1) with red siliceous sands (Uc1.23) in both dunes and low sand rises, and grey clay (Ug5.2) pans.

Fig. 3. Red siliceous sand dunes with claypans in the swales (sub-regions 5 and 1). Such pans have been deepened by wind deflation of the surface during dry periods.

Vegetation in this sub-region is as variable as the soils, with those elements already described for the dunes and stony tablelands being the dominant. In areas of low sand rises and at the foot of some tablelands, moderate stands of mulga *(Acacia aneura)* are found. The red mulga (A. *cyperophylla)* occurs along some water courses.

THE PREDOMINANT SOILS OF THE REGION

Siliceous sands (Quartzipsamment/ Torripsamment)[4]

These are the soils that Prescott (1931) originally named 'desert sandhills'. The name change recognises the fact that they can equally occur in mounded form or in sandplains, as in extensive areas of central Australia. They are the dominant soils of the Simpson/Strzelecki deserts sub-region(1) and a significant component of the Innamincka low hills and plains sub-region(5).

Indeed, the siliceous sands are widespread soils in arid Australia generally where they are usually deep with little profile development (Table 1) except for minimal darkening of the A horizon, although some shallow ones do occur, mostly superimposed upon an unrelated substrate. Red sands (Uc1.23) are common, but some colour variants are seen in the region, particularly the pale (Uc1.21) and yellowish or brownish sands (Uc1.22) in the vicinity of the major streams, lakes and playas, for example in the southern Simpson Desert and northern part of the Strzelecki Desert.

The red and brown sands are the more fertile although nutrient levels are generally low in the group as a whole. The red are usually mildly acid throughout or become alkaline with depth; the brown are more likely alkaline throughout and the pale ones acid, although this last point has not been established for the region in question.

While sands in general have only a low waterholding capacity, by sheer thickness actually store a large body of water, following rains, for plants able to reach the depths involved. This explains why most dunes are stabilised by vegetation, particularly by spinifex *(Triodia basedowii)* or sandhill canegrass *(Zygoch/oa paradoxa).* These soils are certainly prone to wind erosion when

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[4] The great group names according to the International soil classification system, Soil Taxonomy (Soil Survey Staff 1975)

devegetated by activity such as fire, roadworks or mining. They are also subject to water erosion where water is concentrated, for example, by clay cappings on roads across dunes.

Severe erosion can be observed in places on the flanks of dunes with clayier cores. Under conditions of intense rainfall such dune cores cannot accept percolating water as rapidly as the overlying sand, with the result that water may not only run off the surface but also move laterally within the profile. The relatively unconsolidated dune flanks are thus easily eroded.

Grey, brown and red clays (Torrert)

These sub-groups deserve separate discussion as they occur in totally different landscapes and landscape settings.

The grey clays (Ug5.2) are the dominant soils in the floodplains/braided channels/lakes subregion(2) where they occupy virtually the entire area of each component unit. The exceptions are some coarser stream banks and flanking dunes. These soils are characteristically grey structured clay throughout, although there may be a thin surface layer of slightly coarser texture. They occur as minor components of the Simpson/Strzelecki deserts sub-region(1), the gently sloping alluvial plains sub-region(4) and the Innamincka low hills and plains sub-region(5).

Their clays are dominated by smectites so that they have a strong shrink/swell potential that is demonstrated by wide cracking upon drying. Most of these soils form a surface crust after rain but when the crust is disturbed they display the self-mulching characteristic i.e. there is a high grade of pedality right to the surface. The grey clays (Ug5.5), however, which occur typically in claypans and to some extent in other clay plains, are massive at the surface and with large coarse peds below.

Fig. 4. Grey member of the grey, brown and red clays on the floodplain of Cooper Creek (sub-region 2), showing surface seal and cracking. Ground cover is mainly nardoo *(Marsilea drummondii)*.

There is a certain amount of colour variation between dark clays (Ug5.1) on the one hand and brown or red clays (Ug5.3) on the other. Some show a tendency to gilgai formation; some are saline. Where not saline they can be quite productive soils following floods or adequate rains. They have a high water-holding capacity and, because of their cracking, wet to a reasonable depth before sealing occurs.

In this region they are of mainly alkaline reaction (Table 1) and often contain calcium carbonate and gypsum at depth. Contents of soluble salts are variable; calcium is generally the dominant exchangeable cation but sodium and magnesium are significant too. Very little information is available on their fertility, but because they are developed in alluvium they are most likely to be moderately fertile. Two profiles recorded in Jackson & Wright (1960) have just under 0.3% nitrogen in their surface soils.

Red clays are an important part of the stony tablelands and downs sub-region(3) and a minor component of the gently sloping alluvial plains sub-region(4). As detailed earlier these clay soils occur in a complex with desert loam (Or1) soils on the stony tablelands and downs. In this situation they are quite productive following adequate rains. They are generally of alkaline or neutral reaction, often with some calcium carbonate and/or gypsum (Fig. 5) at depth. They usually have coarse structure, often with marked slickensides; they are low in salts in the upper part of the profile, but salts content often increases rapidly below 50-60 cm.

Information from elsewhere indicates that these clays have similar fertility levels to the grey clays and that calcium is again the dominant cation, with magnesium and sodium important as well. Smectites are again the dominant clay minerals.

Desert loams (Haplargid/Natrargid/Paleargid)

These are the important soils of the stony tablelands and downs sub-region(3) but they occur to some extent as well in the gently sloping alluvial plains sub-region(4). Their essential features are moderate to strong texture contrast between thin loamy A horizons (Fig. 6) clearly separated from strong, fine blocky or polyhedralstructured clay B horizons that are red to brown. They are neutral to weakly alkaline at the surface, usually becoming more alkaline with depth. A desert pavement of gravel to stone-size 'gibbers' and a surface crust, sometimes with a vesicular ('bubbly') undersurface are common features but either may be absent. A generally thin A2 horizon can be either unbleached (Or1.23), sporadically bleached (Or1.33), or conspicuously bleached (Or1.43), or is absent altogether (Or1.13). The clay subsoils are friable when moist, moderately to

Table 1. SOME PROPERTIES OF SOILS OF THE NORTH EAST DESERTS REGION

SOILS		USUAL OCCURRENCE		MORPHOLOGICAL PROPERTIES			CHEMICAL PROPERTIES	
GSG[1]	PPF[2]	LOCATION	LANDSCAPE	GENERALISED PARENT MATERIAL	A HORIZON	B HORIZON	SRT[3]	EXCH.CATS[4]
SS	Uc1.21	1	Dunefields	Siliceous sands	A, only	none	neutral/alkaline	
SS	Uc1.22	1	Dunefields	Siliceous sands	A, only	none	neutral/alkaline	
SS	Uc1.23	1	Dunefields	Siliceous sands	A, only	none	neutral/alkaline	
SS	UcS.11	1	Dunefields	Siliceous sands	A, only	none	neutral/alkaline	
SS	UcS.12	1	Dunefields	Siliceous sands	A, only	calcareous	alkaline	
ES	UcS.21	3	Plains with dunes	Siliceous sands	A, only	coherent and	neutral	
L	Um1.43	3	Scarp ridges and mesas	Medium grained-	A, only, firm	none	neutral	
RBH	UmS.3	S	Undulating to low hilly	Medium grained-silca	A, only, firm earthy	red-brown hardpan	acid/neutral	
L/RE	UmS.SI	S	Undulating to low hilly	Medium grained-	A, only, firm earthy	none	neutral	
NSG	Uf6.12	3,2	Undulating plains and	Clays	Red, pedal clays		neutral/alkaline	
GBR	UgS2	2,1,S	Clay plains and	Clays	Grey, deep cracking		alkaline	
GBR	UgS.3	3,2,4	Clay plains and	Clays	Brown and red deep cracking clays		alkaline	>30[5]
GBR	UgS.S	2,1	Clay plains and	Clays	Grey, coarse cracking clays		alkaline	
SB	Gc1.12	4	Plains	Calcareous	Calcareous	Horizon of $CaC0_3$	alkaline	10-2S[5]
SB	Gc1.22	4	Plains	Calcareous-fine	Calcareous	Clay and $CaC0_3$ maxima	alkaline	20-24[5]
SB/CR	Gn1.13	1	Plains	Coarse grained-	A, only, firm	coherent, sandy	alkaline	S-13[5]
RE	Gn2.12	3,S	Plains with sand rises or	Medium grained-	A, only, firm	firm, earthy clays	neutral	
CRE	Gn2.13	3,S	Plains with sand rises or	Medium grained-	A, only, firm	firm, earthy clays	alkaline	
DL	Dr1.13	3	Stony downs, plains and	Finer grained-base	A, only, crusty	red, pedal clays	alkaline	
DL	Dr1.32	3	Stony downs, plains and	Finer grained	A, crusty and	red, pedal clays	neutral	
DL	Dr1.33	3,4	Stony downs, plains and	Finer grained-base	A, crusty and	red, pedal clays	alkaline	20-35[5]
DL	Dr1.43	3	Undulating plains and tableland remnants	Finer grained-base saturated	A, crusty and A_2	red, pedal clays	alkaline	
NSG	Or4.73	4	Plains dissected by floodplains	Coarser grained-quartz rich	A, sandy and A_2	red, massive clays	alkaline	

NOTES:

1.Nearest equivalent great soil group (Stace et al 1968). SS=Siliceous sands; ES=Earthy sands; L=Lithosols; DL-Desert loams; RE=Red earths; CRE=Calcareous red earths; GBR=Grey brown &red clays; SB=Solonized brown soils; RBH-Red & brown harpan soils; NSG=No suitable group

2 Principal profile form (Northcote 1979)

3 Soil reaction trend

4 Total metal cations (Ca+Mg+K+Na) in m.e./100g soil for upper 8 horizon where present

5 Data ffrom similar soils elsewhere

Fig 5 Red member of the grey, brown and red clays with a silcrete-rich stone pavement and fine crystalline gypsum at depth (sub-region 3)

strongly saline, and usually contain gypsum and sometimes carbonates.

Exchangeable cations are invariably dominated by calcium and magnesium, often with significant amounts of sodium. While little information is available on the subject, fertility levels are not significant because of over-riding salinity and the aforementioned lack of penetration of rainwater into these soils.

Solonized brown soils (Calciorthid/Haplargid)

These soils dominate the gently sloping alluvial plains sub-region(4), occur to a minor extent in the swales of some of the dunefields(sub-region 1) and very rarely in the stony tablelands and downs and Innamincka low hills and plains sub-regions (3 and 5). They are earthy soils that are calcareous throughout and generally of loamy textures but with a gradual increase in clay content down the profile. The most common representative is the highly calcareous Gc1.12 although the less calcareous Gc1.22 is important in at least one unit (Table 1). The partly calcareous Gn1.13 is most likely to be found associated with the dunefields.

The solonized brown soils range from shallow to deep, from non-sodic to strongly sodic and may also have a moderate to high soluble salt content. Surface soils are commonly reddish brown with textures ranging from sand to clay loam. Calcium carbonates occur both in the fine earth and as hard segregations which may dominate the middle portions of the profiles, sometimes as a cemented, continuous pan.

These soils are usually massive and may be powdery and loose when dry, particularly following disturbance. The sandier members are elsewhere recorded as subject to deficiencies of trace elements such as zinc, manganese, iron, and copper. They are generally mildly alkaline at the surface and stongly alkaline at depth. Elsewhere, they have poor to moderate fertility with low levels of nitrogen and phosphorus common to most Australian soils. In agricultural areas to the south they have been found to occasionally contain levels of boron toxic to cereal crops (Cartwright et *al. 1986).*

In these arid areas, however, because of moderate depth and adequate water-holding capacity, the solonized brown soils are relatively productive of native forage plants and indeed, without overgrazing, support the highly desirable

Fig 6 Deset loam with a dense silcrete-rich ston pavement with desert varnish, and sporadic bleaching in a thin A horizon (sub region 3 & 4)

bluebushes *(Maireana* spp.) and saltbushes *(Atriplex* spp.) on which sheep in particular do so well. Unfortunately though, part of the north east region has suffered the worst overgrazing excesses in the past, of any of the pastoral areas of South Australia. These and the desert loam soils would have carried the brunt of such overgrazing.

Red earths and calcareous red earths, and earthy sands (Haplargid:Haplargid/Paleorthid:Haplargid/Quartzipsamment/Torripsamment)

The two groups of red earth soils are mostly to be found in the stony tablelands and downs and Innamincka low hills and plains sub-regions (3 and 5), to a lesser extent in the gently sloping alluvial plains sub-region(4), and perhaps in some of the swales of the Simpson/Strzelecki deserts sub-region(1). Earthy sands are mostly confined to the stony tablelands and downs, and Simpson/Strzelecki deserts sUb-regions (3 and 1), and perhaps the Innamincka low hills and plains sub-region(5).

These are all generally red, deep sandy to loamy, porous soils with excellent drainage, hence relatively limited water-holding capacity. They have a significant proportion of void space and a fabric which is due to the coating and bridging of sand grains by clayey materials and iron oxides. The coatings tend to obscure the siliceous nature of the soils to give the impression of finer (loamy) textures.

The earthy sands are generally sand to light sandy loam throughout and range from relatively shallow to very deep.

The red earths encountered in this region range from those with calcium carbonate deeper in the profile, or at least an alkaline reaction trend, to those that are mildly acid at the surface and neutral at depth. They occur mostly in alluvial/ colluvial deposits on gently sloping plains or outwash slopes. Surface horizons range from sand to sandy loam and subsoils from sandy clay loam to sandy clay. Like the solonized brown soils they have a gradual increase in clay content down the profile.

While the red earths have only moderate waterholding capacity they are usually reasonably deep soils and thus store enough water to support open woodlands of low to medium shrubs and small trees such as mulga *(Acacia aneura).* In other areas their fertility levels appear to be rather low and in the eastern states where they are used somewhat for irrigated agriculture, various trace elements are required to optimise yields. The calcareous red earths tend to be sandier than the red earths and therefore have lower water-holding capacity and poorer fertility.

Grey-brown and red calcareous soils and lithosols (Calciorthid/Haplargid/Paleorthid:Camborthid/Haplargid)

Lithosols essentially lack pedological organisation (Table 1) other than some accumulation of organic matter in the surface few centimetres. They are usually shallow sands to clay loams dominated by coarse material that is often partially weathered rock fragments. They may be calcareous throughout in which case they merge with the other soils discussed here. The lithosols are most prevalent in the stony tablelands and downs sub-region(3) where they occur on mesa summits, scarp ridges and steeper slopes. They are generally poor soils, particularly in terms of fertility, water-holding capacity, and stoniness.

The grey-brown and red calcareous soils are most common in the stony tablelands and downs sub-region(3) and to a lesser extent in the gently sloping alluvial plains, Innamincka low hills and plains and Simpson/Strzelecki deserts subregions (4, 5 and 1). Their essential features are light to moderate amounts of calcium carbonate, and little texture increase, throughout the profile. They are usually shallow to moderately deep, soft, powdery or porous (weakly structured) loams to light clays. In this region they are usually light redbrown at the surface becoming paler with depth and with no other profile differentiation other than perhaps some increase in both (nodular) calcium carbonate and compaction.

Little is known about their chemistry but these soils are likely to be rather infertile, with low waterholding capacity, although an example examined by one of us (MJW), from near Roxby Downs, is dominated by the magnesium-rich clay mineral palygorskite (that usually occurs in only small amounts in other arid and semi-arid soils) with smectite and kaolinite.

There are earthy loams that occur particularly in the Innamincka low hills and plains sub-region (5) and to a degree in the stony tablelands and downs sub-region(3), that have no suitable great soil group. They range from shallow to moderately deep and are generally similar to the calcareous loams except that their porous, coherent profiles are calcium carbonate free, at least in the upper part.

Red and brown hardpan soils(Durorthid/Durargid)

The hardpan soils are recorded only in the Innamincka low hills and plains sub-region(5) but since their distribution is imperfectly known it is quite likely that they occur more widely and particularly in the stony tablelands and downs sub-region(3). Wright (1983) suggested that redbrown hardpan should be regarded as independent of most, if not all, soils occurring on it.

Since it has been recorded relatively widely in south-east Queensland and north-west New South Wales, it is likely to be more widespread in this region too, particularly in the stony tablelands and downs of the extreme north-east corner.

The red and brown hardpan soils are thin red, earthy porous loams (Table 1) occurring on a red platy silica-cemented palaeosol, which in these areas seldom exceeds 2 m in thickness whereas the overlying soil is seldom as thick as 50 cm. Because the hardpan is an effective barrier to root penetration these soils have a low water-holding capacity and consequently support little better than sparse, low shrublands. In the southern arid zone, hardpan is often coated by a hard crust of calcium carbonate and consequently mistaken for calcrete, an indurated form of calcium! magnesium carbonates.

FEATURES OF THESE ARID SOIL LANDSCAPES

Nature and origin of desert dunes

Continental dunes of varying areal density occur on about 40% of the surface of Australia, making dunefields the most common land form assemblage (Mabbutt 1977).

The Strzelecki and Simpson dunefields, which dominate the area under discussion, lie largely in topographic basins which are also structural basins that took their present gross form in the Mid to Late Tertiary (Wasson 1982a). Linear dunes of different types are the most dominant form in these dunefields, with narrow crested outnumbering both broad crested and very short narrow crested linear dunes.

The most outstanding feature of these sand deserts is the marked longitudinal arrangement of their dunes; they are continuous for up to 250 km, range in height from 8 to 50 m and have steeper eastern slopes than western. Dune spacing varies from place to place in the desert but is commonly about 300 to 500 m. Despite the apparent potential for transport of sand over long distances around the so-called 'continental-scale anti-clockwise whorl' (Jennings 1968; Wasson 1982a), grain size and petrographic data show that sand has generally not moved very far from its source (Wasson 1982b; 1983).

These linear dunes are both siliceous and clayey. The clay occurs as fine sand-size aggregates often making up to 60% of samples, and some of these 'pelletal' sands are rich in gypsum pellets (Butler 1974; Jessup 1960a). The clay-rich dune sands are derived by groundwatercontrolled deflation of relict alluvium and lacustrine beds (Bowler & Magee 1978; Wasson 1982b; 1983).

Development of sand colour

The common observation by several workers in the Simpson-Strzelecki dunefields is that the reddest sands occur in the north-west and the palest sands are associated with active floodplains (Carroll 1944; Norris 1969; Folk 1976; Wasson 1982b, 1983, 1984; Callen & Farrand 1987; Gardener & Pye 1981). However, the origin of their colour has been controversial for many years and these authors have in turn reviewed the problem in some detail.

Such studies have suggested several basic hypotheses concerning the origin of colour. Several workers (Wopfner & Twidale 1967; Norris 1969; Folk 1976) have proposed that the redness of the dunes increased with age either from continuing accession of dust rich in hematite (red coloured pigment), or from the weathering of contained ferromagnesian minerals. However, Callen & Farrand (1987) conclude that there is no definite evidence for any relative age difference between the darker and lighter dunes, but that there is perhaps a greater preponderance of iron crusts in the Cainozoic sediments beneath the reddest part of the dunes.

The iron-bearing clays or coated quartz grains may have been introduced by the deposition of aeolian dust (Norris 1969; Folk 1976). The dust initially may contain hematite or may transform to hematite over time by weathering of iron contained within the layer silicate structure (Fitzpatrick 1987; Schwertmann 1987).

Schwertmann (1987) presents a schematic competitional model to describe the various interrelated environmental processes that favour either hematite or goethite formation in pedogenic environments. Higher soil temperatures, good aeration and neutral pH will accelerate organic matter decomposition and thereby favour hematite formation (i.e. in arid regions). Ferrihydrite (hydrated poorly crystalline Fe oxyhydroxide) is believed by Schwertmann (1987) to be a necessary precursor for hematite formation and this transformation involves a dehydration step.

Ferrihydrite formation is strongly favoured by a high rate of Fe release (e.g. from ferromagnesian minerals in primary rocks especially in warm climates) and the restricted complexation by organic matter (i.e. in warm climates with good aeration and high pH). This model, therefore, explains the occurrence of hematite in the freely drained red dunes as well as the desert loams, red earths and red clays of this warm arid (desert) region where hematite will form more rapidly due to the higher rate of Fe release in the presence of very low concentrationo of organic matter.

By contrast, soils with yellowish brown colours (i.e. with higher amounts of goethite) are associated with active floodplains where Fe (such as hematite) can be mobilised by reductomorphic processes, redeposited and crystallised mainly as goethite (Fitzpatrick 1987).

Duricrusts

A feature of this central desert region is that it contains a remarkably wide variety of pedogenic duricrusts. They range from being gypseous (gypcretes), calcareous (calcretes), siliceous (silcretes) or ferruginous (ferricretes).

Gypcrete

Gypcrete-capped (0.5-1.5 m thick) tablelands stand 12-45 m high above the western margin of Lake Eyre and, according to Wopfner & Twidale (1967), may represent a surface which was later faulted and dissected. The gypcrete consists of a gravel, sand and lacustrine clay matrix with gypsum thought to be derived from dust blown from dried salt lakes (Jessup & Norris 1971). This rather soluble gypsum cement is stable under the present arid climatic regime. Gypcretes also tend to form in the lowest parts of basins where sulphates crystallise with evaporation of saline ground water near the surface (Mabbutt 1977).

Silcrete

According to Mabbutt (1977) nowhere are silcretes more extensive and geomorphologically prominent than in arid Australia, and particularly in the Lake Eyre Basin (Fig. 1; Wopfner 1978) where silcretes of Cainozoic age cap stony tablelands above desert plains mantled with derived gibbers (Stephens 1971). They often overlie a weathered profile which may be up to 50 m thick (Fig. 7), consisting of an indurated and disturbed fragmental zone, up to 10 m thick, above a kaolinitic pallid zone with mottled ferruginisation near the base (Wopfner & Twidale 1967; Wopfner 1978).

Silcretes range from silica-cemented gravels and sands to a fine microcrystalline silica matrix with floating quartz grains and sometimes with localised concentrations of titanium (mostly in the form of anatase) in association with zirconium and aluminium (Milnes & Twidale 1983). The formation of these silcretes remains uncertain, but several hypotheses suggest that they may form under dry (arid) conditions where high pH prevails to mobilise silica, and strong evaporative conditions occur (Stephens 1971; Wopfner 1978). Milnes & Twidale (1983), on the other hand, suggest a requirement for acid weathering conditions in pedogenic environments to mobilise silica into groundwaters which may then travel considerable distances to suitable depositional zones.

Fig. 7. Silcrete capped residuals (mesas and buttes) showing thick 'bleached' pallid zones overlying mottled zones in Mesozoic shales of the Lake Eyre Basin.

Ferricretes and ferruginous soils

Ferricretes and/or ferruginous soils with underlying kaolinitic pallid zones indicate weathering conditions of strong leaching under warm conditions with seasonally distributed annual rainfall of at least 750 mm. The existence of such ferruginous accumulations in this arid region suggests they are relict, and possibly formed in the Tertiary when climatic conditions over wide areas were more humid than at present (Jessup 1960b; Stephens 1971; Fitzpatrick 1987).

Ferricrete in this region is younger than silcrete, because silcrete in the Lake Eyre Basin formed either on a surface planed in an older ferruginous weathered profile or within overlying sands. Mabbutt (1977) suggests that this relationship, together with the following conditions, may explain why silcrete is restricted to such sedimentary basins: (i) in these less stable settings the older ferruginous soil profiles tended to be eroded, (ii) there were arenaceous rocks suited for silicification, and (iii) the lowland topography favoured the concentration of silica into surface crusts and their subsequent survival.

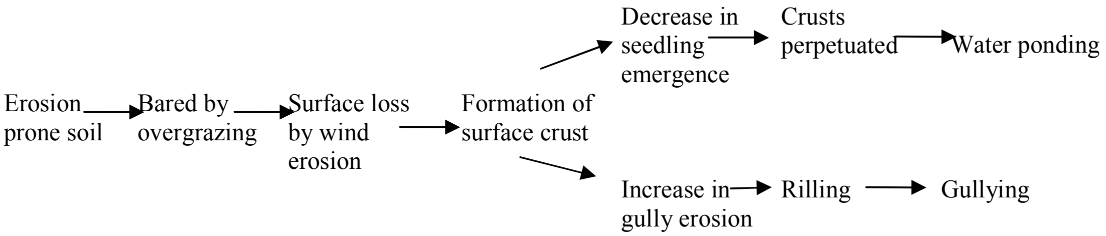
Calcretes and calcareous palaeosols

Williams & .Polach (1969, 1971) described and analysed soil carbonates in calcareous palaeosols from the Lake Torrens area. They found that the carbonate was 450-6950 radiocarbon years older than the coexisting organic carbon and that it probably accumulated largely by illuviation. The carbonate from the Motpena palaeosol in the dune sands most likely originated as calcareous dust from the weathering of older soils while the calcareous Wilkatana and Nacoona palaeosols are thought to have formed from Precambrian limestones in the adjacent Flinders Ranges

Erosion

Impacts of pastoralism

Pastoralism, principally sheep grazing in the south of the region and cattle grazing north of the dog fence (Fig. 1), has been the predominant land use for well over a century. The cumulative impact of grazing, particularly with an increase in kangaroo survival and with the uncontrolled addition of rabbits and feral goats, has been severe. As carrying capacity was lowered, the erosion-prone soils were bared to wind and water, and surface crusts formed that mitigated against seedling emergence. Those seedlings that did emerge were promptly destroyed by rabbits. The following flow diagram summarises the events and processes that give rise to soil erosion in the area:



Because of practically non-existent grazing pressures prior to settlement, and a coincidence of good seasons during much of the period of early exploration, glowing accounts were returned of the country for pastoral purposes. The result was gross overstocking when leases were taken up.

An example from the south-western edge of the region relates to Stuart Creek, a lease that was nominally in John MacDouall Stuart's name until 1864. In that year the 2,600 km^2 property was stocked with 4,000 head of cattle, four times the rate currently acceptable. Nearby Mt Hamilton, with 2,038 km^2 also had 4,000 head but, following the drought of the mid-1860's, the herd was devastated to the extent that only 200 could be mustered. The story was the same for much of the region.

The worst impact of this early overstocking was probably in the southern part of the region where excessive sheep grazing had a devastating effect on the perennial shrubs, particularly the *Chenopod* (bluebush/saltbush) component.

The Soil Conservation Committee (1938) in South Australia reported that the pastoral areas most seriously affected by wind and water erosion were the north-east and far north i.e. the region under consideration here. The Pastoral Board of South Australia furnished a statement for the Committee in which particulars were given of 15 pastoral properties covering an area of almost 20,000 km^2 which at one time carried stock successfully, but by then (1938) had no permanent carrying capacity. On a further group covering over 50,000 km^2, carrying capacity had been 'greatly depreciated' during recent years.

While early scars have at least superficially healed with the passage of time and the enforcement of more realistic stocking rates, concern still remains over the long term impact of grazing on vegetation.

Impacts of mining and exploration

Increasingly this arid region is being subjected to non-agricultural use as mobility of population increases and exploration for oil and gas escalates (Mclaren *et al.* 1986). Destruction of vegetation and disturbance of soil by exploration and mining operations such as open cuts, or by the construction of pipelines, tracks, etc. may cause dust problems and accelerated water erosion. Hence, exploration operations in the Cooper Basin gas fields, for example, are now occurring against a background of strong public opinion that is alert to environmental problems; standards of management in commercial enterprises are generally good, and are required to be so (Mclaren *et al.* 1986). However, in this fragile desert ecosystem the need for long-term soil landscape monitoring is strongly evident.

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5: Hydrology

by D. ARMSTRONG

INTRODUCTION

The hydrology of the north east deserts is dominated by the operation of evaporative processes at the surface and shallow subsurface. The area is interesting hydrologically because of the existence of two distinct, and almost independent, hydrological systems: a surface water/shallow alluvial aquifer system and a deep artesian groundwater system.

Accession of water to both systems occurs primarily outside the region with dramatic responses, in the form of floods in the surface water system. Because of the damping effect of a vast underground storage volume there is little or no detectable response to variations in accession in the deep artesian groundwater system.

Once water has entered the region in either system it appears that evaporation is the sole mechanism by which it can be lost.

SURFACE WATER AND ASSOCIATED ALLUVIAL AQUIFERS

The north east deserts occupy approximately 30% of the area of the Lake Eyre Drainage Basin, one of the world's largest internal drainage systems. In cross section, the drainage basin is highly asymmetrical. It extends 1300 km northeast from the southwestern margin, but the lowest area, representing the terminal lakes, is located only 150 km from the southwestern margin.

Major drainage systems cross the deserts from the north and east; the Warburton and Cooper Creeks both drain, via a complex system of tributaries and distributaries, the pastoral areas of western Queensland. The Finke River, draining an extensive area in the southeast of the Northern Territory, enters South Australia and discharges into the sandhills of the Simpson Desert.

The Macumber and the Neales both originate in the western part of the basin in S. A.; Peake, Warriner and Margaret Creeks drain the southwestern margin and the Frome River originates in the northern Flinders Ranges.

In his excellent account of the flooding of Lake Eyre, Kotwicki (1986 p.9) compares the runoff characteristics of the Lake Eyre Basin with the whole of Australia and the world:

> 'All streams are characterised by extreme variation in discharge and flow duration. Very variable seasonal and annual runoff are caused by tropical cyclonic and summer monsoonal rainfall and extended periods of drought, some lasting for many years. These droughts alternate with major long-lasting floods. Mean annual runoff of the basin is 3.3 km3 or 2.8 mm depth over the entire catchment, significantly less than the 57 mm for the whole of Australia (Brown 1983) and only 1% of the mean annual runoff of all the land areas of the world estimated at 247 mm (Chow 1964).'

In an area of high seasonal and annual climatic variability an extremely long record of rainfall and river flows is required to obtain a useful level of understanding of the hydrological behaviour of a system. Owing to the remoteness of the area such a record does not exist. All drainages in the basin are ephemeral and, at best, we can only rely on indirect methods to advance our state of knowledge pending the accumulation of a suitably long record.

One such method is rainfall-runoff modelling by computer using as input, the available rainfall records and certain parameters describing the assumed behaviour of each component stream within the area modelled.

Kotwicki (1986) modelled the Lake Eyre Basin and, assuming that the deepest point lies at an elevation of -15 m AHD (Australian Height Datum), the model indicates that Lake Eyre North may fill on average to:

AHD level

-12.5 m once in	5 years with an approximate volume of 6.5 km3
-11.7 m once in	10 years with an approximate volume of 11.3 km3
-11.0 m once in	20 years with an approximate volume of 18.0 km3
-10.4 m once in	50 years with an approximate volume of 26.5 km3
- 9.5 m once in	100 years with an approximate volume of 35.5 km3
- 7.5 m once in	500 years with an approximate volume of 62.0 km3
- 6.3 m once in	1000 years with an approximate volume of 76.0 km3

Amongst other points of interest to emerge from the model results was support for the hypothesis that the Warburton/Diamantina/Georgina catchment is the major source of water entering Lake Eyre North. The model showed that 64% of mean annual inflows originate in that catchment whilst 17% comes from the Cooper catchment and 19% from other sources. After a detailed study of the 1949/1950 rainfall figures Mason (1955 p. 18) concluded:

> 'There is no doubt that by far the greater contribution to the waters in the lake came from Queensland.'

It appears that though persistent heavy rain in the South Australian section of the basin may prepare the way for major flows in the rivers, true floods result from prolonged heavy rain in the Queensland part of the basin. A notable exception occurred in 1984 when Lake Eyre South filled as the result of abnormally heavy rains over the southwestern margins causing flooding in the Warriner, Margaret and Gregory Creeks and the Frome River.

Seepage losses from the creeks are difficult to evaluate but are the source of recharge to the shallow alluvial aquifers which occur beneath the braided reaches of the creeks.

Elsewhere the drainage lines are incised into the relatively impermeable clays derived from the weathering of the Bulldog Shale and Oodnadatta Formation where seepage losses are believed to be minimal after an initial wetting-up of the bed and banks.

Supplies of stock quality water generally can be obtained from wells penetrating the shallow alluvial aquifers. Pastoral properties such as Cordillo Downs rely on such shallow wells for their entire stock water supply when waterholes in the creeks have dried up.

Due to the dominant influence of evaporation in the hydrological regime, all surface water is ultimately lost to the atmosphere, leaving behind all dissolved salts. Figures quoted by Kotwicki (1986) for the Diamantina at Birdsville and Cooper Creek at Innaminka show a median value of 100110 ppm of total dissolved salts. Such water may be regarded to be of excellent quality by any standards but, when the enormous volumes involved in a flood event are considered, each event represents the importation to South Australia of huge tonnages of salt.

As an example, Tetzlaff & Bye (1978) estimated the total inflow to Lake Eyre North in the 1974 filling to be 34.2 km3. At 100 ppm this represents the addition of 3.42 million tonnes of dissolved salts to the lake storage. These dissolved salts contain the necessary ions to form a number of compounds including sodium, potassium and magnesium chlorides, calcium and magnesium carbonates and calcium and magnesium sulphates.

The Lake Eyre North brines (Bonython 1955) are sodium chloride brines and the solid salt analyses indicate 90% NaCl, a little gypsum and 9% water. The other components of the floodwaters are clearly precipitated as gypsum (which Bonython estimates to be ten times more abundant in the lake environment than NaCl) and dolomite, the latter probably close to the inlet points.

In dry conditions, deflation is the main mechanism by which salt is lost from an area such as Lake Eyre (Mabbutt 1977). Interaction with the local groundwater system probably results in some loss of salts to the shallow water table when the lake is filled and return of salts when the lake bed is dry. This component of the salt balance would depend on the frequency of filling, duration of dry periods and rate of upward movement of salt via upward leakage of water from the deep artesian aquifer. This upward movement of deep aquifer water inhibits the natural tendancy of the dense lake brines to sink beneath the bed of the lake.

THE ARTESIAN GROUNDWATER SYSTEM

The deserts of the northeastern part of South Australia overlie the southwestern margin of the Eromanga Basin, a broad sedimentary basin containing rocks of Jurassic and Cretaceous age.

The Eromanga Basin covers 1 x 10E6 km2 and is linked to the Surat Basin in Queensland and New South Wales and the Carpentaria Basin in Queensland, forming what is popularly known as the Great Artesian Basin, covering a total area of 1.7 x 10E6 km2 or a fifth of the area of the Australian continent

The latest Jurassic and earliest Cretaceous rocks are the sandstones which form the major artesian aquifer in South Australia and extend to the western flanks of the Great Dividing Range in Queensland and New South Wales. The sandstones are overlain by a sequence of shales and mudstones which serve as confining beds allowing artesian pressures to develop in the sandstones.

The general hydrology of the Great Artesian Basin has been summarised by Habermehl (1980) but the South Australian portion of the basin has received little attention in the literature since the work of Jack (1930), Ward (1946), Stanley (1971) and Shepherd (1978).

The present day geometry of the basin, (Habermehl 1980) produces an artesian flow pattern which approaches the northeastern desert region of South Australia from two directions, meeting on a north south line through Lake Eyre.

To the east of Lake Eyre, present day flow enters the State from the eastern margins of the basin where artesian pressures are maintained by relatively high rainfall on the Great Dividing Range.

West of Lake Eyre flow originates from the Northern Territory and South Australia. It is likely that the present flow regime is the current stage in a continuing evolution over the 65 x 10E6 years since the end of Cretaceous sedimentation. Tectonic activity and changes in climate could have significantly modified the flow regime since its inception.

Observed artesian pressures, water temperatures and total dissolved solids content of the water from a series of artesian wells located on a north-south cross-section following the Birdsville Track are shown in Fig. 1.

Artesian waters originating from the west, although suitable for stock, are of relatively poor quality because of high sulphate content; they are also corrosive. Water originating from the north and east is of better quality and contains dominantly sodium bicarbonate and chloride.

The best quality artesian water occurs in a tongue extending down the Birdsville Track. This tongue of good quality water (Fig. 2) grades laterally to the east and west into poorer quality water, due to the upward migration of more saline waters contained in the underlying Cooper and

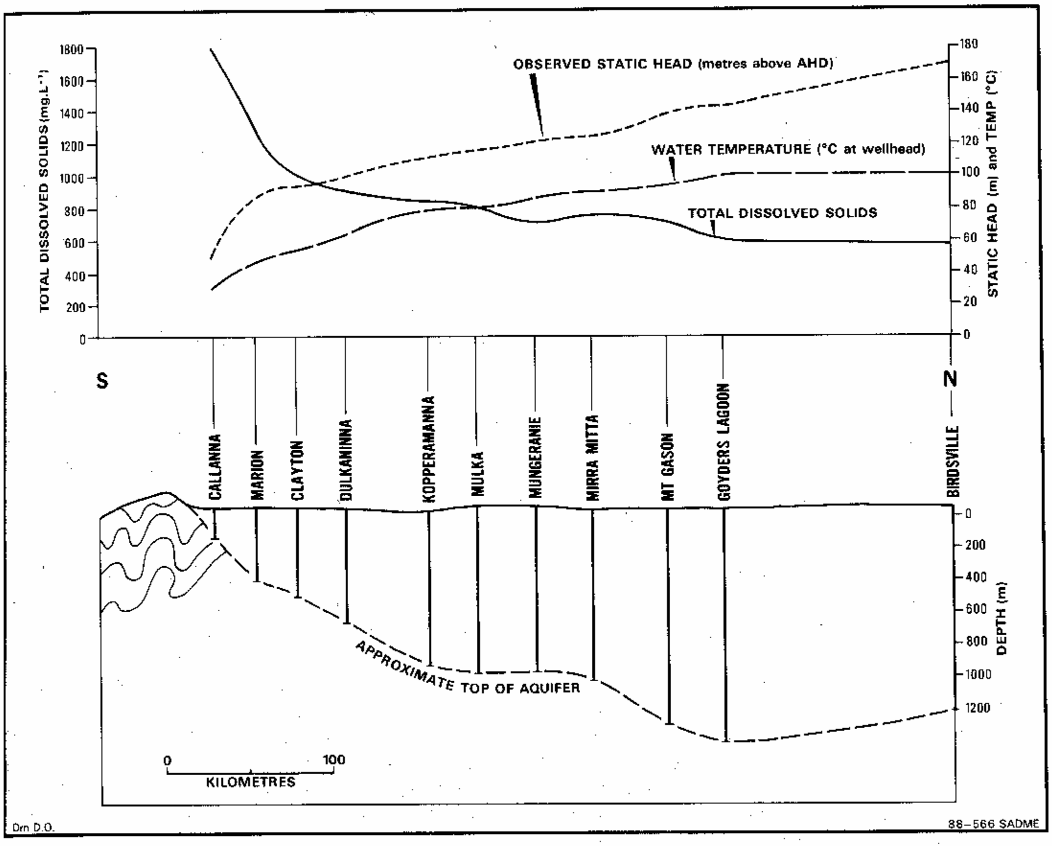

Fig. 1. Hydrogeological cross-section along the Birdsville Track.

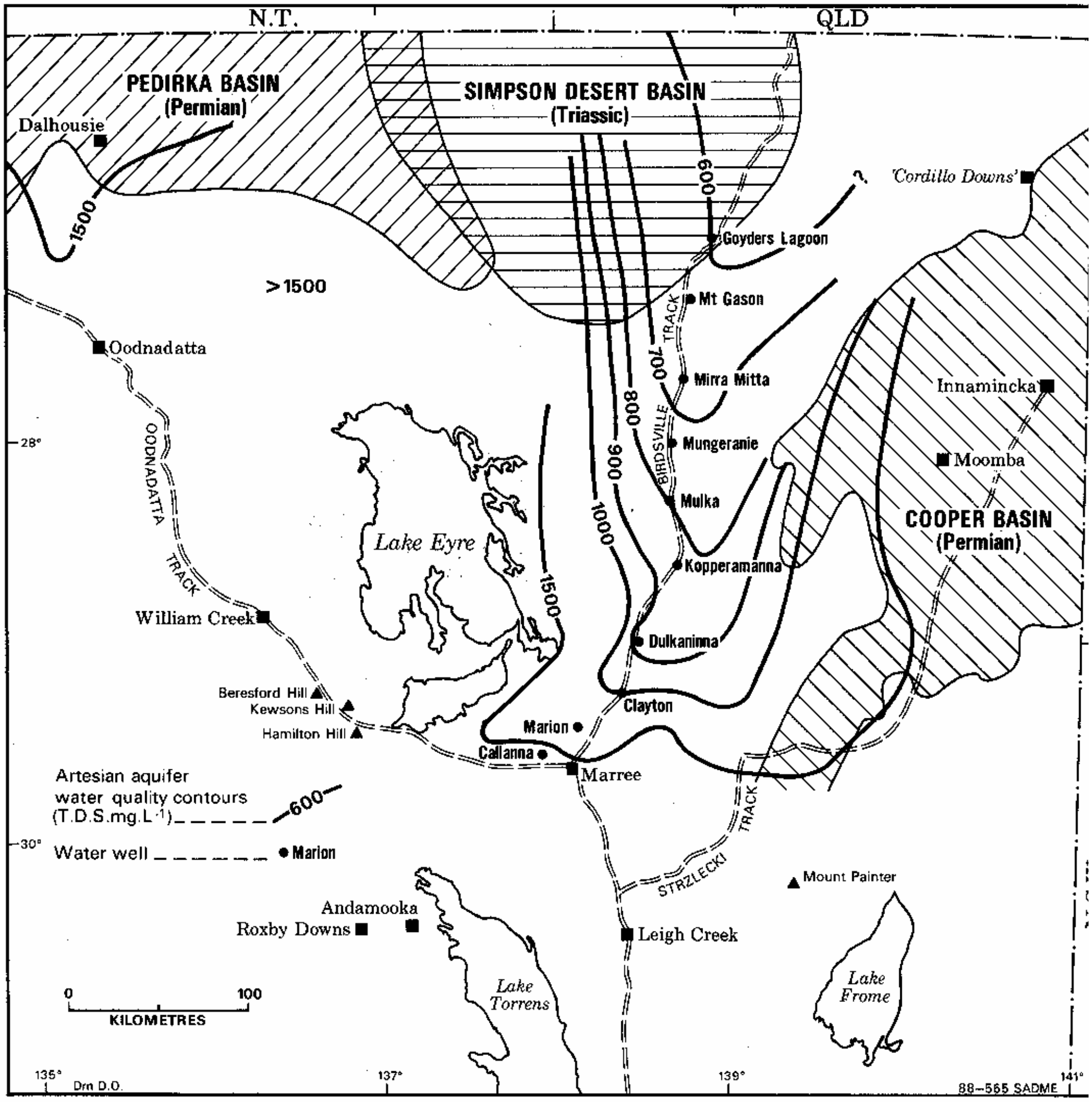

Fig. 2. Water quality contours and well locations.

Pedirka Basins. The Birdsville Track fortuitously follows the sub-surface ridge (the Birdsville Track Ridge) which separates the Cooper Basin from the Pedirka Basin, thus enabling the stock route to be watered by the best quality artesian water available in the region.

Upward Leakage and Springs

The major flow mechanism operating in the artesian aquifer is horizontal flow in response to the hydraulic gradient (pressure gradient) which exists between the northern State border and the southwest margin of the basin. Habermehl (1980) estimates the velocity of horizontal flow to be 1-5 metres per year. Flow is not possible without discharge at the downflow end of the system. In the north east deserts this discharge takes the form of flow from waterbores throughout the area, and from a series of springs which appear around the southern and southwestern margins of the basin.

The observed flows are not sufficient to account for the drop in pressure across the basin, and it is necessary to invoke an additional component of discharge to adequately dissipate the pressure.

This invisible component of discharge is vertical leakage of deep aquifer water which moves up through the confining shales, evaporates close to the land surface and manifests itself in the concentration of salts at the evaporative surface. The vertical hydraulic gradient, which acts as the driving force for vertical upward leakage, is equal to the difference in elevation between the artesian aquifer pressure surface and the evaporative surface (which lies just below ground level), divided by the flow path length which is essentially the depth below ground to the top of the aquifer.

At the site of a flowing waterbore, the artesian pressure surface falls to the elevation of the top of the bore and a cone of depression develops around the bore. Within this cone of depression the vertical hydraulic gradient is reduced and therefore upward leakage is reduced. Water which would normally leak upwards, now flows towards the bore in response to the local horizontal hydraulic gradient induced by the bore, and is discharged to the surface. The cone of depression stabilises when the flow rate from the bore is equal to the rate of reduction in leakage throughout the area of the cone. In this way the flow from the bore represents a volume of water which would have been lost by leakage and evaporation and provided no other bores lie within the cone of depression, there is no impact on the regional groundwater regime.

Leakage tends to be more important near the southern and southwestern margins where the aquifer is shallow and the vertical hydraulic gradient is steep.

The Olympic Dam Project Water Supply Scheme is able to extract water from a wellfield near Bopeechee with relatively minor effects on the surrounding groundwater system by capturing water that would otherwise be lost by leakage (Armstrong & Rowan 1987).

The springs associated with the southern margins of the Eromanga Basin represent a form of concentrated vertical leakage where the leakage rate exceeds the evaporation rate and water appears at the surface.

The largest of the spring complexes, located at Dalhousie, discharges 90% of the total spring flow in South Australia through 40 separate springs situated on a broad anticlinal structure. The remaining 10% of the total spring flow emerges from over 70 sites widely distributed around the southwestern margins.

Most of these springs are associated with structural disturbance to the confining shales resulting from minor faulting. Artesian water finds its way along discrete flow paths which permit leakage flows to become concentrated.

Concentrated flows frequently attain sufficient upward velocity to pick up and transport particles of aquifer or shale to the surface where they are deposited, forming low mounds. To the west of Lake Eyre the water chemistry favours the formation of travertine limestone which cements the particles to produce the classic stoney mounds such as the Bubbler and Blanche Cup.

Extinct stoney mounds such as Hamilton Hill, Kewson's Hill and Beresford Hill bear witness to a period when aquifer pressure was much higher than at present and serve to indicate the transient nature of springs of this type.

A spring will cease to flow when the artesian pressure falls, or the flow path becomes blocked or an alternative, more direct flow path opens up. A spring may also become extinct if its mound grows to a level at which a much reduced flow is not sufficient to maintain an effective lip in the vent, in which case the water then will become static.

Vertical leakage beneath gibber plains in the vicinity of mound springs and elsewhere has been examined by Woods (1988) who finds that a well-defined salt profile, indicating evaporation of artesian aquifer water leaking upwards, exists beneath the gibber plains. The salt concentration reaches a peak value only 20 cm below the surface. Chloride levels are so high that salt crystals are present in the soil at this depth. It is for this reason that the gibber plains do not support vegetation except after rain when grasses can grow until the newly acquired shallow soil moisture is depleted.

Preliminary analysis of the chloride profiles indicates evaporation rates of between 1 and 33 m per year. These apparently small rates of leakage assume great significance when thousands of square kilometers are considered and each square kilometer loses up to 33 megalitres per year.

Discharge and Management

The measured or estimated discharge from the basin in South Australia is made up of:-

Flowing bores	210	megalitres per day.
Springs		
Dalhousie	54	megalitres per day.
Others	6	megalitres per day.
Cooper Basin petroleum and process water	12	megalitres per day
Olympic Dam Project township and industrial water supply	9	megalitres per day
TOTAL	291	megalitres per day.

Water used by the Olympic Dam Project is exported from the basin via 100 km of pipeline and is thus the only element of the measured discharge which is not lost by evaporation within the basin.

Discharge due to leakage cannot yet be quantified but is believed to be at least equivalent to the known visible discharge.

It is estimated that only 10% of the water from the flowing bores is effectively used for stock and domestic purposes, the remaining 90% running many kilometers overland in bore drains eventually to be lost by evaporation.

In an attempt to conserve valuable pressure and water, the State Government is developing a policy of phasing out bore drains in favour of distribution by pipes, equipped with tanks and troughs, accompanied by a programme of rehabilitation of bore casing and headworks, so that flows may be controlled. Uncontrolled flowing bores that cannot be rehabilitated are backfilled and abandoned.

The basin is unlikely to run out of water but, unless carefully managed, could easily be so depleted of pressure that pumping of water to the surface would be the only way to obtain a water supply. This could have impli· cations for the economics of the pastoral industry in the area.

A further consequence of reduced pressure could be localised reversal of the leakage direction around pumping centres which would eventually lead to deterioration in water quality as water, containing salts concen· trated by evaporation, is drawn into the artesian aquifer.

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6: Climate

by R. J. ALLAN

INTRODUCTION

Climatically, the north east deserts lie at the heart of the arid core of the Australian continent. Nevertheless, they overly the Great Artesian Basin and encompass the South Australian portion of the Lake Eyre Basin (1,140,000 km2), the largest inland drainage basin in Australia (Fig. 1). Seasonal changes result from shifts in the position of the high pressure belt, from the southern portions of the continent in summer to the latitudes of central Australia in winter. Regionally, the northern Flinders Ranges exerts the major modifying influence on the broad climatic pattern.

Maximum temperatures average 36-39°C in summer and 18-24°C in winter, with the coolest temperatures in any season (maximum and minimum) in the northern Flinders Ranges. During winter July is the coldest month, with mean minimum temperatures of around 5°C experienced over the sandy deserts, and around 3°C in the Flinders Ranges. The greatest likelihood of frost occurs in winter. Prevailing winds are from the south-southeast during spring to autumn and more variable in winter, when the subtropical anticyclonic belt is over the centre of the continent and the number of calm days increases (Mollenmans et at. 1984). Median annual rainfall is of the order of 100-150 mm, while mean annual evaporation exceeds 3,600 mm (Kotwicki 1986, 1987). Thus the dry climatic regime is a consequence of high evaporation which generally exceeds rainfall by an order of magnitude or more throughout the year. However, marked seasonal variations in evaporation occur, with average summer values reaching 450-500 mm in January grading to an average winter low of 90-100 mm in July. Only extreme precipitation events temporarily act to reverse this situation.

Rainfall variability in the north east is spatially and temporally amongst the highest in Australia (Allan 1985, 1988a). However, the occurrence of surface water is not simply a function of local rainfall. A myriad of tributaries feeds the major river systems of the basin (Cooper Creek, Diamantina-Warburton and Georgina Rivers), bringing flood waters from tropical/subtropical Queensland through the north east deserts to the basin terminus at Lake Eyre. Lesser tributaries (Frome and Clayton Rivers) occasionally carry flood waters to Lake Eyre from the northern Flinders Ranges. In most years flood waters extend to the Coongie Lakes system on the North West branch of Cooper Creek (Ogilvie 1947), and to Birdsville on the Diamantina. Only in major f100dings do waters extend down the majority of the tributaries to Lake Eyre. Thus the lake itself is filled only during periods of extensive tropical to inland rainfall, although, .on average, some waters from the Diamantina-Warburton system reach Lake Eyre North every few years (Kotwicki 1986).

SYNOPTIC AND CLIMATIC INFLUENCES

The principal synoptic influences on rainfall in the north east deserts are of tropical origin. They take the form of moist tropical airmass incursions, rain and monsoon depressions and thunderstorms (Allan 1988b). Nevertheless, mid-latitude influences allied with frontal activity often are involved in such rain producing mechanisms. Occasionally, cut-off low pressure systems of more distinct mid-latitude origin are responsible for widespread rainfall, particularly if they interact with the relief of the northern Flinders Ranges (Allan 1985; Cooper 1976).

On longer time scales, major rainfall and flooding extremes are a manifestation of one phase of the El Nino Southern Oscillation (ENSO) phenomenon which involves ocean-atmosphere interactions across the Indo-Pacific region (Allan 1985, 1988c). In fact, extensive rainfall events, and in particular major fillings of Lake Eyre, are linked to the anti-ENSO phase (opposite to ENSO) of the phenomenon (Fig. 2). During such episodes, cloudiness and convective activity are enhanced in the Australasian region, with above-average rainfall during the winter-spring seasons often extending into summer, following an early onset and southerly incursion of the monsoon. Less extensive floodings are associated with transient synoptic features influencing the region (Allan 1985; Allan et at. 1986)

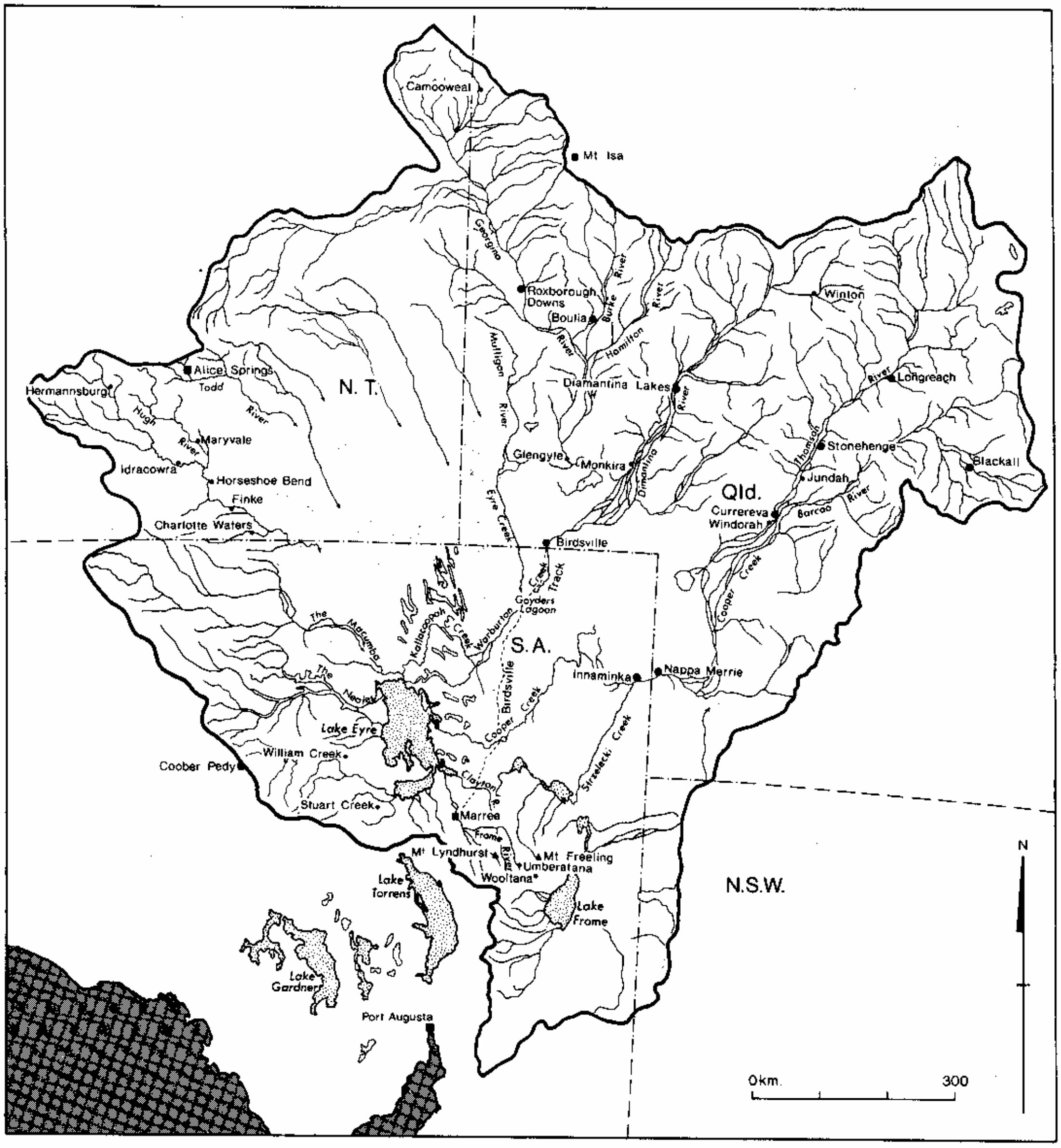

Fig. 1. Lake Eyre Drainage Basin. Locations marked with large dots are river gauging stations (From Allan 1985).

The most recent periods of protracted anti-ENSO activity occurred from May 1973 until October 1974 and again from February 1975 until March 1976 (Allan 1988b). During the years 1973, 1974 and 1975, above-average annual rainfall was recorded over 95%, 95% and 91% of the Australian continent respectively (Allan 1985). The north east of the State was inundated and vast flows occurred in all of the major rivers, tributaries and through low lying interdune corridors; both Lake Eyre and Lake Frome were filled. In significant portions of the Lake Eyre Basin falls of up to 400% above-average were recorded (Allan 1988b). The north east (Rainfall District 17) recorded such falls in August 1973, January and April 1974 and February 1976. Stream gaugings at the only two stations in the vicinity of the South Australian portion of the basin (at Birdsville and Innamincka: Fig. 1) recorded peak flows in February 1974 and March 1976 of 2.5 and 1.3 km3 and 6.5 and 2.8 km3 respectively (Kotwicki 1986).

Other periods of extensive rainfall and flooding in the north east also can be related to anti-ENSO

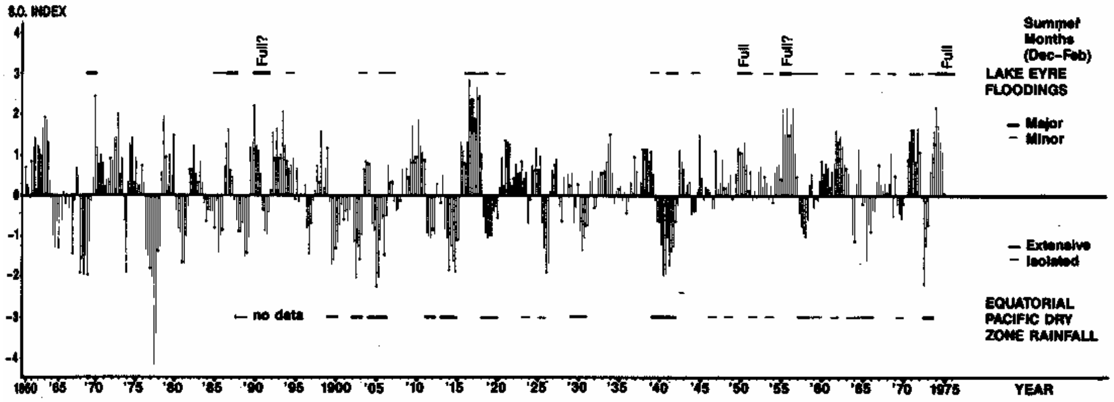

Fig. 2. El Nino Southern Oscillation (ENSO) relationships with Lake Eyre floodings/fillings. Positive Southern Oscillation (S.O.) Index values indicate anti-ENSO events while negative S.O. Index values indicate ENSO events.

episodes. As noted by Allan (1985), major Lake Eyre floodings and anti-ENSO periods (positive Southern Oscillation phases) occurred in 188687, 1889-90, 1916-17, 1920-21, 1949-50 and 1955-56 (Fig. 2. Further evidence has suggested that the 1916-17 and 1920-21 periods were major floods, while there is still doubt about the situation in 1940-41). Widespread flooding in the Coongie Lakes region during March 1963 (Allan 1988a), was related to a period of anti-ENSO influence from April 1962 to May 1963. Anti-ENSO conditions from August 1970 until February 1972

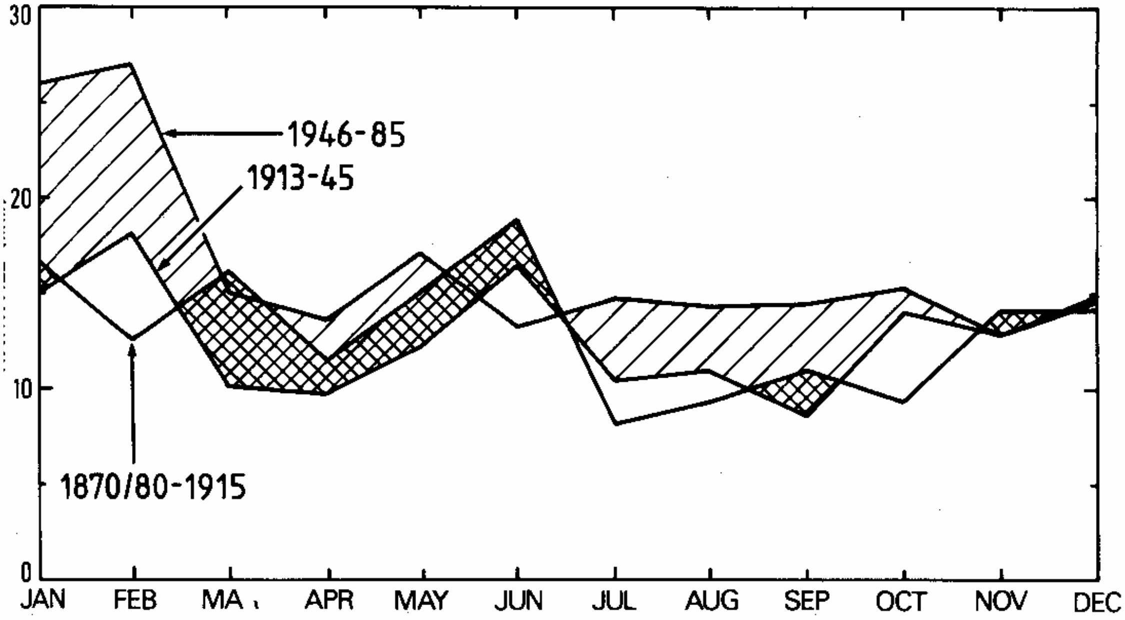

Fig. 3. Monthly mean rainfall distribution for District 17 surrounding the South Australian portion on the Lake Eyre Basin for the periods, 1870/80–1915, 1913–45 and 1946–85. Checked hatching denotes extent of monthly mean totals higher in 1870/80–1915 than in 1913–45; cross hatching denotes extent of monthly mean totals higher in 1946–85 than in 1913–45.

also had links with above-average rainfall in the north of the State. In March 1971, a rain depression caused widespread flooding in the northern Flinders Ranges, isolating the Arkaroola settlement (Sprigg 1972). During January 1972, Hendrie (1972) reports that there was widespread rainfall and flooding in the northern Flinders Ranges and on the eastern margins of Lake Eyre.

HISTORICAL CLIMATIC FLUCTUATIONS

There is considerable evidence that Australian climatic patterns, including ENSO/anti-ENSO influences, have not remained fixed over the last 100-150 years of instrumental records (Pittock 1983, 1984; Allan 1987). Such fluctuations also can be seen in rainfall records for the northeast. Fig. 3 shows mean monthly rainfall in District 17 (which covers the entire north east deserts region) for three historical periods. Although the earliest period is more uncertain due to the use of stations with a number of different starting dates, comparison of the three data sets clearly shows an increase in summer rainfall from the 1913-45 to the 1946-85 period. In a region of low rainfall, this change (of the order of 75-80%) is extremely significant. In fact, Allan (1985, 1987, 1988b) equates it with a greater influence-intensity of anti-EN SO episodes in more recent decades. This interpretation is supported by smaller increases in autumn and spring rainfall between 1913-45 and 1946-85. Relationships with the earlier 1870/80-1915 period also are of interest, because they suggest that wetter conditions occurred in autumn to early winter months when compared to the later 1913-45 averages. Overall, these results concur with findings of a marked decrease in rainfall over the eastern half of the continent from 1881-1910 to 1911-40 (Gentilli 1971) and a reversal of this trend from 1913-45 to 1946-78 (Pittock 1983).

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7 Salt Lakes: The Limnology of Lake Eyre

by W. D. WILLIAMS

INTRODUCTION

A large number of salt lakes lies within the north east deserts. None is permanent. Included are many small and several large ones of which the best known and largest is Lake Eyre, a lake of 9,330 km2 area when filled with water and with a bed some 15 m below sea-level. So far, only Lake Eyre has been explored limnologically in any comprehensive way, and it is Lake Eyre, therefore, which provides the focus of the present chapter. Other salt lakes of the region, here simply named, include Kanunka, Palankarinna, Pitikanta, Ngapakaldi, Blanche, Callabonna and Frome. All, like Lake Eyre, are usually dry. Freshwater lakes, at least some more or less permanent, are discussed in Chapter 10.

The salt lakes of the north east are not alone in the lack of scientific attention accorded them. Most salt lakes worldwide have received scant attention. There are many reasons for this. Not least is that until relatively recently salt lakes were regarded by most limnologists as uncommon, inaccessible and essentially uninteresting bodies of water inhabited by a few widespread organisms of no significant commercial interest (Williams 1986). Ideas of this sort are erroneous. Additionally, the public at large has tended to perceive salt lakes as desolate wastelands, as barren, dreary places: a perception that can hardly have served to ignite scientific interest in them. Early perceptions of Lake Eyre provide a case in point. A recurring theme in all accounts of its early exploration was the 'desolation' of the lake, and its useless nature. Eyre is said (Serventy 1985), on first sighting the lake, to have stared in horror at 'one vast, low and dreary waste'. Warburton (fide Serventy 1985) noted: 'Lake Eyre was dry - terrible in its death-like stillness and the vast expanse of its unbroken sterility'. Lewis (fide Serventy 1985), after his explorations of 1874-75, said: 'I sincerely trust I may never see it again. It is useless in every respect, and the very sight of it creates thirst in man and beast.' Even Gregory (1906), of whom one might have expected more objectivity, seemed to have been repelled by the lake: 'The earth was repulsive in its arid forlorn barrenness, and the sky was still more repulsive in its sunless pall of cloud.'

Whatever the case with regard to limnological and popular perceptions, in reality inland bodies of salt water are not significantly less common in terms of total volumes and lake numbers than freshwater lakes (cf. table 1, Williams 1986). It is true that many salt lakes are inaccessible, including many in the north east of South Australia (though not all, by any means), but there are many salt lakes in Australia and elsewhere which are readily accessible for study. Moreover, scientifically, salt lakes are of interest for many reasons: they are, for example, of interest to ecologists because they are discrete and relatively simple ecosystems, to physiologists because plants and animals living in them possess an array of adaptations to environmental conditions that most organisms find intolerably stressing (e.g. high salinities and temperatures, frequent desiccation, high light intensities), and to palaeolimnologists because salt lakes are sensitive natural devices for recording past climatic changes. Commercially, salt lakes are of interest because a number of organisms living in them are valuable as animal foodstuffs (brine shrimp) or produce valuable by-products (13carotene, glycerol). Of course, the sediments of dry salt lakes or the brine of those containing water are important commercial sources of many minerals in addition to salt (sodium chloride) itself.

As for the biota of salt lakes, previous ideas have again proved erroneous. Perhaps they have been shown to be wrong by studies of Australian salt lakes in particular. These are inhabited by an assemblage of animals, if not plants, unique to the continent. Moreover, the fauna displays regional differences of a sort which easily distinguish the major regions where salt lakes occur.

An important limnological division of salt lakes, and one applicable both to those in Australia and elsewhere, is into those which predictably contain water and those which do not, i.e. those which contain water on a regular or seasonal basis and those which do not (Williams 1985). The general relationship between predictability and climate

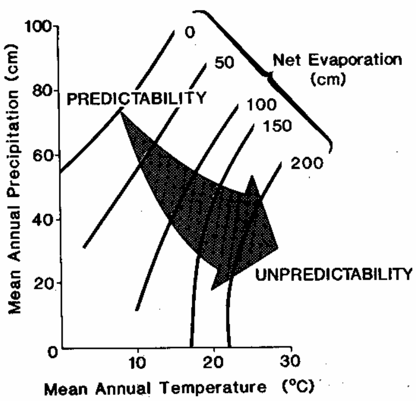

Fig. 1. General relationship between the predictability of water presence and climate. After Williams (1985).

is indicated in Fig. 1. There can be no doubt as to where the salt lakes of north east South Australia lie in this figure. It was essentially for this reason that Lake Eyre, as an exemplar of an episodically-filled salt lake, was studied by Williams & Kokkinn (1988).

Here, emphasis is given to the biological features of Lake Eyre; non-biological features are discussed only in so far as they illustrate the general nature of the physico-chemical environment inhabited by the aquatic biota of the lake. More detailed accounts of certain non-biological features are given in Chapter 8. Even so, it is hoped that this chapter will be sufficiently comprehensive to be an independent introduction to the limnology of Lake Eyre, without, at the same time, providing excessive overlap with Chapter 8.

The account of basic non-biological features (the limnological background) is preceded by a brief historical resume of the scientific exploration of the lake. This is more a convenient and succinct method of listing the most significant studies on all aspects of the lake's limnology thus far than an attempt to provide a review of previous studies. Many of these studies, in any event, are referred to elsewhere.

This chapter, it must also be noted, deals only with the extant biota of Lake Eyre. Not discussed are palynological or palaeontological studies documenting the nature of fossil floras and faunas. For an introduction to studies of this sort - on material from both Lake Eyre and Lake Frome -, reference should be made to Ludbrook(1953, 1956, 1963), King (1956), Singh (1981), Wells & Callen (1986) and Pledge & Tedford (Chapter 17).

HISTORY OF SCIENTIFIC EXPLORATION

Lake Eyre South was first seen by white men in 1840 when E. J. Eyre, after whom the lake is named, began European exploration of the region. The first explorers to see Lake Eyre North were C. H. Babbage who explored the region between Lake Eyre North and South in 1858 and J. M. Stuart who first saw Lake Eyre North in 1859 while exploring the region to the west of it. Several late nineteenth century expeditions to the region followed these early reconnaissances and a bibliography to accounts of them is given bj Gregory (1906: Appendix III; see also 1908) who also visited the lake briefly. There is little 01 significant limnological interest in these earlj accounts, and it was not until the twentieth century that serious scientific exploration of the lake began. In the main, it followed brief and episodic floodings, namely those in 1949-52, 1974-78 and 1984-85. Many results 01 explorations which followed the 1949-52 flood were published jointly by the South Australian Branch of the Royal Geographical Society 01 Australasia (Bonython 1955a-f; Mason 1955; Penman 1955; Price 1955). Others appeared separately (Mawson 1950; Fenner 1952; Bonython & Mason 1953; Bonython 1956). The Royal Geographical Society of Australasia also published a series of papers concerned with the 1974 flood (Bonython & Fraser 1989). Within the present context, important papers in this series were those by Bonython (1989), Allan (1989), Bye & Wills (1989a, b), Dulhunty (1989a, b), Johns (1989), Barker, Cornwall & Lay (1989) and Glover (1989). Separate studies made of events associated with the 1974-78 flood include those of Vickery (1974), Bayly (1976), Ruello (1976), Bye et al. (1978) and Tetzloff & Bye (1978). Events during the 1984 flood were studied by Allan (1985), Allan et al. (1986) and Williams & Kokkinn (1988).

Of course, Lake Eyre has attracted scientific attention at times other than when flooded, predominantly from those interested in geological and geomorphological phenomena. Notable early studies of this sort, and pre-dating the 1949-50 flooding, are those of Fitzpatrick & Strong (1925) and Madigan (1930). Important later studies were those by Baas-Becking & Kaplan (1956), Bonython & King (1956), Towner (1954-56), Bonython (1960, 1961, 1963, 1974), Johns (1963), Wopfner & Twidale (1967), Twidale (1972), Dulhunty (1974, 1975, 1977a, b, 1978, 1982, 1983a, b, 1987), Loffler & Sullivan (1979) and Magee et al. (1988). Important but more general recent references to the lake include those of Mabbutt (1977), Dulhunty (1977c), Bowler (1981), Kotwicki (1986), Hammer (1986), De Deckker (1988) and Lothian & Williams (1988). Javor's

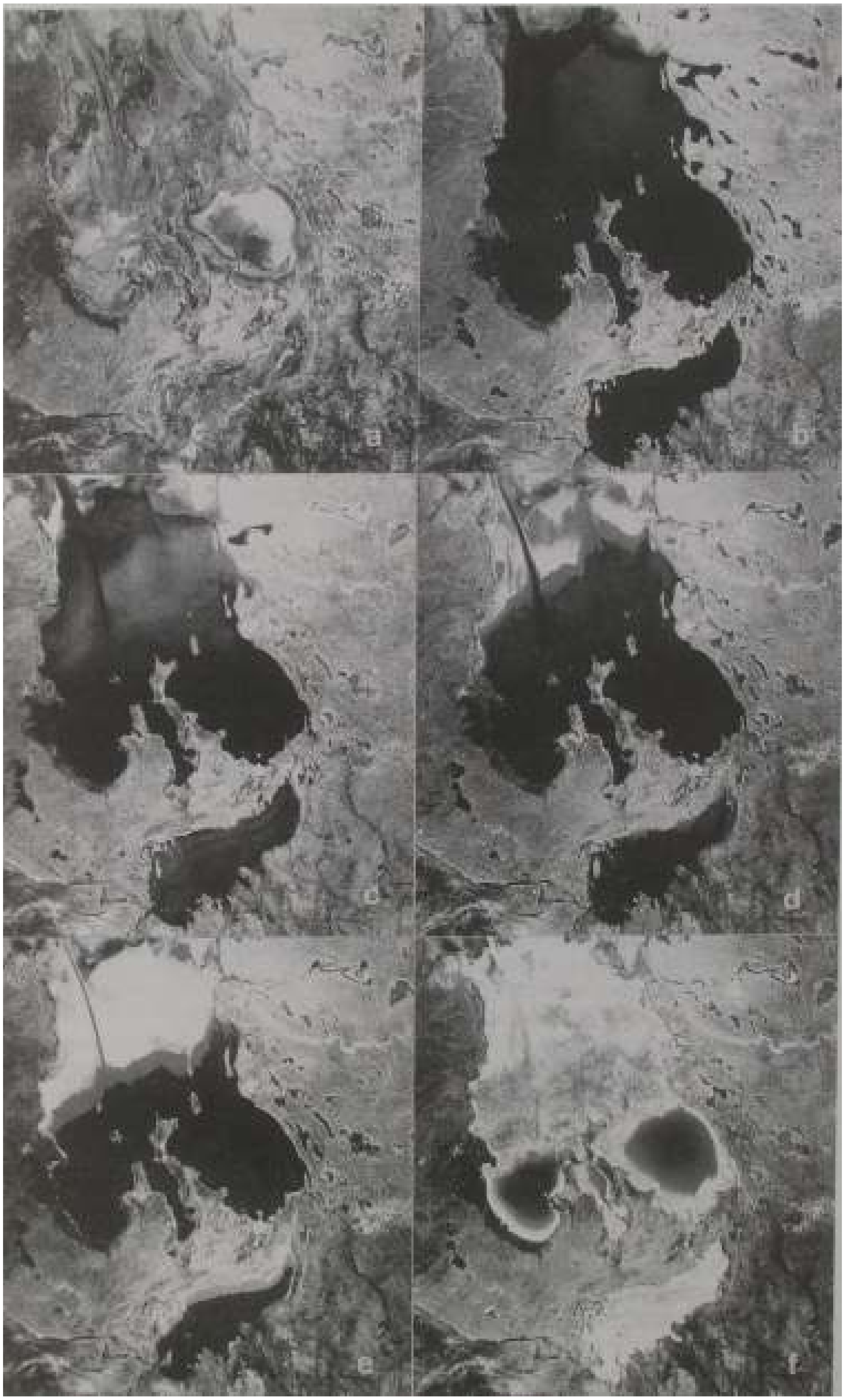

Fig 2. Extent of water coverage immediately before and and following January 1984 flood as photogtaphed by Lndsat a, 20 Dec 1983; b, 22 Feb 1984, c, 21June 1984,d, 27 Oct 1984; e, 12 Nov 1984, f, 4 Mar 1985. Landsat imagery provided bt they Aust Centre for Remote Sensing, Aust Surveying and land Information Group, Dept of Adminsitrtive Services

(1989) recent account of Lake Eyre is largely a review of the microbiological processes in the lake and is based mainly on the earlier works of SaasSecking & Kaplan (1956). Kotwicki's (1986) account is an excellent introduction to hydrological features but deals also with many other aspects. Finally, brief note is appropriate in a book of this sort of several 'popular' books which either focus upon or make extensive reference to Lake Eyre and its environs. Gregory's (1906) general account was followed by accounts from Madigan (1936, 1946), R. Dulhunty (1975, 1979, 1986), Mossel & Kuhne (1978) and Serventy (1985).

THE LIMNOLOGICAL BACKGROUND

Lake Eyre (ca. 28°30' S, 137°E) is the terminal lake of one of the largest (1.14 x 106km2) global endorheic drainage basins. This basin extends over large parts of South Australia, Queensland and the Northern Territory, and its climate is arid to semi-arid throughout.

Mostly flat, a good deal of the basin lies <150 m above sea-level, with about 90% of it lying <500 m. Lake Eyre itself has a bed which lies ca. 15 m below sea-level. The lake is part of a very old lake system, some sediments of which date back as far as the early Tertiary. Tectonic upwarping south of Lake Eyre following aeolian deflation of surface sediments gave rise to the present lake in arid post-Pleistocene times. During the Pleistocene, the site of Lake Eyre was occupied by a large freshwater lake, Lake Dieri, which extended over an area five times the area of the present Lake Eyre when full.

Lake Eyre is an ephemeral lake and usually dry, but there is evidence of infrequent prehistoric fillings, a reasonable presumption of a filling in 1890, and certain knowledge of four fillings this century (1949-52, 1974-78, 1984-85, 1989-). During documented fillings, the lake contained water for -44 (1949-52), -51 (1974-78) and -13 months (1984-85). At the present time (February 1990), it has contained water for -11 months and is not yet dry. The filling in 1984-85 differed from previous documented fillings in that it resulted from heavy rainfall in the immediate lake environs and over the lake itself; previous fillings resulted from rainfall over the more distant parts of the lake's catchment. The southern end of the lake usually fills first and, as Fig. 2, based on satellite photography clearly shows, retains water the longest. Less extensive (minor) fillings of the lake also occur; more frequent, they cover parts of the lake for less than 12 months.

Although Lake Eyre is widely referred to as a single entity, in fact two distinct lakes are involved: a large northern lake, Lake Eyre North, which connects during major floods via the Goyder

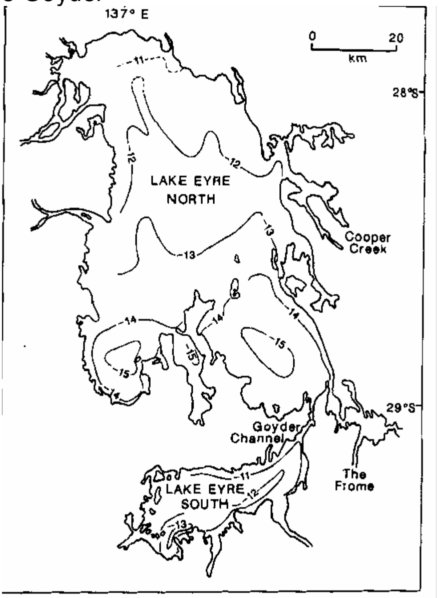

Fig. 3. Configuration of Lake Eyre North and South and the bathymetry of the lake. Based on Bye *et al.* (1978) and Kotwicki (1986). Contours are metres below A.H.D. (sea-level).

Table 1. MAJOR MORPHOMETRIC PARAMETERS AT 1974 FLOOD LEVEL OF LAKE EYRE NORTH & SOUTH. After various sources

Parameter	Lake Erye Nth	Lake Eyre Sth
Area km^2	8430	1250
Max length km	144	64
Max width(km	77	24
Mean width km	59	20
Max depth m	5.7	3.7
Mean depth	3.3	1.9
Volume km^3	27.7	2.4
Volume development^1	1.7	1.5
Shoreline length km	1390	328
Shoreline deveopment^2	4.3	2.6

1 (mean depthx3)/max depth

2 shoreline length/2√(area x π)

Channel (13 km long and up to 2 km wide) with a smaller southern lake, Lake Eyre South. The beds of both lakes are remarkably flat, though overall there is a gentle north/south gradient of some 2 to 4 cm km^{-1}. When dry, a salt crust up to 0.5 m thick covers large areas of the southern part of Lake Eyre North with thinner salt crusts in parts elsewhere (total salt mass ca. 4-7 x 10^8 tonnes); all salt crusts completely dissolve during major fillings. Over large areas, these crusts overlie water-saturated sediments, so-called 'slush'. Saline yellow-red clays, sand and organic mud comprise the bed of Lake Eyre North throughout its central and northern areas. Both lakes are bordered by well-defined shorelines with low cliffs in many places. The configuration of the lakes and their bathymetry is indicated in Fig. 3, and major morphometric parameters (at highest 1974 levels) in Table 1.

When water is present, it is always saline (i.e. contains > 3 g 1^{-1} total dissolved salts), but salinity varies greatly in space and time. Meromixis has frequently been reported such that the salinities of bottom waters overlying salt crusts approach saturation values (350 g 1 -1), whereas in surface waters at the same place and time they are an order of magnitude less in value. Horizontal variation is also marked; surface salinities may be just above 3 g 1 $^{-1}$ near major influents and, contemporaneously, several times that value in southern parts of the lakes, especially Lake Eyre South. Temporal variation is no less marked. The general picture is that at a given location salinities are high for a short period after crust inundation, rapidly decrease as water volume increases, and slowly increase as the lakes dry. Fig. 4, based on samples collected from a fixed position in Lake Eyre South during 1984, illustrates this slow increase - here from a value of <25 to one of >250 g 1^{-1}

Fig. 4 also illustrates that, at the location in question, sodium and chloride were the dominant ions at all salinities. This is a constant phenomenon throughout the lake at all times. Ionic composition is similar in the sediment brines, but contrasts with that of waters in the underlying artesian basin, the Great Australian Artesian Basin; here, sodium is still important, but (bi)carbonate is more important than chloride. Representative analyses (Table 2) illustrate these several points. In summary, the brines of Lake Eyre mostly comprise sodium chloride (90-95%), with smaller amounts present of magnesium sulphate (5-7%), magnesium chloride «4%) and calcium sulphate « 2.5%).

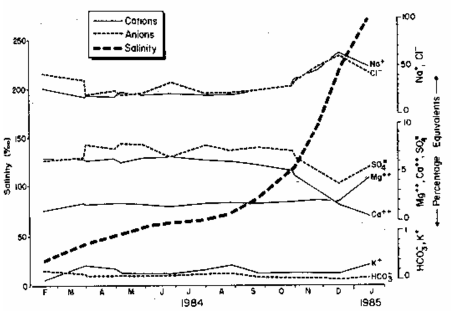

Fig. 4. Salinity and chemical composition (as percentage equivalents of major ions) of Lake Eyre South, February 1984–January 1985. From Williams & Kokkinn (1988).

As to the question of where these salts originate, in addition to contributions from influent streams, many authors believe that atmospherically contributed salt, ultimately of marine derivation, is the most likely major source. Note, however, that the salt present in Lake Eyre is regarded as part of a complex and ongoing dynamic transfer process involving movements between northern and southern lakes (in both directions), loss to the system (wastage), and gain (accumulation). Such a process is more in line with modern hydrological ideas concerning the extent to which salt lakes are 'closed' systems than previous ideas on this subject.

THE BIOTA

Much less scientific attention has been given the aquatic biota of the lakes than accorded their physico-chemical features. Indeed, there was no systematic attempt by any biologist even merely to collect specimens during the 1949-52 flood, and plants and animals recorded then (Bonythón 1955f; Baas-Becking & Kaplan 1956) were largely the result of isolated collections by non-biologists (mostly of terrestrial forms, and without, in the case of aquatic forms, accompanying salinity data) that were subsequently submitted to taxonomists for identification.

Rather more information accrued after the 1974-77 flood. Ruello (1976) and Glover (1989) made brief observations on the fish (and bird) fauna, Bayly (1976) studied samples of the plankton of Lake Eyre North collected at intervals in 1974 and 1975, and Mossel & Kuhne (1978) and Serventy (1979, 1985), in popular accounts, made observations on the avifauna. Following the 1984 flood, Williams & Kokkinn (1988) examined the aquatic fauna of Lake Eyre South; they studied samples collected regularly between February 1984 and January 1985 from a single locality.

None of these later studies, as their authors would agree, is in any way a comprehensive study of the aquatic communities within Lake

Table 2. REPRESENTATIVE ANALYSES OF WATERS FROM LAKE EYRE NORTH AND SOUTH AND ELSEWHERE.

Sample	Value[1]	Salinity	Na	K	Ca	Mg	Cl	S0$_4$	C0$_3$ + HC0$_3$
Lake Eyre South, 1922[2]	A	92.7	32.8	0.4	1.8	0.4	51.6	5.6	0.1
	B	-	91.8	06	5.7	2.0	93.3	7.6	0.1
Lake Eyre South, 14.2.1984[3]	A	25.5	9.1	0.0	0.6	0.1	14.3	1.3	01
	B	-	92.5	0.0	6.5	09	94.2	6.1	0.2
Lake Eyre South, 19.5.1953[4]	A	185.7	68.8	0.1	1.8	1.0	107.5	6.4	0.1
	B	-	94.4	0.1	2.8	2.7	95.6	4.2	0.0
Lake Eyre North, sediment, 15.5.1953[5]	A	286.4	108.2	0.0	10	1.5	167.3	8.4	0.0
	B	-	96.4	0.0	1.0	2.6	96.6	3.6	0.0
Goyder Channel, 28.10.1979[6]	A	320.8	120.8	0.6	0.7	2.1	186.9	9.6	0.1
	B	-	95.9	0.3	0.6	3.2	963	3.7	0.0
Muloorina Billabong, 28.10.1979[7]	A	1.8	0.575	0.006	0.004	0002	0276	0.019	0.949
	B	-	96.1	0.6	0.8	08	308	0.0	69.2

[1] A, g 1^{-1}; B, as percentage of equivalent sum of total cations.

[2] Sample collected August 1922. Recalculated from Fitzpatrick & Strong (1925).

[3] From original data summarized in Williams & Kokkinn (1988).

[4] From Bonython (1956). Sample collected off Artemia Point.

[5] From Bonython (1956). Sample from lake bed sediments at Prescott Point.

[6] From unpublished analysis by M. Johnson (pers. comm.). At the time, both Lake Eyre North and South were quite dry.

[7] From unpublished analysis by M. Johnson (pers. comm.). This billabong is fed by bore water from the underlying artesian basin, and is located just south of Lake Eyre North.

Eyre, nor adds much to our understanding of in situ ecological processes.

Thus, Ruello's (1976) short note grew from an incidental observation of a massive fish kill in Lake Eyre North, and Bayly's account was essentially an attempt to provide a first inventory of the plankton. Williams & Kokkinn's studies were designed only to examine their hypothesis that the fauna of episodically filled salt lakes comprises widespread, easily-dispersed species.

The following account, therefore, is incomplete: it is simply a first attempt to provide an integrated list of recorded biota when water is present, a commentary on some interesting features of certain species, and a brief discussion of some general matters concerning the nature of the biota.

Phytoplankton

Although studies of the phytoplankton are usually amongst the first to be made of the biota of salt lakes, surprisingly few such studies have involved Australian salt lakes, as Hammer (1986) noted. As for studies of the phytoplankton of Lake Eyre, they are conspicuous by absence. Table 3 provides a thin and undoubtedly incomplete list of taxa recorded thus far. It does not include the salinity at which taxa were collected simply because in most cases this parameter was not determined.

Of the taxa recorded, *Dunaliella salina* was noted by Baas-Becking & Kaplan (1956) as the chief species of *Dunaliella*, and *Nodularia*, *Anabaenopsis* and *Glaucocystopsis* as the most significant taxa by Bayly (1976). Bayly (1976) did not record *Dunaliella*, presumably because his collections were restricted to the early part of the salinity cycle, viz. when salinities were still <40 $^{o}/_{oo}$. *Nodularia* was recorded by him at salinities between ca. 15 and 40 $^{o}/_{oo}$, *Anabaenopsis* between - 25 and 40%0, and *Glaucocystopsis* between ca. 17 and 40 $^{o}/_{oo}$; these 'maxima' may well have been exceeded since sampling stopped after August 1975 but salinities would have risen thereafter. Most of the taxa listed in Table 3 are commonly found in saline lakes, with *Dunaliella*, especially *D. salina*, the most typical of all algae found in highly saline localities. Perhaps the ability of *Dunaliella* species to adapt quickly to rapid changes in salt concentration (Brown & Borowitzka 1979) favours its presence in Lake Eyre. Only two taxa, *Chodatella* (= Lagerheimia) and *Glaucocystopsis* are somewhat unusually recorded in this sort of environment. The absence of systematic collections, and especially of associated salinity data, pre-empts further discussion.

Table 3. PHYTOPLANKTON RECORDED FROM LAKE EYRE. Based on Hol & Fremy (1933), Bonython (19551), Baas-Becking & Kaplan (195B), Bayly (1976) and Hammer (1986).
Bacillariophyta
Amphora coffeaeformis (C. Agardh) Kutzing
Pleurosigma sp.
Navicula sp.
Gyrosigma sp.
Chlorophyta
Dunaliella salina Teod.
D. minuta Lerche
D. parva Lerche
D. euchlora Lerche
D. viridis Teod.
Chodatella (= *Lagerheimia*) sp
Dinophyta (= Pyrrophyta)
Peridinium sp
Cyanobacteria
Nodularia spumigena Mertens
Lyngbya sp.
Oscillatoria sp.
Microcystis sp.
Anabaenopsis sp.
Glaucocystopsis sp.
Aphanocapsa litoralis Hansg

Macrophytes

No submerged macrophytes have been recorded. This would be unremarkable were it not that macrophytes (species of *Ruppia* and *Lepilaena*, *Lamprothamnion papulosum*) are commonly found in many Australian ephemeral salt lakes where they are an important part of the food web. However, their absence from Lake Eyre (undoubtedly a valid conclusion from the absence of records) is not surprising. There can be little doubt that the explanation lies in the long intervals between the occurrence of suitable conditions, the brevity of these (*vis-a.-vis* macrophyte lifecycles) when they do occur, and the great distance of Lake Eyre from saline localities which do provide suitable conditions for the growth of macrophytes.

Microbial Communities

Samples of brine from Lake Eyre obtained in 1929 and collected by C. T. Madigan, on subsequent culture in Holland, yielded a rich microbial assemblage (Baas-Becking & Kaplan 1956). Later samples, collected in 1953 and 1954, likewise proved to have a rich microbial life: direct microscopy revealed many forms associated with the brine, salt crust and mud surface. Baas-Becking & Kaplan (1956), who studied these samples (and, incidentally, whose pioneering work in this area seems inexplicably to have been largely overlooked by students of salt lakes except Javor (1989)), isolated *inter alia*: photosynthetic and heterotrophic sulphate-reducing bacteria, thiobacteria which oxidize sulphur to sulphate, photosynthetic purple bacteria (on the surface mud), as well as *Halobacterium halobium* (as *Bacterium halobium*). None of these bacteria is unexpected since similar forms are known to occur in a variety of Australian salt lakes (Borowitzka 1981). Microbial processes in Lake Eyre were briefly reviewed by Javor (1989).

In addition to bacteria, Baas-Becking & Kaplan (1956) made passing reference to the plentiful occurrence of colourless ciliates and flagellates (Bodo species) amongst the microbial forms seen by them. No further details of these were given. Finally, it may be noted that well-defined benthic microbial mats (sensu Bauld 1981) appear to be absent - no doubt a reflection of the lack of sufficient protective sedimentation - and lack of sufficient moisture when the lake is dry.

Zooplankton

The only studies of the zooplankton available are those by Bayly (1976) and Williams & Kokkinn (1988); the former studied samples from Lake Eyre North following the 1974 flood, and the latter from Lake Eyre South following the 1984 flood. Their data are listed in Table 4. Fig. 5 indicates the patterns of occurrence found in the two lakes.

Three major points emerge from a consideration of the findings of Bayly (1976) and Williams & Kokkinn (1988). First is the rather low percentage of species common to both lakes (20%); only *Brachionus plicatilis*, *Daphniopsis ?pusilla*, *Microcyclops platypus* and *Moina baylyi* occurred in both Lake Eyre North and South. This low degree of species congruence may reflect a real faunistic difference between the lakes, but more likely it reflects the lack of samples from Lake Eyre North *after* salinities began to exceed 60 g 1^{-1} and, because of the rapidity of events, from Lake Eyre South before a salinity of 25 g 1 - 1 had been reached. Whatever the case, the dominant zooplankton taxa (at least at the generic level) in both lakes also occurred in both lakes, viz. *Microcyclops* spp., *Moina baylyi* and *Diacypris* spp.

A second major point is that with the single exception of *Diacypris* sp. a (Table 4), which appears to be undescribed and endemic to Lake Eyre South (p. De Deckker pers. comm.), all of the taxa have been found in salt lakes elsewhere in Australia, and some, the rotifers, cosmopolitan. Even the cladoceran *Moina baylyi*, originally thought to be endemic and restricted to Lake Eyre (Forr6 1985), has been found elsewhere; subsequent to its collection by Williams & Kokkinn

Table 4. ZOOPLANKTON OF LAKE EYRE NORTH AND LAKE EYRE SOUTH. Data from Bayly (1976) and William: & Kokkinn (1988).

Taxon	Lake Eyre North	Lake Eyre South	*Salinity Range
Rotifera			
Hexarthra tenniea (Levander)	+	-	7-25
Braehionus plieatilis Muller	+	+	16-27
Anostraca			
Parartemia minuta Geddes	-	+	25-163
Copepoda			
Boeckella triarticulata (Thomson)	+	-	7
Apocyclops dengizieus (Lepeschkkin)	+	-	7-39
Microcyelops platypus (Kieffer)	+	+	15-71
Mieroeyleops sp. a	-	+	25
Microcyclops sp. b	-	+	87
Ciadocera			
Daphniopsis ?pusilla Serventy	+	+	15-58
Moina baylyi Forrot	+	+	7-87
Ostracoda			
Heteroeypris sp,	-	+	25-42
Diacypris aff. *dietzi* (Herbst)	+	-	
D. todiens (Herbst)	+	-	7-25
D. whitei (Herbst)	+	-	
Diacypris sp. a	-	+	42-163
Ilyocypris sp.	+	-	N.A.
Mytilocypridini	-	+	42-58
Trigonocypris globulosa De Deckker	-	+	49-61
Reticypris kurdimurka De Deckker	-	+	49-65
Mytiloeypris splendida (Chapman)	-	+	51-65

*A combination of data in Bayly (1976; by interpolation) and Williams & Kokkinn (1988; fig. 6 and table 1). Referred to by Bayly (1976) as M. *mongoliea* Daday.

in 1984 it was recorded from Lake Buchanan, Queensland (Timms 1987). In this regard, the zooplankton of Lake Eyre broadly supports the hypothesis of Williams & Kokkinn (1988) that episodically-filled salt lakes, such as Lake Eyre, are not important evolutionary loci, and as a result have a biota which must have good dispersal mechanisms and which is widely dispersed. This matter is also referred to later.

The third major point is that most of the taxa which dominate the zooplankton of salt lakes throughout southern Australia, namely species of the calanoid *Calamoecia*, the ostracod *Australocypris*, and the cladoceran *Daphniopsis*, appear to be either absent or (in the case of *Daphniopsis*) rare in Lake Eyre. Conversely, *Moina baylyi*, so common in Lake Eyre, has never been found in southern lakes. The absence of *Calamoecia* from Lake Eyre is particularly outstanding, presumably reflecting its apparently poor dispersal abilities (Maly 1984).

Bayly (1976) and Williams & Kokkinn (1988) found *Daphniopsis* to be rare; it was regarded by them as probably a stray from nearby localities. Even so, Kokkinn & Williams (1987) suggested on the basis of scanning electron microscopy studies of ephippia (resting eggs) that a new species may be involved common to Lake Eyre and Lake Buchanan, Queensland. Note also (see Fig. 5) that the data from Lake Eyre North and South show no well-defined successional patterns such that species occurrences are confined to relatively narrow salinity ranges and succeed each other as specific tolerances are exceeded. On the contrary, they suggest, in line with the views of Williams et al. (1990), that, so far as true halophiles and halobionts are concerned, salinity is relatively insignificant as a primary determinant of species occurrences over wide salinity ranges.

Benthic invertebrates

The only reported benthic invertebrates are

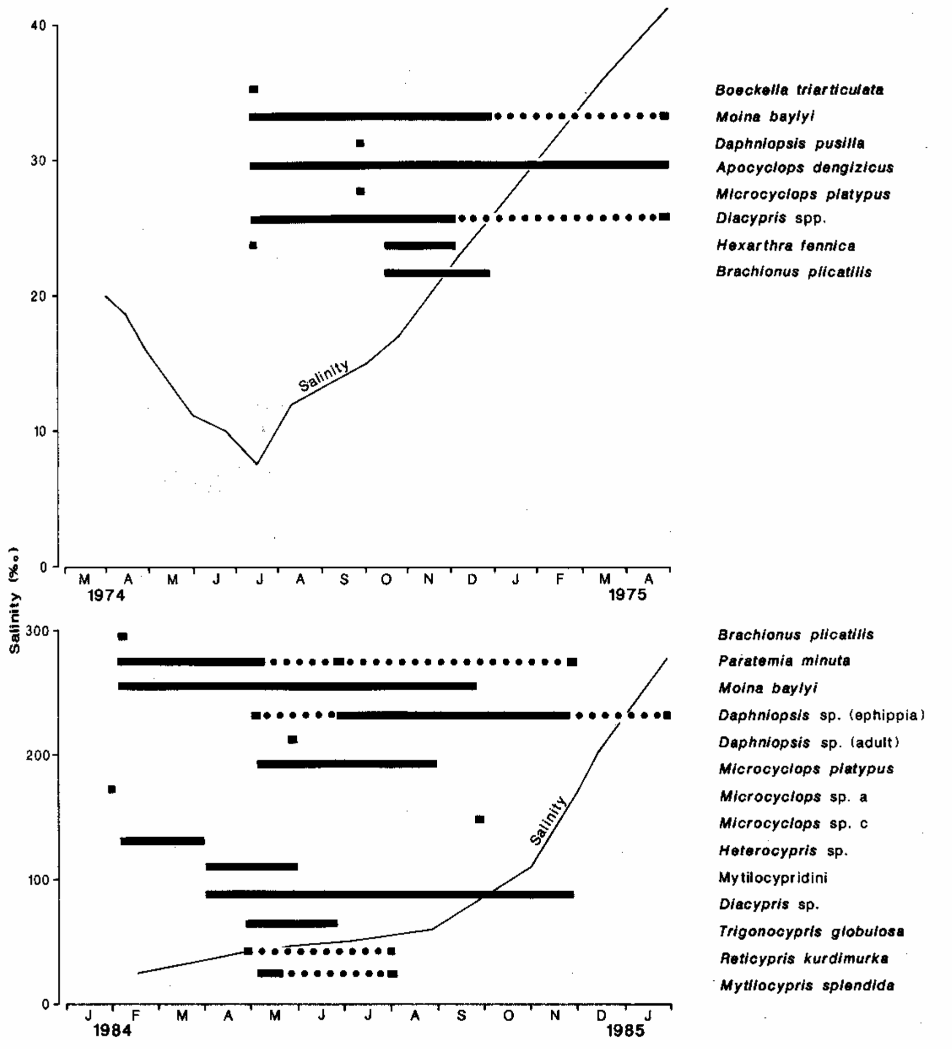

Fig. 5. Patterns of zooplankton species occurrences in Lake Eyre North and Lake Eyre South. Diagrams adapted from Bayly (1976) and Williams & Kokkinn (1988). Note that salinity values indicated for Lake Eyre North are composite values derived from samples obtained from both lakes.

insects: larval *Tanytarsus barbitarsis* Freeman (chironomids), adult *Berosus munitipennis* Blackburn (beetles), larval *Berosus* sp. (probably *B. munitipennis*), and ephydrid larvae (brine flies) (Ruello 1976; Williams & Kokkinn 1988). Additionally, *Austrochiltonia australis* (Sayee) (an amphipod crustacean) occasionally occurs; a single individual was found at a salinity of 51 g 1-1 in Lake Eyre South on 5 May 1984.

The composition of the benthic fauna also contrasts strongly with that of ephemeral salt lakes in southern parts of Australia. There, *Haloniscus searlei* Chilton (an oniscoid isopod) and *Coxiella* (a gastropod), in particular, are common, and *Tanytarsus barbitarsis* is not. The differences are neither surprising, nor difficult to explain. Although *Haloniscus* and *Coxiella* can survive dry conditions for a while, their resistance.

to desiccation is limited and they could not survive for as long as the periods for which Lake Eyre is dry. Moreover, they are passively dispersed. In contrast, *Tanytarsus barbitarsis* has an active winged adult form, and so can disperse easily and widely, but it cannot survive when water persists for less than a full year. It is common in southern Australian lakes which are more or less permanent. [The amphipod is clearly a stray and was probably washed in from a nearby creek; it belongs to a genus of halotolerant forms which appear to be easily dispersed and are widely distributed throughout southern Australia.] Note that *Coxiella* (as *Coxiellada gilesi* (Angas)) is often recorded from Lake Eyre in the malacological literature (e.g. Macpherson 1957), but such records refer not to collections of living specimens but to fossil collections (e.g. Ludbrook 1956). Nevertheless, although *Coxiella* has not been reported with certainty as living in Lake Eyre, there is an unpublished record of live *C. gilesi* from the Margaret River near Lake Eyre South in semi-permanent pools (W. Ponder pers. comm.). A similar situation may prevail for the Foraminifera. There are no definite records of live specimens from Lake Eyre, though several fossil forms have been recorded (Ludbrook 1953; see also Cann & De Deckker 1981). Perhaps foraminiferans, too, will be discovered in nearby semi-permanent waters.

Fish

Some 25 species of fish have been recorded from the Lake Eyre drainage basin (Glover & Sim 1978a, b; Pollard et al. 1981), but only two from Lake Eyre in large numbers, and just three more rarely. Bonython (1955f) recorded the presence of *Nematalosa erebi* (Gunther) [as *Fluvialosa richardsoni* (Castelnau)], Ruello (1976) that of *N. erebi*, *Craterocephalus eyresii* (Steindachner), and, in very small numbers, *Macquaria ambigua* (Richardson) [as *Plectroplites ambiguus* (Richardson)], Williams & Kokkinn (1988) *C. eyresii*, and Glover (1989) *N. erebi*, *Retropinna semoni* (Weber), *C. eyresii*, *M. ambigua*, and *Leiopotherapon unicolor* (Gunther). Given the high salinities of Lake Eyre, its depauperate fish fauna is scarcely surprising: all of the species involved are more typical of freshwater localities, for there are no species of inland fish in Australia confined to saline lakes (as, for example, there are in Africa).

All species are broadly distributed throughout central Australia and have wide physiological tolerances. Thus, *N. erebi*, the bony bream or hairback herring, has an extensive range on the Australian mainland and can tolerate temperatures of 9-38°C and salinities of < 1 to ca. 35 g 1^{-1}. It has a catholic diet which includes plant material and detritus. Initial populations of the species would have arrived in floodwaters, but no doubt its unspecialized diet, the high fecundity of females, and its pelagic (floating) eggs would have brought about the subsequent development of large populations and their wide distribution in the lake. Ruella (1976) estimated that at least 2,000 tonne of the fish were present in the lake before the mass mortality he noted.

Similarly, *C. eyresii*, the Lake Eyre or Central Australian hardyhead, is widely distributed throughout central Australia and can tolerate temperatures between 10 and 37°C and salinities as high as 110 g 1^{-1}! (Merrick & Schmida 1984) It is said to be omnivorous. Little is known about its life-cycle, but ovaries contain in excess of 1,000 oocytes so that under favourable circumstances rapid reproduction is likely. Ruello (1976) estimated that 80 tonne of this species was present in the lake before mass mortality occurred. According to Merrick & Schmida (1984), this mortality occurred when salinity in the lake was 28 g 1^{-1}.

M. ambigua, the yellowbelly or golden perch, likewise, is widely distributed in central Australia and can tolerate temperatures from 4 to 37°C and salinities up to 37 g 1^{-1} (Merrick 1976; Llewellyn & MacDonald 1980). Like the other species, fecundity is high, but unlike these species, *M. ambigua* is a carnivore. Its diet no doubt included them.

Finally, both *R. semoni*, the Australian smelt, and *L. unicolor*, the spangled grunter, have wide geographical distributions, considerable physiological tolerance, and are carnivorous (Merrick & Schmida 1984).

Birds

The list of birds associated with Lake Eyre is long, but there are few species whose presence is directly related to the occurrence of water in the lake (and food organisms therein) (Table 5). Unfortunately, perhaps, they do not include the flamingo, the best-known bird associated with salt lakes worldwide; although flamingoes were once present in the area they are now extinct in Australia.

All species of Table 5 have extensive Australian ranges and include all species frequently observed at ephemeral salt lakes in southern Australia. Presumably, however, most of the species listed occurred at the lake before rising salinities killed the fish on which many fed. In highly saline ephemeral salt lakes in southern Australia, the commonest species recorded is the banded stilt; at Lake Eyre the commonest species recorded during the floods beginning 1974 and 1984 seem to have been pelicans, silver gulls,

Table 5. WATERBIRDS OBSERVED AT LAKE EYRE. Derived mainly form Ruello (1976) & Serventy (1985)

Common name	Scientific name
Hoary-headed grebe	*Poliocephalus poliocephalus* (Jardine & Selby)
Australian pelican	*Pelecanus conspicillatus* Temminck
Great cormorant	*Phalacrocorax carbo* (Linnaeus)
Pied cormorant	*P. varius* (Gmelin)
Black swan	*Cygnus atratus* (Latham)
Pink-eared duck	*Malacorhynchus membranaceus* (Latham)
Red-capped dotterel	*Charadrius ruficapillus* Temminck
Black-winged stilt	*Himantopus himantopus* (Linnaeus)
Banded stilt	*Cladorhynchus leucocephalus* (Vieillot)
Red-necked avocet	*Recurvirostra novaehollandiae* Vieillot
Silver gull	*Larus novaehollandiae* Stephens
Whiskered tern	*Chlidonias hybrida* (Pallas)
Gull-billed tern	*Gelochelidon nilotica* (Gmelin)
Caspian tern	*Hydroprogne caspia* (Pallas)

great cormorants and whiskered terns, waterbirds more typically associated with freshwater lakes.

Discussion

The preceding account has addressed broadly the question of *what* biota is present when Lake Eyre contains water. The most obvious questions which follow are: how can this aquatic biota survive in such a locality, with variable and high salinities, long periods of aridity between aquatic phases, and great isolation; and, what processes operate within and between the various communities of this unusual ecosystem?

The first thing to note with regard to the tolerance of the biota to the variable and high salinities is that such conditions are far from unique, and a suite of adaptations to them has evolved in many groups of animals and plants found in saline lakes. Many of these adaptations can be expected to be part of survival strategies in the Lake Eyre biota. It is unlikely that any unique ones occur. The two basic adaptations involved are osmoconformity (internal cell pressures approximate outer salinities), found in all 'plants' and some animals, and osmoregulation (physiological mechanisms moderate internal pressures), found in certain animals. Thus, the Halobacteria are osmoconformers which maintain internal cell pressures by accumulating large amounts of inorganic ions, especially potassium. Probably both inorganic and organic sustances are used to maintain cell pressures in the Cyanobacteria, but *Dunaliella* uses glycerol alone. Amongst the animals, *Parartemia* is probably an osmoregulator, and Moina an osmoconformer.

Again, a suite of adaptations to desiccation has evolved amongst the biota of ephemeral saline lakes. They include resistant spores, seeds or vegetative parts, in the case of plants, and resistant adults, larvae or eggs for animals. It is conceivable but unlikely that some of these resistant stages can survive in the damp muds of Lake Eyre for the entire period between floods. More plausible is the likelihood that resistant stages developed in other localities not so infrequently flooded are dispersed into Lake Eyre when water occurs in this lake. This hypothesis is supported by Williams & Kokkinn (1988) who found that for the most part the fauna of Lake Eyre consisted of widespread species. Such an explanation also indicates how an environment so isolated as Lake Eyre can be quickly populated. The suggestion of Bayly (1976), referring to *M. baylyi*, that vast numbers of resistant eggs may be dormant on the bed of Lake Eyre for very long periods, and the isolation of Lake Eyre prevents the spread of *M. baylyi* southwards, is not supported.

Finally, what can be said about ecological processes within the lake? Here, speculation must prevail, but probably of a sort not too far removed from reality, given the apparent simplicity of the ecosystem.

The top of the food chain is occupied by fish eating birds which, from all accounts, are chiefly pelicans, silver gulls, great cormorants and whiskered terns. Some of these are known to eat aquatic insects so would also feed on *T. barbitarsis*. Of the major fish present, one, *M. ambigua*, is a carnivore, whereas the other two, *N. erebi* and *C. eyresii*, feed on invertebrates and organic detritus. The zooplankton community, of which *M. baylyi* and *Diacypris* spp. are significant elements, presumably feeds largely on the phytoplankton, but at least some of its members may also ingest bottom detritus. Fig. 6 provides a visual framework for these speculations

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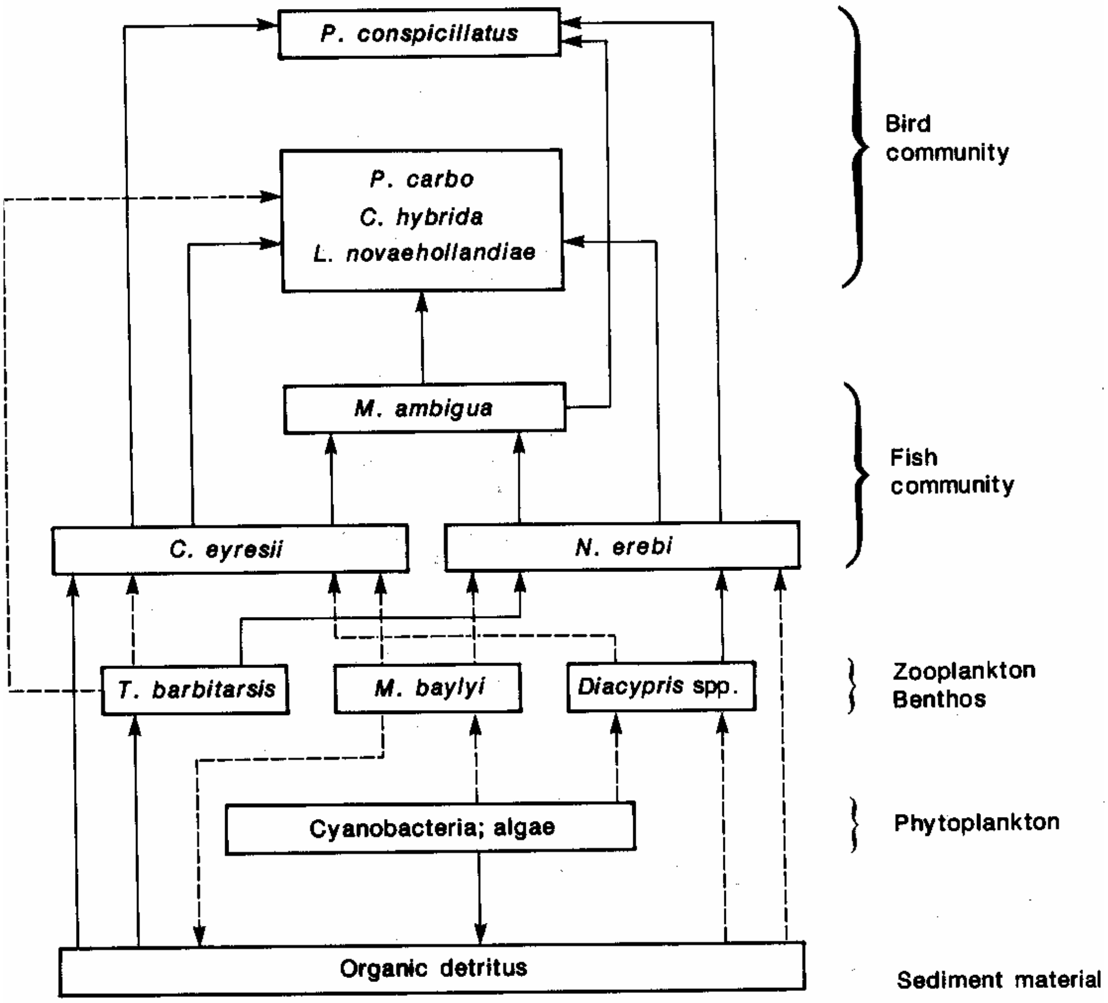

Fig. 6. Suggested food web in Lake Eyre before death of fish. Dotted lines indicate pathways more speculative than unbroken lines.

It should be added that even if the sort of trophic relationships conceptualized in Fig. 6 are valid, they apply to only that period when fish, in particular, have not exceeded their environmental tolerances (particularly for salinity). As the lake becomes more saline and the fish community disappears, trophic relationships must inevitably simplify.

EPILOGUE

It will be abundantly clear that a great deal remains to be discovered concerning the limnology of Lake Eyre, and especially with regard to biological features. Perhaps if this chapter does no more than underscore the paucity of our knowledge, and more clearly outline the sort of questions to be addressed whenever the lake fills, then some useful purpose will have been served.

In the interim arid phases, limnologists can only echo Robert Burns: 'The desert were a paradise, If thou wert there, if thou wert there.'

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8: Lake Eyre

by J. A. DELAHUNTY

INTRODUCTION

The late Pleistocene saw the retreat of ice sheets and glaciers, and this, combined with the northerly drift of the Australian Plate, resulted in what had been a pluvial central Australia becoming arid and semiarid. Ephemeral Lake Eyre evolved from Lake Dieri which was a permanently filled and essentially freshwater ancestor (David & Browne 1950; Loftier & Sullivan 1979; Dulhunty 1983a). Gregory (1906 p. 151), one of the first geologists to study Lake Eyre, commenting on the evolution of the deserts in which the great salt lake is set, wrote: 'less and less rain fell upon its shores; the vegetation withered; the once green, succulent herbage was replaced by dry, spiny plants; the giant marsupials died of hunger and thirst; hot winds swept across the dusty plains, and the once fertile basin of Lake Eyre was blasted into Desert'.

Lake Eyre, the world's fifth largest terminal lake, is the geodetic sump of the largest internal drainage system in the world, covering approximately 1 300000 km^2, or almost 1/6th of the Australian continent (see Chap. 6, Fig. 1). The lake is situated in the most arid part of the country, with a mean annual rainfall of less than 125 mm, and an annual evaporation rate of about 2.5 m (Bonython 1955). Summer shade temperatures reach 50-55°C, and a reading of 61°C has been reported (Price 1955).

Lake Eyre covers 9330 km^2. It consists of two parts: Lake Eyre North with an area of 8030 km^2 and Lake Eyre South covering 1300 km^2. They are linked by the Goyder Channel, 13 km long and 1.2 km wide, through which water flows freely when waterlevel in either part of the lake exceeds the highest point in the channel (Bonython 1955; Allan *et al.* 1986; Dulhunty 1978).

In the early nineteenth century little was known about central Australia, but rivers running inland suggested a large lake or inland sea of some kind. Explorers who searched for it found only deserts. In 1840 Edward John Eyre became the first European to see the shore of Lake Eyre South, though he believed it was part of Lake Torrens. John McDouall Stuart sighted Lake Eyre North in 1859. Other explorers joined the search but no inland sea was found.

Geological observations in the adjacent areas began in 1881, but the lake itself remained virtually unknown until Madigan flew over it in 1929 (Madigan 1936). The Cenozoic history of the Lake Eyre Basin was studied in the sixties (Stirton *et al.* 1961; Wopfner & Twidale 1967), and the region is now a central research interest for many Australian and overseas palaeontologists, biologists and geologists.

ORIGIN AND TOPOGRAPHY

Lake Eyre is coincident with the lowest part of the Australian continent. This is due to regional downwarping and to subsidence along faults. The evidence for downfaulting at the western margin of Lake Eyre North has been documented elsewhere (Wopfner & Twidale 1967) and need only be summarised here. The western margin of the lake, though crenulate in detail is regionally linear. Mound springs in the vicinity are distributed in linear zones. The region is one of modern seismicity. The stratigraphic section exposed in the gypcrete-capped cliffs is intersected also beneath the adjacent lake bed. Thus the Lake Eyre salina is certainly related to faulting, but whether it occupies a fault-angle depression or a downfaulted block is not yet clear. Deflation has played only a minor role in its development.

The bed of Lake Eyre lies below sea level. The lake bed falls in altitude some 4 m in 120 km from the northern shoreline to the southern bays. The lowest areas are located near the southern shores of Lake Eyre North, Madigan Gulf and Jackboot and Belt bays (Fig. 1). There the final evaporation of brine takes place and the thickest salt crusts are formed.

The lowest point in the lowest region in Australia has been sought on both dry saltcrusted and watercovered bottoms of the three bays. It is possible, or even probable, however, that buckling of otherwise rigid salt crusts (Dulhunty 1987) by horizontal compressional forces may have caused warping of the Holocene sediments.

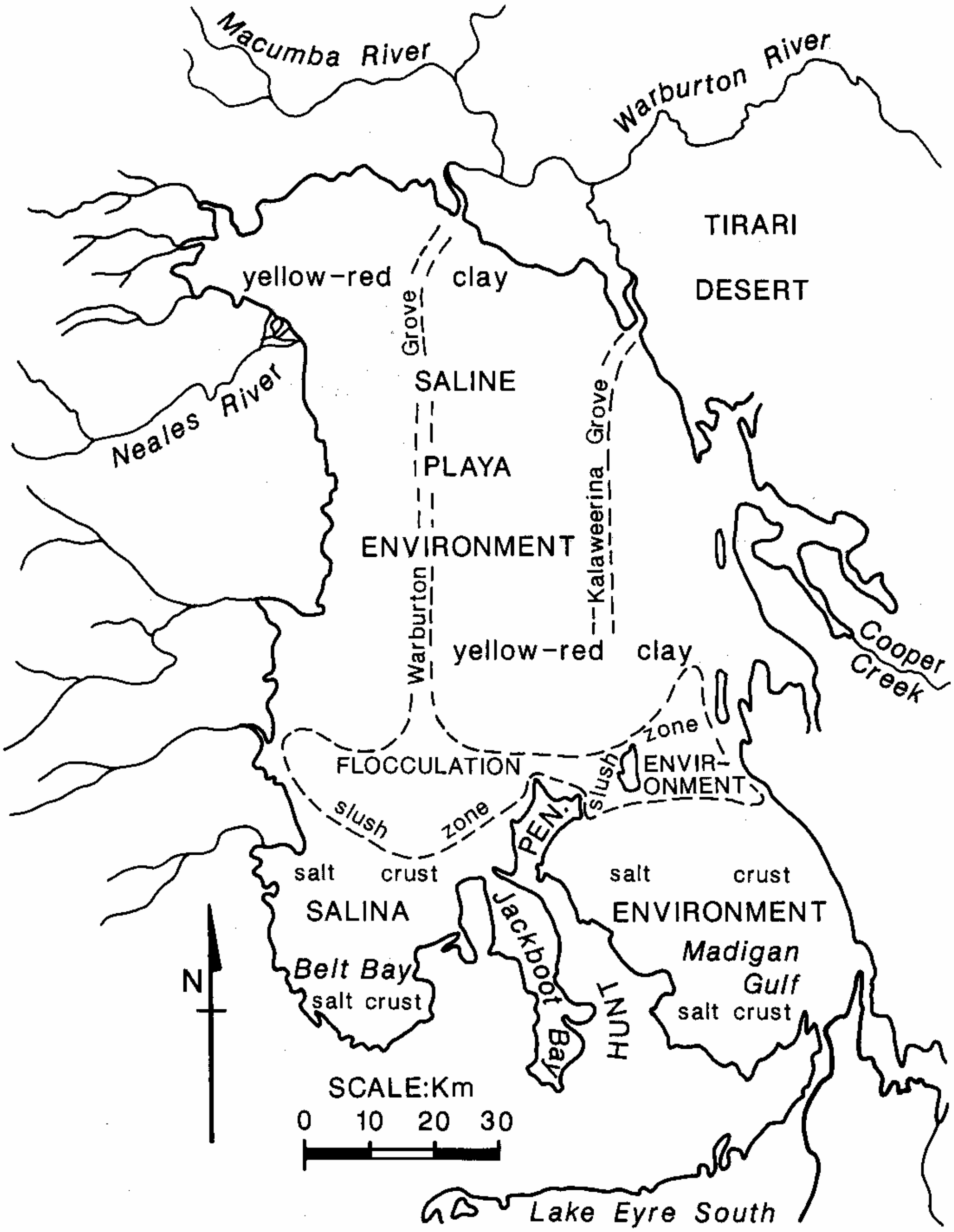

Fig. 1. Holocene sedimentary environments of Lake Eyre North.

It may be appropriate to suggest that the lowest point on the Australian continent occurs somewhere in the southern bays of Lake Eyre North, that it may change location in time, and that the nearest approximation to the level value of this surface may be the mean of lowest values found at different times by both bathymetric and drylake levelling in the lowest areas of the three bays: 14.8 m below sealevel (Australian Height Datum).

Two long, straight, narrow, parallel-sided grooves extend from south to north across the northern half of the bed of Lake Eyre North, and are in general alignment with the eastern and western shores. The groove nearest the western shore, the Warburton Groove, is 85 km long, 4.6 km wide and 54 cm deep (Dulhunty 1977a). That nearest the eastern shore, the Kalaweerina Groove, is 40 km long, 2.7 km wide and 13 cm deep.

As a result of slight tilting of the lake bed to the south, the flood-waters of infrequent major fillings flow south along the grooves until they are submerged when the lake is filled. More frequently water associated with minor floodings flows along the grooves. Consequently they could normally be expected to have become meandering water courses, owing to the very low gradient over which they pass, and the unconsolidated nature of the silt in which they have developed. Absence of meandering and their near linear nature, strongly suggest very recent or contemporary origin and control by some tectonic factor, such as faulting associated with rifting along the western side of the lake (Wopfner & Twidale 1967).

Two additional depressions running south from the Neales Estuary along the western shore, and south from the Cooper Estuary along the eastern shore, were indicated by soundings in 1974-75 (Bye *ef a/.* 1978). They are called the Neales and Cooper depressions. They have been attributed to scouring by water flowing south along the shores, rather than being grooves of tectonic significance (Dulhunty 1977a) , possibly taking advantage of cliff-foot weathered zones associated with groundwater seepage.

SHORELINE SHINGLE TERRACES

When Lake Eyre contains water, its shores are actively eroded by wave action, producing well defined shorelines with shelving strands or low cliffs rising abruptly from its almost flat bed. At places such as Babbage and Hunt peninsulas and in Belt Bay, shores are eroded in lithified materials such as dolomite, silcrete and ferruginous siltstones (Williams 1975). This has produced shingle which is washed across the strand by wave action to form terraces running parallel to the shoreline at a level a little above maximum mean lakelevel of the filling.

The filling of the lake in 1974 produced the highest level known since European settlement. A study was made of shingle terrace development in relation to lakelevel and wave action (Dulhunty 1975). Shingle was moved up the strand as the lake filled to form terraces during the period of maximum mean lakelevel. These materials and forms were abandoned when water level fell. Old partly eroded terraces formed during prehistoric fillings of the lake stand at levels of 280, 160 and 70 cm above that of the 1974 filling. Their significance is difficult to assess. They have been attributed to slightly higher lake levels in the recent past (Dulhunty 1975) but the sediments have not been dated and the role, if any, of recent tectonism has not been determined.

SALT CRUSTS

Salt crusts up to about 50 cm thick occur over lakebed sediments in the southern bays of the north lake. No salt crusts form on the northern higher half of Lake Eyre North. Water entering from estuaries along the northern shoreline flows south, dissolving any thin encrustation of salt which may have formed by evaporation of rising groundwater on the yellow-red clay surface since water last entered the lake.

The surface of the south lake stands 1-2 m higher than that of the southern bays in the north lake. Here salt crusts up to 20 cm thick occur after overflow from the north lake has carried salt in solution through the Goyder Channel, as it did in 1974 (Dulhunty 1978). Some salt may be returned by solution in north-moving groundwater, but mass return occurs when the south lake fills and overflows into the north lake, as in 1984 (Allan *et al. 1986).*

Estimates of the total amount of salt in Lake Eyre vary from about 400^6 to 700^6 tonnes (Bonython 1956). It appears to have been transported into the lake in solution in riverwater and shallow groundwater, and has accumulated since the lake became terminal in late Pleistocene time. The salt is very similar to sea salt but has a somewhat lower potassium content. The salt is connate, that is derived from the weathering of rocks exposed within the Lake Eyre catchment Wohns 1963; Bon~hon 195~.

Salt crusts rest upon sediments deposited during major fillings during which all previously precipitated crusts were largely dissolved. When flood-waters enter the lake, salt is dissolved until depth of water exceeds half the maximum wavelength of wind driven waves. Bottom water is then no longer disturbed and a saturated brine layer forms over any residual salt crust. This retards further solution until the depth of water is reduced by evaporation to less than half maximum wavelength, when the brine layer is disturbed and residual crust dissolved (Dulhunty 1977b).

When the lake fills, salt crusts are largely dissolved and fresh sediments are deposited upon those of previous fillings. As water dries up new salt crusts are formed over the newly-added sediments.

FLOODING AND FILLINGS

Surface waters occasionally find their way to the bed of Lake Eyre. The salina is also the sump into which shallow subsurface waters slowly migrate. The subsurface flows keep the lakebed sediments damp or wet up to the limit of the capillary fringe above the watertable.

Prior to the first recorded filling of the lake in 1949 (Bonython & Mason 1953), it was thought that no appreciable quantity of river water could enter the lake (Madigan 1936). From 1949 to 1960 records were kept by Bonython (1960); from 1972 to 1983 by the Dulhuntys (J. Dulhunty 1975; R. Dulhunty, 1984, 1986), and in 1984 by Allan *et al.* (1986). Such records over the last 35 years covered three major fillings, but there are numerous occasions when limited areas of shallow water, from minor flooding or local rain, blow about in the southern bays of the north lake. Surfacing groundwater also keeps the lakebed wet and boggy in many places between major fillings and minor floodings. It is now evident that some surface water, of widely varying extent, may occur on the lakebed for up to 75% of the time.

Most of the river waters that flow into Lake Eyre originate in the northern and northeastern parts of the catchment, within the summer monsoon zone with mean annual rainfalls of 370-500 mm. Floodwaters frequently flow south from the divide into semiarid low-lying Channel Country, where much is lost to evaporation. Any water which passes through the Channel Country enters the deserts around Lake Eyre where there are further evaporation losses, but small volumes may survive to enter the lake depression. Less frequently, when monsoon depressions move further south than usual, and particularly after two or more consecutive wet years, huge volumes of water flow through the Channel Country and deserts, producing major fillings over the whole of the lakebed to depths of 6.1 m as in 1974 (J. Dulhunty 1977b; R. Dulhunty 1984; Bye *et al.* 1978) and as much as 8.5 m in the prehistoric past (Dulhunty 1975).

ENVIRONMENT AND SEDIMENTATION

The southerly tilt of the Lake Eyre depression provides a gentle slope resulting in the development of three different environments of ephemeral lacustrine sedimentation within Lake Eyre North (Dulhunty 1982, 1986).

These are (Fig. 1):

1 In the north almost two-thirds of the bed is an arid saline playa environment occupied bj yellow-red saline clay at least 3 m deep, normally moist and reasonably firm to walk on, but without hard salt crust. It contains some silt, a little fine sand, and in places thin surface layers of black organic mud. It is periodically inundated but water drains to the south before completely evaporating.

2 Madigan Gulf, Jackboot and Belt Bays at the southern end of the north lake, together constitute the lowest places in the Lake Eyre internal drainage system and the final sump for both surface and underground waters. They form an arid terminal salina environment. Here, final evaporation of brines forms hard salt crusts over brine-soaked gypseous sediments (Johns 1963). Black organic muds (Baas-Becking & Kaplan 1956; Cane 1962) occur in layers between sediments and salt crusts. The sediments are Holocene deposits about 4 m thick, representing a mixture of introduced materials and indigenous evaporites, accumulated under conditions of a true arid terminal salina.

3 The northern playa area and the southern salina are separated by a narrow east-west 'slush-zone', some 10 to 15 km wide, extending 80 km across the full width of the lake. This could be described as an arid saline flocculation environment where salt crusts are either very thin or absent. The sediments consist of extremely fine clay and organic mud of the consistency of grease. They are impossible to walk on or traverse even with the lightest of wheeled vehicles. They appear to have accumulated largely as a result of flocculation and deposition of suspended clay and colloidal organic matter, where muddy freshwater meets water made saline by solution of salt crusts in the salina environment to the south.

CONTEMPORARY SEDIMENTATION

During the 1974 filling of Lake Eyre North, as described by J. Dulhunty (1982, 1986) and R. Dulhunty (1984), floodwaters carried large quantities of sand, silt and clay down the Neales, Macumba and Warburton rivers and Cooper Creek. Fine sand was deposited in their wide shallow channels with low gradients in the Simpson and Tirari deserts. Limited quantities of even finer sand were carried into the lake to form low-profile deltas close to river estuaries. Following the filling, sand in the lake deltas and river channels dried and blew out into shoreline lunettes and longitudinal sand ridges.

Floodwater carrying silt and clay spread out over the northern playa area of the north lake depositing progressively finer fractions of silt and clay, until they reached a slush zone. Here, the still muddy-coloured floodwater met the highly saline water in the southern salina. This flocculated suspended clay and colloidal organic matter which settled rapidly, clearing the muddy water. From the air, yellow-coloured water could be seen to the north of the slush zone and clear blue water to the south.

The floodwater, having deposited most of its introduced sediments, moved on over the salt crusts in the southern salina. Here, early in the filling, turbulent shallow water quickly dissolved salt and attained a salinity of over 40 g/l. When water depth (4 m) exceeded half the maximum wavelength of 8 m, bottom water ceased to be disturbed and a thin layer of 5-15 cm of brine formed over the residual salt, protecting it from further solution. Continued flow of freshwater from the north then diluted surface water, reducing its salinity to 10 *gll* or less, depending on depth of filling. This developed salinity layering, ranging from saturated brine on the bottom to low salinity, or almost freshwater on top (Dulhunty 1977b).

The last of the introduced organic matter which escaped flocculation over the slush zone, together with appreciable quantities of indigenous organic debris, settled into the bottom brine on top of the residual salt crust. Addition of organic matter continued, and precipitation of colloidal gypsum occurred, which under attack by sulphur reducing bacteria, yielded hydrogen sulphide and precipitated iron sulphide. As a result the brine layer gradually became a black, colloidal, gypseous and evil-smelling fluid. After drying and colloidal compaction, this is believed to become the black muds of Lake Eyre (Dulhunty 1974) and other Australian lakes (Cane 1962).

Two years after the 1974 filling, water depth fell to less than half maximum surface wavelength, and the bottom brine layer was disturbed and diluted by mixing with overlying lower-salinity water. The remaining salt crust then went into solution, allowing the immature black mud to settle on to the surface of pre-existing salina sediments, to await final evaporation of brines and capping with a new salt crust, and so become part of the Holocene sedimentary record

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9: Mound Springs

by W. E. BOYD

INTRODUCTION

Mound Springs are small but important sources of permanent water extending along an arc through north east South Australia (Fig. 1). The mound springs occur along the southern and southwestern margins of the Great Artesian Basin and represent, at a very small scale, the flow of water through the world's largest subterranean water basin. They are veritable 'oases in the desert' (Harris 1980-81), being foci for plant, animal and human life in an otherwise harsh environment. The springs are not merely physical features, however, also having biological and cultural importance. For features which every interested observer comments that too little is known, there is already much known. This account attempts to collate that knowledge and integrate it into a natural history of one of the arid zone's most remarkable features.

Early European explorers appreciated the importance of the mound springs, using them as camp sites and discussing their potential role in the opening up of this country for future European occupation. John McDouall Stuart, for example, discovered, named and described many mound springs during his survey of potential pastoral runs in 1859 (Williams 1979; Harris 1980-81). Recognising the importance of these water sources, and subsequently using them to support his transcontinental crossing in 1861-2, Stuart described his impressions of the many springs that he visited. Warburton described and named many springs during his 1858 expedition, and his observations extended to remarkably perceptive speculation about the processes of formation of these natural features. Warburton's explorations were continued by Babbage who discovered yet more springs (Cobb 1975). During W. G. Goyder's triangulation survey of the 1860s more springs were discovered, although the most impressive group of springs, those at Dalhousie, were not discovered until 1870 when an Overland Telegraph survey team came across them. Symon (1984) recounts the discovery by surveyor R. R. Knuckey, who originally named the springs after a colleague, but eventually changed the name, and followed a long tradition by using the family name of one of the survey team's benefactors, Lady Edith Ferguson, daughter of the Marquis of Dalhousie.

ABORIGINAL OCCUPATION

The springs were important foci for aboriginal activity, as indeed they were for a short time after the first Europeans arrived. Evidence comes from abundant archaeological remains scattered around many of the springs, and from the mythology of the tribes occupying this region. Harris (1980-81) and Lampert (1989, based on unpublished reports by Potezney 1978; Lampert 1985; Hughes & Lampert 1985) described the rich scatters of prehistoric debris around springs throughout this region. Of eight springs examined north of William Creek, for example, only one failed to provide evidence of large camp sites, and at Dalhousie Springs one major site extends for nearly three kilometres. The material evidence collected at these sites consists of stone tools such as tulas, pirris, microliths and seed grinders, and appears largely to originate from later Holocene sediments, a dating which is generally supported by artifact typology. At Welcome Springs and at one site in the Dalhousie Springs area, however, occupation may be of early Holocene age.

The traditional people of this region belonged to the Guyani (or Kujani), Arabana, Aranda and Wongkanguru (Tindale 1974; Harris 1980-81; Krieg 1985). Although little is known of these people, since they had largely been detribalised and scallered by the time interested scientists such as Baldwin Spencer worked in the area (Harris 1985), the myths that have been recorded emphasise the importance of the springs as primary Dreamtime sites. Hercus (1980), describes the role of the springs in aboriginal histories, where they represent such things as ancestral snakes, graves, campsites and heaps of native onion peelings. Hercus also describes the ways in which aboriginal myths explain these natural phenomena; the movements of water in the Bubbler, for example, are the convulsions of the ganmari snake, killed there by the Guyani ancestor.

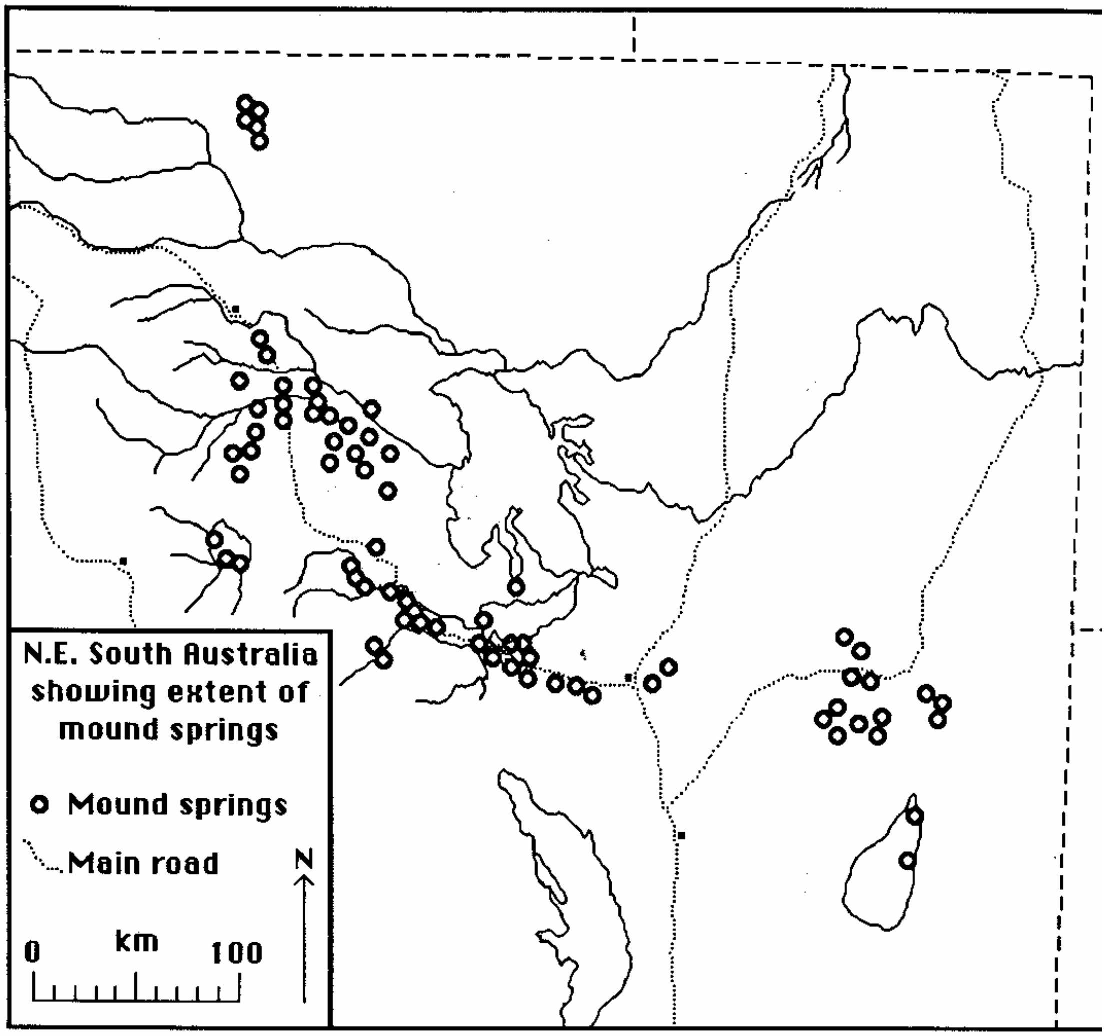
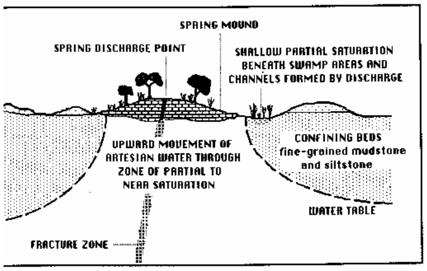


Fig. 1. Extent and location of the Great Artesian Basin mound springs and groups of mound springs in Sou
Australia (after Casperson 1979, Fig. 2).

SEDIMENTS

The springs are associated with mounds, or accumulations of sediments (Fig 2). Varying in shape and size from being almost imperceptible to distinct morphological features (Boucaut et. al 1986; Cobb 1975; Draper & Jensen 1976; Forbes 1958; Symon 1985a). The mounds are up to 8 m high and may be the tens of metres across, circular or oval in plpan and low in profile. The two large mounds at Fred Springs, for example, measure 130 x 30 m and 60 x 30 m in plane and are 8 m and 4 m high respectively \. Others are smaller, such as those at Lake Frome, the largest of which is described by Peake-Jones (1952) as 8-10 ft high (2.5-3m) and approximately 100 paces in circumference (approx 25 m diameter).

The spring water emerges as seepages, as flowing springs at a point or into pools of standing water. Some mounds have several spring outflows, usually due to one spring head becoming blocked by the accumulation of sediments and being replaced by seepages which may start to flow from the sides of the mounds. These seepages may then become the main foci for later flow or themselves become blocked up. Forbes (1958) describes mounds at Lake Frome with pools at the top and seepages on the sides, whereas at other springs, such as Gosse Springs, the only flow issuing from the mound is via small seepage areas. In many areas, the springs are evident only as damp patches in the soil or, as described by Boucaut *et al. (1986)* at Dalhousie Springs, as temporary mud heaps,



2. Section of the inferred structure of a typical active mound spring (after Casperson 1979, Fig. 3) (no scale implied).

drying up and being reworked over only a few years.

Depending on the rate of water flow and the morphology of the mounds, moderately large and impressive pools may form over the spring site, some feeding streams several kilometres long. Notable examples are the mounds of Blanche Cup, the larger springs at Dalhousie, and the famous 'bubbling' spring at The Bubbler.

Where the springs emanate from a mound, the latter is composed of one or more of several types of sedimentary material, of which there are three main sources: chemical precipitates derived from precipitation of dissolved solids in the spring water near the spring head; clastic material derived from the surrounding area and usually wind-blown and trapped in the vegetation around the spring; clastic material derived from the subsurface sediments and brought to the surface by the spring water. Organic detritus derived from the plants which grow on the mounds is less frequently a source of sediment. Precipitation from the spring waters forms the abundant carbonate mounds of tufa and limestone. At Lake Frome, for example, Draper & Jensen (1976) describe one set of mounds as largely formed from a tufa, composed of aragonite and calcite *(c.* 30% each) with lesser quantities of quartz and dolomite, and a more compact carbonaceous carbonate rock comprising primarily calcite and dolomite. Williams & Holmes (1978) estimate that a typical spring with a small discharge of 200 L/hr *(c.* 0.06 L/sec.) and a solute concentration of 4 g/L would deposit about 170 tonnes of calcium carbonate in 1,000 years, which would be enough to build a hemispherical mound 3 m high. The precipitation of these dissolved solids also accounts for some older spring-related sedimentary rocks. In the Billa Kalina area, for example, Ambrose & Flint (1981) record two stratigraphic units associated with former springs, one of which is a cream to pale brown limestone and limestone-cemented gravel. Similar relict sediments are recorded south of Lake Eyre (Jessup & Norris 1971) and in the Dalhousie area (Krieg 1985). Near Coward Springs Wopfner & Twidale (1967) interpret two dolomitic limestones as Pleistocene spring precipitates.

Most of the mounds are not composed entirely of precipitates, and layers of clay, silt and sand, frequently cemented with carbonate, are evident. The relative quantities of clastic to precipitated sediment depends on the relative rates of water flow, precipitation and the input and trapping of the clastic components. Draper & Jensen (1976) record a second set of mounds at Lake Frome which are largely clastic, the material considered to be largely aeolian in origin, having accumulated during a dry-lake phase in which, presumably, the supply of clastics outstripped the supply of precipitates. This clastic material may have been trapped, in this case, by moisture and algal growth, although the presence of vegetation on the mound would have helped. At Lake Frome, the clastic mounds have a carbonate capping which helps to preserve the mound. Where this capping is damaged, the mound quickly deflates. In many other spring mounds the clastics and precipitates are deposited together, resulting in a mixture of carbonate-cemented clastic mound sediments. Two sediment cores from Coward Springs (Ludbrook 1959) comprise a mixture of various limestones, quartz, clay and mud containing, in places, remains of Foraminifera, molluscs, ostracods and plants. The clay and mud probably represents sediment brought up from the underlying Cretaceous sediments by the spring water, since the Foraminifera are Aptian (Lower Cretaceous) in age. The spring mound sediments at Dalhousie and Lake Callabonna are, likewise, considered to be partly derived from the underlying Cretaceous sediments, although in both of these examples, fossil evidence of the type shown at Coward Springs is not available, and interpretation is based on sediment lithology (Stirling 1900; Firman 1971; Krieg 1985).

In addition to the sediments discussed above, plant detritus layers are recorded at several mounds. Symon (1985a) mentions the presence of dried-out peaty mounds at Peake Ruins Springs, also noting that at Twelve Mile Spring peat may have been burnt. At Gosse Spring the mound contains interlayered peat and sand beds (A. Johnstone pers. comm.). At other springs peat is not present, but the plants formerly growing around the spring are preserved as components of the mound sediments in the form of carbonate casts (Williams & Holmes 1978).

Two other biologically-derived organic sediments are also associated with the mound springs. The first occurs in only a few spring outflow channels where plant-derived material is accumulated. Of note in this respect are the large springs at Dalhousie, the largest of which has a 7 km long outflow tail forming a swamp in which peat up to 1 m thick has been deposited (Boyd 1990). The second plant-derived sediment is very different and is described by Callen (1981) at Lake Frome, where pre-Holocene sediments of uncertain age (Late Miocene/Early Pleistocene) are interpreted as being algal mound spring limestones.

GREAT ARTESIAN BASIN AND NATURE OF THE SPRING WATERS

The importance of the precipitation of dissolved solids in the formation of the spring mounds has been referred to above. To explain the presence of these dissolved solids and the variation in the precipitates formed, it is necessary to consider the spring water sources. The springs represent the final stages of water movement through the world's largest subterranean water basin, the Great Artesian Basin (Fig. 3). The basin consists of a system of interbedded aquifers, or watercontaining beds, and aquitards, or water-confining beds. The former mainly comprise continental sandstones, and the latter siltstones and mudstones. Overlying the entire sequence is a thick marine sequence deposited during the Cretaceous which acts as a confining aquitard (Habermehl 1980). Habermehl provides detailed descriptions of the hydrogeology and hydrochemistry of the Great Artesian Basin (1980, 1982, 1986a, 1986c), following the earlier work of Jack (1923), Ker (1963), Ward (1950-51) and Forbes (1958), and building on the catalogues of hydrochemical data collected in the systematic surveys of Williams (1974, 1979), Cobb (1975), Draper & Jensen (1976), Kinhill Stearns (1984), Mitchell (1985) and Boucaut *et al.* (1986). From these sources, the major characteristics of the spring hydrology may be identified.

The major directions of water movement through the basin may be identified from consideration of water pressures across the basin (Jack 1923; Ward 1950-51; Habermehl 1980). From this, and from water chemistry variation, two sources for the artesian water are apparent. The major is in the uplands at the eastern margin of the basin in Queensland, and a second, considerably less significant source, at least in terms of quantity, is along the western margin in the uplands west of the Simpson Desert and Lake Eyre. The importance of these two sources is that, although water quality appears to be moderately uniform across most of the basin, at the margins, especially to the south and southwest, it becomes notably variable, water becoming, amongst other things, increasingly saline (Habermehl 1986c; Shepherd undated). Consequently water quality in the South Australian mound springs varies, falling into two major water types. Those waters from the eastern source tend to be carbonated and relatively rich in sodium and fluorine, whereas those of western origin are sulphated, thus being corrosive and hard, and relatively poor in sodium and fluorine but richer in calcium (Jack 1923; Ward 1950-51; Forbes 1958; Ludbrook 1980). In the area south of Lake Eyre, for example, Kinhill Stearns (1984) recognises two major water chemistry gradients. The first is from the high carbonate/moderate chloride/low sulphate waters from the bores north of the Wagianna Springs complex to the low carbonate/high chloride/moderate sulphate waters further to the west in the area of the Francis Swamp Springs. This gradient is attributed to the regional mixing of waters from the two major source areas. Kinhill Stearns' second chemical gradient represents a second mixing effect, in this case resulting from the mixture of Great Artesian Basin water and groundwater which has passed through gypsum· rich rocks. The main pattern reflecting this mixing is the locally-increasing calcium and sulphate levels between the Wangianna and Francis Swamp springs, a pattern which apparently correlates well with the known distributions of gypseous deposits in this region as mapped by Jessup & Norris (1971). A similar effect is evident where ground water, artesian bore water and spring water are compared; in such cases, there is evidence that not all the water from the springs is artesian water. Some mixing and preferential

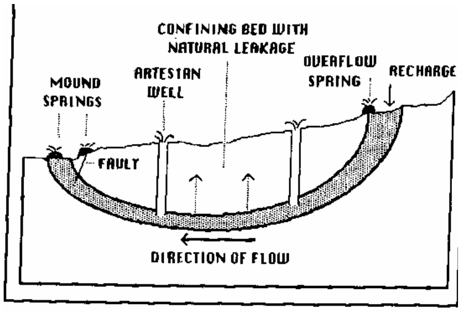


Fig. 3. Diagrammatic cross section of the Great Artesian Basin showing the eastern recharge area, flow through the aquifer, and springs related to the faulting and outcropping of the aquifer on the western margin of the basin (after Thomson & Barnett 1985, Fig. 3, and Ponder 1986 Fig. 3)

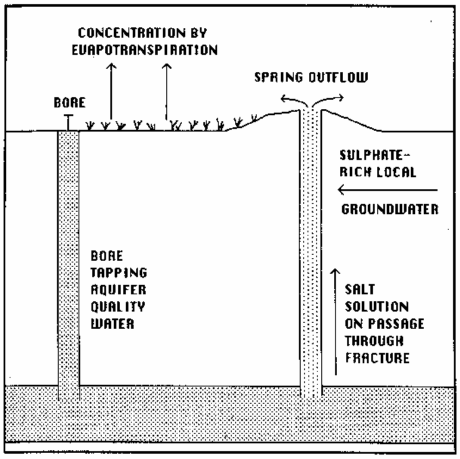


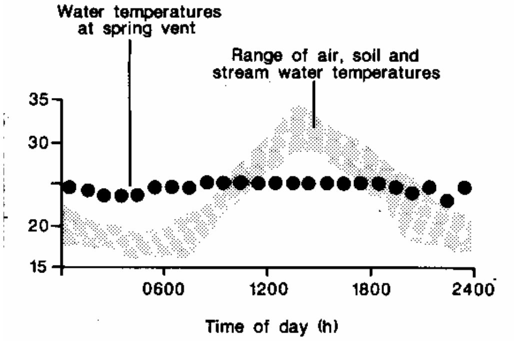
Fig. 4. Summary of the presumed major processes influencing the quality of mound spring water (after Kinhill Stearns 1984, Fig. 3.1).

evaporation appears to occur, although the full effects of these processes, for example at Emerald Springs and Warburton Springs, are not yet fully understood (Holmes *et al.* 1981; Kinhill Stearns 1984) (Fig. 4).

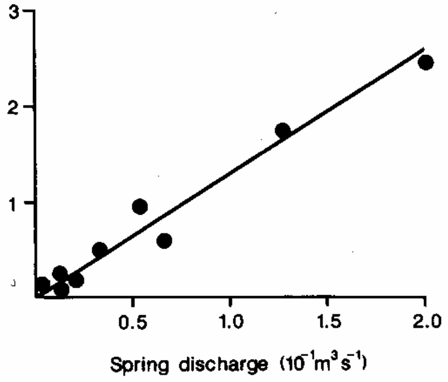
One of the distinctive characteristics of the mound springs is that the water flowing from them is warm, with temperatures mostly 20-35°C, but extremes of 14° and 46°C being recorded. At Dalhousie, water temperatures are 30° - 46°C, being generally lower in the southern springs of that group (Williams 1974). Boucaut *et al. (1986)* explain this phenomenon by the shallow, and in places exposed, aquifer beds being more susceptible to evaporation through the soil in this southern area and, possibly, also due to lower geothermal temperatures. Mitchell (1985) records that seepages tend to be warmer than spring pools and that within pools temperature remains relatively constant, except, at Blanche Cup, where temperature variations may be explained by the presence of a large standing crop of submerged macrophytes. Ponder (1986) records a similar constancy of water temperature at a spring in the Hermit Hill complex (Fig. 5).

WATER FLOW AND SPRING DISCHARGE

Several studies have investigated the rates and quantities of water flow from the springs, using such methods as fluorescent dyes, weir gauging, current meters, bucket measures, visual estimations and estimations based on area of outflow vegetation (Cobb 1975; Holmes 1975; Williams & Holmes 1978; Holmes *et al.* 1981; Kinhill Stearns 1984; Black & Woolard 1985) (Fig. 6). Flow rates are generally low, and vary from virtually nil to moderately strong. Holmes *et al.(1981),* for example, measured the flow from 15 springs recording a median discharge rate of 69 m^3/day, for a range of 1.7-337 m^3/day (approximately equivalent to 1, 0.02 and 3.9 L/sec. respectively). Some of the springs at Dalhousie have the largest discharge rates, the maximum being of the order of 14 ML/day (162 L/sec) although this is unusual, with most springs flowing at less than 10 L/sec., and a few at as much as 85 L/sec. (Habermehl 1982; Harris 1985).



ig. 5. Water, air and soil temperatures in different microhabitats in and around a mound spring in the Hermit Hill spring complex in 1984 (after Ponder 1986, Fig. 6), showing the range of soil, air and downstream water temperatures close to the spring, and the temperatures of the spring water as it emits from the spring vent.



ig. 6. This suggested relationship between the area of a spring-fed swamp and the discharge from that spring provides a possible technique to measure the water outflow rate from mound springs (after Williams & Holmes 1978, Fig. 5).

Annual fluctuation in spring discharge rates appears to be insignificant, although the flow of water away from the springs varies, probably reflecting seasonal changes in evaporation. Evaporation has an important effect on surface water availability and, at Dalhousie, Holmes (1975) suggests that the effects are such that winter spring discharge is able to support an area of vegetation some three and a half times that supported in the summer; Holmes calculates that evaporative loss at these springs may be of the order of 7 mm/day/ha, this being equivalent to a spring discharge of 0.81 L/sec. Holmes *et al.* (1981) suggested that significant evaporation must also occur from bare ground below which the water table is sufficiently shallow to supply water by upward capillary rise. They were able to plot the subsurface water table from two springs, identifying the roles of evaporation and seepage into the soil.

Williams & Holmes (1978) estimate that spring discharge accounts for about 20% of the discharge of the total input of the Great Artesian Basin, with the springs at Dalhousie accounting for about half of that discharge; within South Australia Dalhousie Springs may account for as much as 80-90% of the spring discharge (Williams 1974). The remaining 80% of the Great Artesian Basin discharge is probably by vertical leakage (Habermehl 1980, 1986a; Thompson & Barnett 1985) (Fig. 3). Various estimates of total water quantities involved have been made. Ludbrook (1980) quotes values of total discharge for the entire Great Artesian Basin being of the order of 30,000 ML/year (equivalent to *c.* 950 L/sec.): considerably less than the extracted (bore) quantities (approximately 77,000 MlLyear or 2,440 L/sec.). Habermehl (1980, 1986a), quotes a total value of 1,500 L/sec. for the natural discharge from the springs. Whatever the correct value, it appears that only a relatively small proportion of the total water entering the basin is either discharged through the springs or extracted. Furthermore, a significant proportion of this flowing water is extracted, and it must be assumed that at least some of this extracted bore water formerly flowed out at the springs. This raises the issue of what effect historical water extraction from the Great Artesian Basin has had on the natural spring flow.

HISTORICAL CHANGES IN DISCHARGE RATES

It is difficult to assess exactly what medium term (historical time scale) spring-flow fluctuation has occurred and what the effects have been. Once pastoral farming became established, the demand for artesian water increased, and consequently many bores were sunk, some 01 which have subsequently gone out of use but still flow. Much of the water from these has been used inefficiently, in particular flowing along open drains that allow substantial evaporative loss. There is little evidence to suggest that significant reduction of spring flow has occurred, although the absence of evidence is not proof. At Emerald Spring, flow measurements have been recorded for over a century, starting in 1858 when Babbage recorded 175,000 gal/day (equivalent to 9.3 L/sec.), and followed two years later, supposedly after a drought year, with Goyder recording 20,023 gal/day (1.1 L/sec.) (Threadgill 1922, reported by Cobb 1975); in 1923, the South Australian Mines Department recorded 50,000 gal/day (2.7 L/sec.) and the same value was recorded in 1961 by Ker (1963) and Cobb (1975). Cobb does not comment on the long tem trends implicit in these figures and Casperson (1979) casts doubt on the validity of the earliest records. Holmes *et al. (1981)* suggest that flow-rate changes between November 1977 and May 1978 represent a genuine decline in spring flow related to changes in the water pathways and the proportions of water escaping via the springs and by leakage. At Lake Frome, Draper & Jensen (1976) record an ob· served decline of around 25-30% of the flow during the last 30-40 years (Cailen 1974), but this appears to be a rather unusual situation where regional tilting, may have modified the artesian flow. Habermehl (1980, 1986a) takes a different approach using sophisticated computer ground· water models (Habermehl & Seidel 1979; Seidel 1980) suggesting that during the early part of the period from 1880 to 1970 spring discharge and vertical leakage (the natural discharges of the basin) decreased in response to the increase in artificial discharge. However, as a result of the consequential pressure decline and steepening' of the hydraulic gradient of the artesian flow, recharge of the aquifers increased by about 25% presumably compensating to some extent the decline in natural discharge. Habermehl concludes that the discharge is such a small proportion of the artesian reserves that further extraction will have little, and in general, only local, effects on outflow.

GEOMORPHOLOGICAL SETTING OF THE MOUND SPRINGS

Further evidence for major prehistoric changes in water pressures, gradients and flows occurs, at most groups of active springs, in the form of larger, higher-elevation, extinct mounds (Fig. 7). These occur throughout the region, usually in association with present springs, suggesting that although there have been changes in the

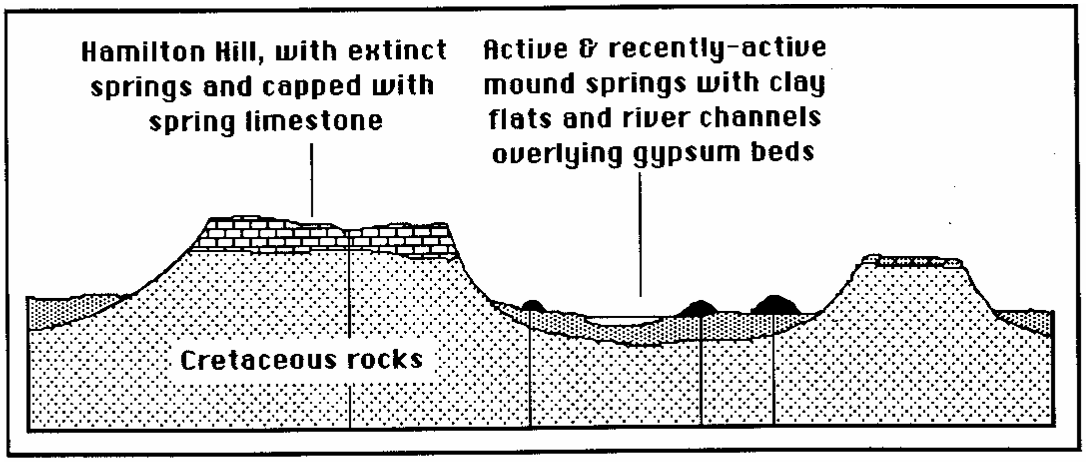


Fig. 7. Diagrammatic geological section of the mound springs of the Strangways area illustrating the topographic relationships between active and extinct mound springs (after Thomson & Barnett 1985, Fig. 8). Note that the top of Hamilton Hill lies approximately 28 m above the surface upon which the modern mound springs sit.

hydraulic behaviour of the artesian outflow, the locations of outflow have not changed substantially at the regional scale. In general the springs which are presently or recently active occur in topographic lows. The springs of Lake Eyre and Lake Frome, for example, occur on the lake floors of the saline flats themselves, the Warburton Springs occur in a clay pan depression, the springs at Dalhousie lie in the lowlands between the remnant mesas of a dissected plateau, and the large area of Francis Swamp contains many mound springs (PeakeJones 1952; Cobb 1975; White 1978; Ambrose & Flint 1981; Callen 1981; Boucaut *et al. 1986).* However, most of the mound springs are found in the floors of valleys or broad creek channels. In Cobb's (1975) account of the mound springs of the area covered by the Marree, Curdimurka and Billa Kalina geological map sheets, springs such as Davenport Springs, Bopeechie Spring, Beatrice Spring and Priscilla Spring occur in such locations. In this region and elsewhere, examples of a third important type of location is also found with, for example, the springs at Hermit Hill and the Peake Ruins occurring at the base of hills (Cobb 1975; Symon 1985b). These hills are often composed of basement rocks, and the significance of this geological association is discussed below. A consistent aspect of the topographic location of the active and recently active mound springs, is that they are topographically lower than both the apparently older and quite extinct mounds, and the various limestones and lime-cemented conglomerates considered to be associated with Pleistocene spring activity (Cobb 1975; Thompson & Barnett 1985; Habermehl 1986a, etc). This topographic separation between older and more recent spring deposits may be explained in terms of the lowering, by erosion, of the land surface, and the consequential lowering of the spring outlet levels.

GEOLOGICAL CONTROLS ON THE LOCATION OF MOUND SPRINGS

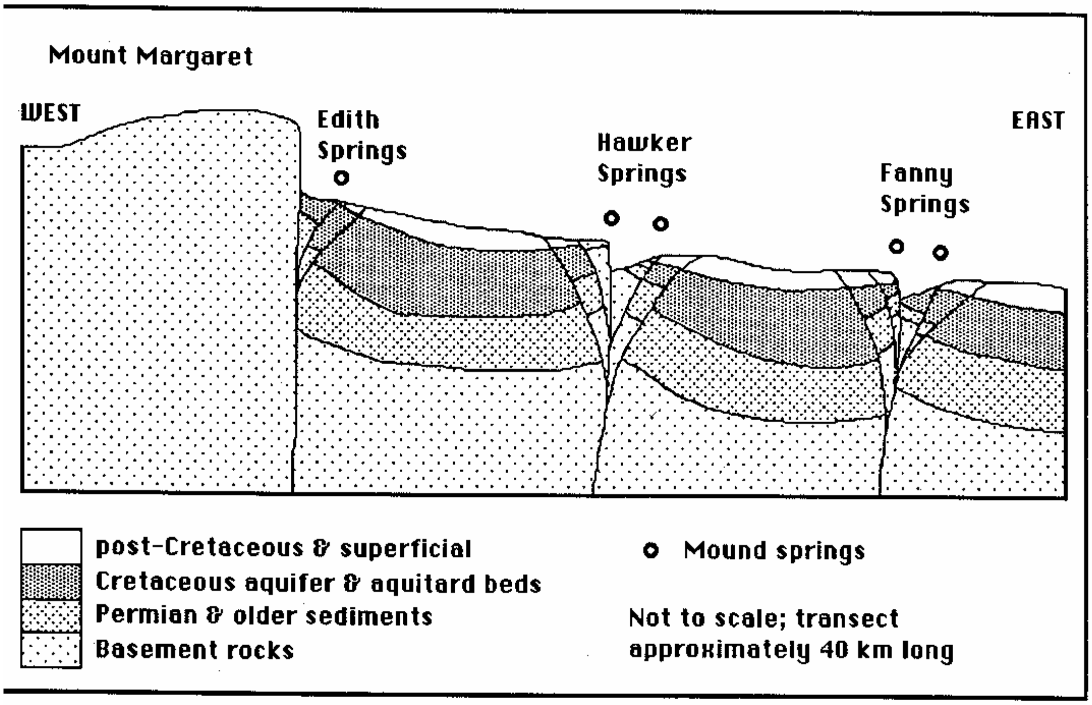
Drawing on observations by Ker (1963), Wopfner & Twidale (1967), Williams (1975), Williams & Holmes (1978), Ambrose & Flint (1981), Thompson & Barnett (1985), Boucaut *et al. (*1986*)* and Krieg (1986), as well as on new data, Aldam & Kuang (1988) reviewed the geological influences on spring location, recognising five major controls (Fig. 8). The first two are related to the erosion of the confining beds. The aquifer may be brought closer to the present land surface where subsurface basement highs occur, causing erosion of the confining bed. Alternatively, where the confining beds outcrop, probably due to erosion, artesian water pressure may be sufficiently high to escape through the confining bed. The other three controls are related to faulting. Basement wrench faults may be reactivated to the surface, allowing water discharge through these wrench faults themselves or through subsidiary faults. On the other hand some springs are associated with trapdoor faulting where two faults intersect. Finally, the active springs generally are associated with topographic lows such as stream channels, which are often structurally controlled

Examples of all of these controls are found throughout the region. At Dalhousie, for example, the springs are associated with a collapsed basement dome, erosion of the anticline having exposed and thinned the aquitard; in addition to this effect, faulting along the axis of the anticline allows water discharge from the aquifer in places where the aquitard is not sufficiently thin (Boucaut *et al.* 1986; Aldham & Kuang 1988). The seepages along the base of Hermit Hill, and along the margins of the Dennison and Peake Ranges (Fig. 8), represent the interruption of artesian flow by the presence of basement bedrock outcrops (e.g. Ker 1963; Thompson & Barnett 1985), and the alignments of springs in Lakes Eyre, Callabonna and Frome are probably fault controlled (Ker 1963; Williams 1975).

PALAEOBIOLOGY

Evidence for the palaeobiology of the mound springs is relatively sparse, although both zoological and botanical fossils have been found at a number of mound springs and associated with spring-related sediments. Macroscopic plant remains, including casts of reed and other plant stems, are described from some active spring mounds (Ludbrook 1959; Williams & Holmes 1978; Habermehl 1986b), and in some cases, spring limestones contain algal structures or, as at Lake Frome, oogonia of *Chara* sp., an aquatic alga (Callen 1981; Habermehl 1986b). Some of the other, older, spring-related sediments also yield plant fossils, the notable one being a Pleistocene conglomerate deposited in a spring channel at Dalhousie Springs, containing moulds and casts of female fruiting cones, bark and wood, probably referable to *Allocasuarina* sp. (Boucaul *et al.* 1986; Krieg 1985; Mollenmans 1989). Finally, amongst Chapman's (1937) list of Tertiary silcrete flora from central Australia, there are records from William Springs of four species probably dating from the Oligocene (Wells & Callen 1986).

In addition to these botanical fossils, several mounds, such as those at Hermit Hill, contain peat layers which contain macroscopic remains of plants and fossil pollen. At Dalhousie Springs, an initial pollen analysis indicates the presence of a range of types, mostly representing the wetlands associated with the springs, and including pollen of all the major plant components found there (Boyd 1990). The relative composition of these plants appears to have fluctuated, and probably represents changes in the swamp vegetation and, possibly, the spring outflow rate during the last 2,000 years or so. The value of



g. 8. Diagrammatic geological section showing the location of the mound springs east of the Peake and Denison Ranges illustrating the role of the structural control over mound spring location, in this case with springs located along echelon fault systems (after Aldam & Kuang 1988, Fig. 7).

these peat deposits has been commented upon by Symon (1985a) who also identified the rare plant *Gahnia trifida* (cutting grass) as an indicator of present or recently removed peat soils, and suggests that this plant may be considered important in programmes of dating botanical history.

Fossil animal remains appear to occur as rarely as the plant fossils. Gastropod shells are recorded in the sediments at several springs (Ludbrook 1959; Wopfner & Twidale 1969; Williams & Holmes 1978; Habermehl 1986b), and at Hermit Hill, fossil shells, probably of Pleistocene age, are similar to those presently living at the springs. These latter finds suggest that local speciation of hydrobiid gastropods occurred early in the history of the springs (Kinhill Stearns 1984). In addition to these relatively commonly-occurring invertebrate fossils, fossil ostracods are recorded from one sediment core at Coward Springs (Ludbrook 1959), and in the Pleistocene sediments at Dalhousie containing the probable *Allocasuarina* moulds of possible insect nests or burrows are present (Boucaut *et al.* 1986; Krieg 1985). Fossils of only one mammal appear to be associated with the mound springs, which, given the present relative lack of mammal activity at the springs, is perhaps not surprising. At Hergott Springs, while the vent was being cleared for use as a bore, teeth and a mandible referable to *Diprotodon* sp. were recovered, and another *Diprotodon* mandible has been found in the limecemented sediments of the Welcome Springs mound (Ward 1950-51; Williams 1980).

AGE

Fossil plants and animals draw attention to the problem of the age of the mound springs, although they are not the only evidence. Little is known of the absolute age of the springs, although there is general agreement that the onset of spring activity predates the Holocene. Archaeological evidence indicates that human occupation of the springs has occurred for at least around 5,000 years (Lampert 1989), and in general the extinct spring mounds are regarded as Pleistocene in age. Certainly the evidence for endemic speciation amongst several groups of animals suggests a relatively long existence, but offers little qualitative input. Several authors have suggested that some of the present biological components may be relics from wetter climate periods, possibly the end of the Tertiary Period, or derived from organisms present then (e.g. Symon 1985a; Miller 1987). Mollenmans (1989) suggests that the *Allocasuarina* fossils at Dalhousie represent a former more humid climate, but they may reflect a post-Tertiary Pleistocene phase. Further evidence for the considerable antiquity of the springs is suggested by Jack (1923) who considers that the patterns of salinity and dissolved solids within the artesian water indicate the antiquity of the springs as outlets for the artesian basin, since the water flowing directly from the intake zones to outlets has had time to flush out zones through the older, more stagnant, and consequently more highly mineralised water, and to refill them with fresher water.

The geomorphic contrast between the topographically lower active springs and higher extinct springs is evidence of the age of the mound springs, and the relation between these higher extinct mounds and other geomorphological features is important. Using this type of evidence, Wopfner & Twidale (1967) argue that mound springs were active and forming sediments 80,000-40,000 years ago. Likewise, the Lake Eyre springs are regarded as Holocene, since they appear to overlie Holocene lake sediments (Williams 1975). However, such evidence does not indicate the age of the initial spring activity, and perhaps such an age cannot be confidently derived (Boucaut *et al. 1986).* Nevertheless, consideration of geological relationships provides some input, and Jessup & Norris (1971) and Callen (1977, 1981) suggest possible late Tertiary ages for the onset of spring activity. Consideration of the tectonic and erosional activity at Dalhousie, however, leads both Boucaut *et al.* (1986) and Krieg (1985) to consider a more recent age, possibly early Pleistocene, but probably more recent; Boucaut *et al.* suggest a probable maximum age of around 1-2 million years, whereas Krieg opts for an age of no younger than mid-Pleistocene, dismissing Callen's (1977) mid-Miocene suggestion which is based on lithological similarities between different beds.

CONSERVATION AND MANAGEMENT

The springs have sufficient ecological and environmental significance to require special attention to be given to their conservation and long-term preservation. Ponder (1986) comments on the considerable potential of the springs for evolutionary and ecological studies, Lampert (1989) laments the damage being done by cattle and humans to the important archaeological sites associated with the springs, Mitchell (1985) discusses the fragility of the unique microfaunas of the springs, and Casperson (1979) and Symon (1984) comment on the range of justifications, both geological and biological, for considering conservation measures vitally important. The message is the same: if we are not careful, untold damage may yet be inflicted on those springs remaining in relatively good condition. Such concern evolved during the 1970s (e.g. Wright 1972), resulting in the publication of a review of the mound springs by the Department of the Environment (Casperson 1979). More recently Harris (1980-81) advocated that one of the necessary approaches towards the successful conservation management of the mound springs was public ownership of at least some of the springs. Whereas no mound springs were included in any form of national or regional park at that time, the situation is changing with in late 1985, the formation of Witjira National Park, a park which now includes the important spring complex at Dalhousie (see Chapter 19).

Effective management requires good bases upon which to make decisions. One of the major potential threats to the mound springs appears to be the impact of reduced water level following major extraction of water from the Great Artesian Basin for large-scale developments such as the Roxby Downs Olympic Dam Project. Although Habermehl (1980) argues that mining of the artesian water is not possible due to the equilibrium processes operating in the artesian system, the models used to reach this conclusion clearly indicate that substantial water extraction significantly lowers the water levels locally (Habermehl & Seidel 1979; Seidel 1980). Habermehl later (1986b) argues that these local effects may be reduced by the implementation of a variety of techniques, such as the reconditioning of wells, upgrading of well heads and the installation of piped distribution systems, which would result in the more efficient use of artesian water. In this context, the Department of Mines initiated a programme of bore rehabilitation during the late 1970s (Boucaut & Beal 1977). An alternative approach is adopted by Kinhill Stearns (1984), who investigated the environmental impact of the establishment of a well field associated with the Roxby Downs project. Kinhill Stearns' approach involved assessing, first, the biologically important aspects of the springs, i.e. what plants, animals and communities are at risk from changes in water levels, and, secondly, what water level changes are likely, given a range of possible geological and hydrological conditions. Further refinement of such assessment may be possible as the entire spring system becomes more fully understood (Aldam & Kuang 1988). However, Kinhill Stearns is already able to provide a set of conclusions (with which many conservationists may disagree) which, nevertheless, stand as the only major systematic assessment of this problem, In general Kinhill Stearns saw little threat to any of the critical springs, these being defined as those springs worthy of special consideration on account of their flora or fauna, with the major likely impacts of large scale water extraction being confined to some of the most degraded springs, Kinhill Stearns also provide a list of mound springs for which conservation management ought to be implemented, this list including the spring complexes at Peake Ruins and Strangways (on the basis of the flora), the complexes at Freeling Springs and Hawker Springs plus a number of individual springs (on the basis of the Hydrobiidae fauna), the complexes at Hermit Hill and Francis Swamp (for both the flora and fauna), and the Blanche Cup and Strangways complexes as good examples of mound spring formation and active-waning-extinct cycles.

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10: Coongie Lakes

by J. R. W. REID & J. T. PUCKRIDGE

INTRODUCTION

The Coongie Lakes is a series of impermanent, shallow lakes, fed intermittently by the North West Branch of the Cooper Creek. The lakes are the terminus for most flows along this branch, which is a regular, annual (or more frequent) event, initiated by rains in the vast catchment area of central and south-western Queensland, upstream of Innamincka (Ogilvie 1947). The Main and North West Branches diverge approximately 25 km west of Innamincka, and it is thought that a bar or sill in the Main Branch near the disjunction causes all water to pass down the North West Branch, until rising levels allow this barrier to be breached (Reid & Gillen 1988). An exceptional flood is required to send water down the Cooper to Lake Eyre, its ultimate terminus (see Badman in press; Kotwicki 1986 for further details).

The lakes are the focus of public attention (Sinclair 1987). Their biological wealth and diversity have been documented (Foale 1982; Mollenmans et al. 1984; Reid & Gillen 1988), and calls for adequate protection made. Coongie Lake is listed in the Register of the National Estate, while a much greater region is included within the RAMSAR Convention Treaty as a wetlands region of international importance for waterbirds.

Tourist numbers have increased over the past two decades (Gillen 1988) and a growing hydrocarbon exploration and production industry has been established: factors that, combined with the established cattle grazing practices, may conflict with perceived conservation requirements. The issues and the conflict have been addressed in the Innamincka Station Rangelands Assessment Manual (South Australian Department of Lands 1986), while recommendations for management and protection have been detailed by Reid & Gillen (1988).

An understanding of the hydrology and geomorphology of the area is central to an ecological perspective of the district's natural history. These topics are discussed in chapters 5 and 3. An appreciation of the complexity of the habitats (temporal and spatial), and the processes operating between organisms and between organisms and their environment is equally germane.

The major water bodies in the Coongie Lakes district are depicted in Fig. 1. Flooding is considered to be the most crucial factor in shaping the life history patterns of the lake's aquatic organisms, and flooding through the lakes system is a sequential process. Water travels relatively smoothly through discrete channels along the North West Branch, lined by magnificent river red gums, to Tirrawarra Swamp - a large densely vegetated (coolibah-lignumriver coobah) internal delta. Here the water spreads out (to a width of four km) through a myriad of small braided channels for some five km, before entering the large, well-defined Kudriemitchie Channel. This channel empties directly into Coongie Lake, and this point marks the end of the occurrence of red gums. Coongie and the closely connected lakes to the east (Marroocoolcannie and Maroocutchanie) fill to a depth of about 1.5 metres before a sill at the start of Browne Creek is breached, when water can proceed north to Lake Toontoowaranie. This lake also needs to fill to about 1.5 metres before Ellar Creek can flow into Lake Goyder. When Lake Goyder fills to a depth of one metre or more, Lake Marradibbadibba directly to its east begins to fill.

These six can be regarded as the main lakes in the system. They receive water regularly from floods along the Cooper, and are fringed by fine stands of coolibah. Whereas Coongie is rarely totally dry, Lake Marradibbadibba is mainly dry. The depth of each lake is comparable and, at two metres, water extends to the fringing woodland. In 1988, higher levels resulted in peripheral lakes receiving flood waters. First, Lake Mundooroounie is fed by a channel midway along Kudriemitchie Waterhole, while water spills out to the west near the Coongie Yards to feed lake Apachirie. An unnamed lake five km SSW of Coongie also fills at this stage, and the waters of Maroocutchanie may extend 10 km south of its customary shoreline. Later, and given sufficient water to fill Lake Toontoowaranie to about 2.5 m, water heads north-west along the Apanburra Channel to Lake

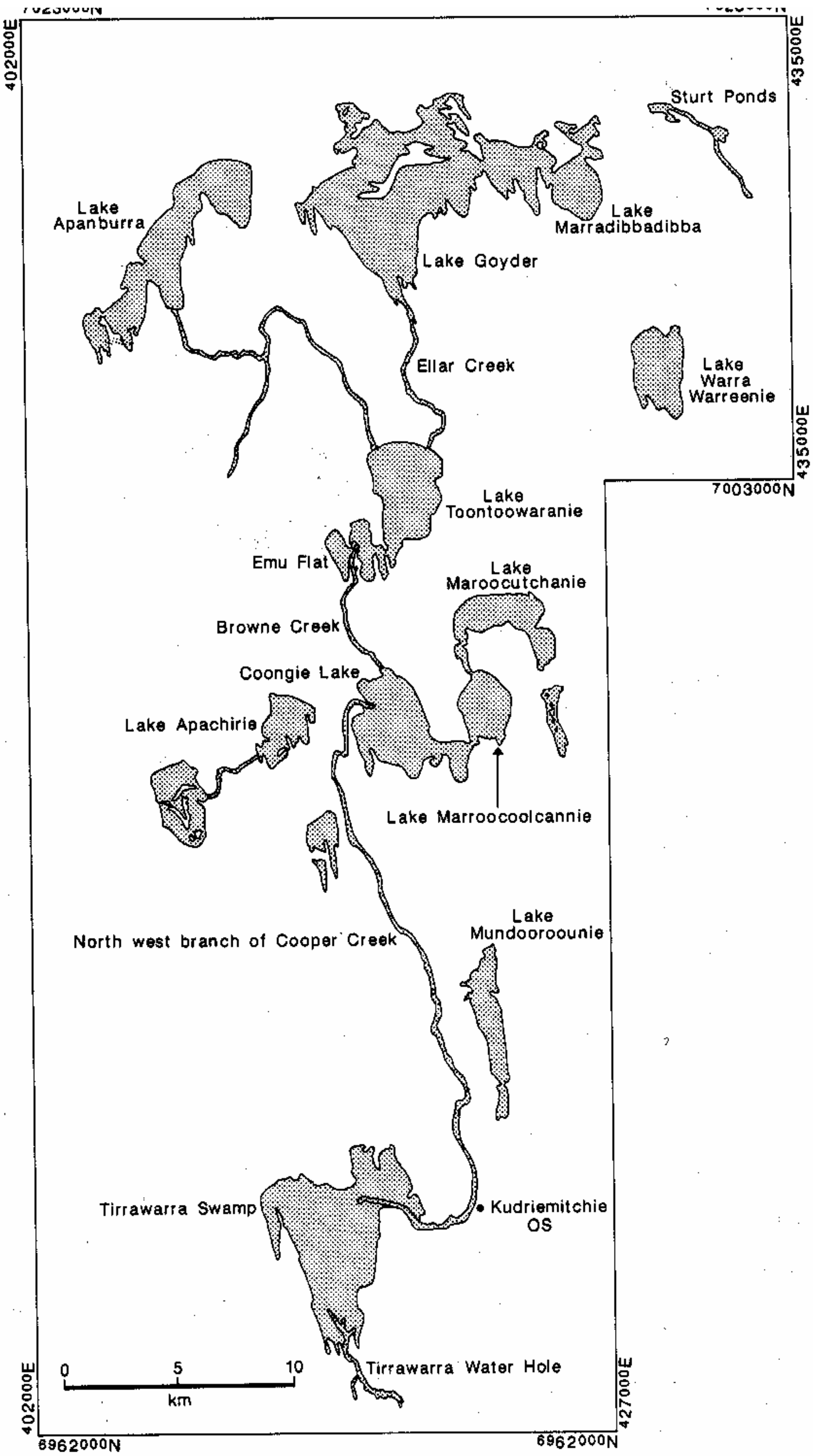

Fig. 1. The Coongie Lakes district, showing the major waterbodies.

Apanburra. Later again, water can spill out of Marradibbadibba into the Sturt Ponds, and then feeds lakes Lady Blanche and Sir Richard.

In an exceptionally large flood, when most of the land is under water, the Coongie Lakes are no longer terminal. Floodwaters travel west 30-40 km past Apanburra, and then south to rejoin the Main Branch of the Cooper and thence to Lake Eyre.

In country with such gentle gradients and low relief, a relatively small increase in water level can inundate a vast area of floodplain. Newly flooded, shallow wetlands are characteristically productive biologically (Maher & Carpenter 1984). A complex and abundant fauna of waterbirds, fish, frogs, macroinvertebrates, zooplankton and phytoplankton quickly takes advantage of these rich, ephemeral conditions.

As important as flooding is to aquatic life histories, local rainfalls generate the greatest activity within the terrestrial environment. As with floods, the intensity and magnitude of rainfall, and the time of year at which it occurs, are critical determinants of the nature and extent of the biological response.

One of the most striking aspects of the Coongie Lakes landscape is the intricate juxtaposition of floodplain and dunefields. The abundance of water in this, the arid core of Australia is remarkable. Regrettably, no detailed analysis of the district's geomorphology to account for this complexity has been undertaken.

The majority of dunes is longitudinal, tending about 15-20 degrees west of north, which is their direction of travel. The regularity of this pattern is interrupted by floodplain units, and, close to the lakes and other major floodplain features, dunes frequently are aligned differently. For instance, low traverse dunes are featured around the lakes' northern shorelines. Sand colour varies from near-white to orange-brown (Wasson 1983). Rich red dunes, characteristic of parts of the Simpson Desert, are not represented in the district. The paler, younger dunes generally are found close to their presumed sediment source, the major water bodies (and chiefly along their northern and north-western margins), and the richer coloured dunes are further away or lie adjacent to (in fact advancing into) the southern and eastern lake shores.

These 'separate' land systems of dunefield and floodplain are in fact linked by the processes described above- flooding, sediment deposition, deflation, dune building and dune travel- and a continuum of landforms is therefore involved. This landform diversity, together with a highly variable rainfall and flooding regime, results in the diverse array of habitats, which are themselves in a state of flux.

Dryland and wetland habitats cannot be demarcated readily on account of the exceptional hydrological variability of Cooper Creek and the limited relief of the area. When the Cooper is in full flood, as in 1974, only the dune crests are not inundated, whereas after a prolonged dry spell, even Coongie Lake may dry completely. Therefore, the approach of treating the aquatic and terrestrial environments separately, as adopted here, is simplistic and somewhat misleading; much of the district supports, if intermittently, both terrestrial and aquatic organisms. Some of the ecological processes (e.g. the dramatic community shifts) which occur when rainfall or flooding create new aquatic habitats (or as these habitats subsequently dry out) will be described, because these processes and the interplay between the terrestrial and aquatic components of the Coongie Lakes environment are considered especially important.

THE TERRESTRIAL ENVIRONMENT

The dryland habitats around the lakes are as rich in life as the waters. Some of the distribution patterns of plants and animals are described to permit an appreciation of the broad distinctions (as between dune and floodplain communities) and more subtle patterns, such as the occurrence of small mammals and reptiles within the floodplain environment in relation to substrate differences (e.g. cracking vs hard-setting clay, or clay only vs clays/loamy clays with a sandy veneer).

Only long continued observation would reveal the extent of temporal change that the terrestrial communities undergo each year and between years. The changes may be episodic (as following a heavy rainstorm), cyclic (e.g. annual, in response to temperature variation), or of a longer term.

Approximately 350 species of plants have been collected in the Coongie Lakes district (Mollenmans et *a*l. 1984; Gillen & Reid 1988) a remarkable figure for a district flora in the arid zone. Notable are the recently discovered endemic daisy Brachycome coongiensis (Munir 1987) and three nationally threatened plants: *Echinochloa inundata*, *Frankenia cupularis* and *Goodenia lobata* (Leigh et al. 1981). The abundance of the highly palatable channel millet (*E. inundata*), attributed by Gillen & Reid (1988) to the seven year absence of cattle from the Coongie Paddock, is especially heartening.

The association of plant species within the district was reported by Gillen & Reid (1988). Patterns of distribution and association were considered briefly. The broader groupings of plant associations which were generated also serve as a useful basis for discussion of animal communities.

Table 1. VEGETATION ASSOCIATIONS IN THE COONGIE LAKES DISTRICT, BASED

WOODLAND COMPLEX	1. *Eucalyptus microtheca - Sclerolaena intricata* +/- *Atriplex velutinella*
	2. Depauperate version of the above
	3. *Eucalyptus microtheca - Muehlenbeckia cunninghamii* +/-
INTER DUNE LOW-FLOODPLAIN COMPLEX	4. *Halosarcia indica - Sclerolaena intricata*
	5. *Muehlenbeckia cunninghamii - Sclerolaena intricata - Atriplex*
	6. *Eragrostis australasica*
	7. *Muehlenbeckia cunninghamii - Chenopodium auricomum - Sclerolaena patenticuspis*
	8. Intergrade
	9. *Sclerolaena intricata / S. bicornis - Muehlenbeckia cunninghamii*
	10. As above with *Maireana coronata*
	11. *Sclerolaena calcarata / S. intricata*
	12. *Morgania floribunda - Crinum flaccidum - Osteocarpum acropterum*
	13. *Atriplex eardleyi - Sclerolaena intricata*
	14. *Eragrostis dielsii* +/- *Sclerolaena lanicuspis - Malacocera albolanata*
	15. *Sporobolus mitchellii*
	16. *Marsilea drummondii*
SAND DUNE CREST COMPLEX	17. *Zygochloa paradoxa* +/- *Acacia ligulata*
	18. *Acacia ligulata* +/- *Atriplex velutinella - Aristida holathera*
	19. *Acacia ligulata* +/- *Zygochloa paradoxa - Sclerolaena intricata - Gunniopsis quadrifida*
	20. *Acacia ligulata - Triodia basedowii - Zygochloa paradoxa*
	21. *Triodia basedowii*
SANDY DUNE SLOPE – INTERDUNE COMPLEX	22. *Crotalaria cunninghamii - Atriplex velutinella - Trichodesma*
	23. *Atriplex velutinella - Gunniopsis quadrifida* +/- *Acacia ligulata*
	24. *Atriplex velutinella - Sclerolaena intricata - Gunniopsis quadrifida*
	25. *Acacia oswaldii - Atriplex velutinella*
	26. *Sclerolaena diacantha - Eragrostis dielsii* +/- *Acacia ligulata*
	27. *Aristida holathera - Acacia ligulata*
CLAYPANS	28. Barren clay pans

Quantitative data were gathered at 148 sites and analysed using a computer programme (UPGMA) which sorts (hierarchically) sites sharing similar characteristics (species presence and abundance) into groups (cluster analysis).

Within the five broad vegetation groups, or complexes, distinguished (Table 1), 28 plant associations were identified and considered to be meaningful biologically. The cluster analysis revealed a primary division between sand dunes (80 sites) and floodplain/interdune corridors (66 sites), whereas the remaining two sites were devoid of vegetation (barren claypans). The greater diversity of the floodplain environment is indicated by the greater number of vegetation associations recognised there (16 as opposed to 11 within the dune environment).

Ordination of the sites (Fig. 2) gives a two dimensional representation of the cluster analysis, and enables interpretation of environmental influences that most readily account for the depicted sequence of plant associations along axes (or putative environmental gradients). The long axis, labelled water relations, relates the position of sites or groups to frequency of inundation, distance from water and height above water. Correlated with this influence is soil type - sites subject to frequent inundation have predominantly clay soils, while sites not subject to inundation have sandy soils (dunes). From Fig. 2, it will be seen that the *Sporobolus mitchelli* grassland (15), subject to seasonal inundation, is placed at one end of this axis, whereas dune crest and upper slope associations (17, 20 and 21, dominated by sandhill cane-grass *Zygochlea paradoxa* and the spinifex *Triodia basedowii*) are placed at the other end. The Eucalyptus woodland complex and the floodplain/interdune are placed close together (and intergrade), but separately from the various dune and sandy slope associations (which also intergrade). Discrimination along the shorter axis is not interpreted as readily and may not necessarily have a consistent environmental basis. However, in most cases, those associations generally found on the 'sandier' soils, within the two broad groups of associations, occur towards the top of the ordination figure.

Of the five broad vegetation groups, the barren claypans do not support a vertebrate community. The four remaining groups support distinctive animal communities, although some groups need refining or subdivision on the basis of soil type or vegetation to adequately describe small mammal/reptile and bird habitats respectively.

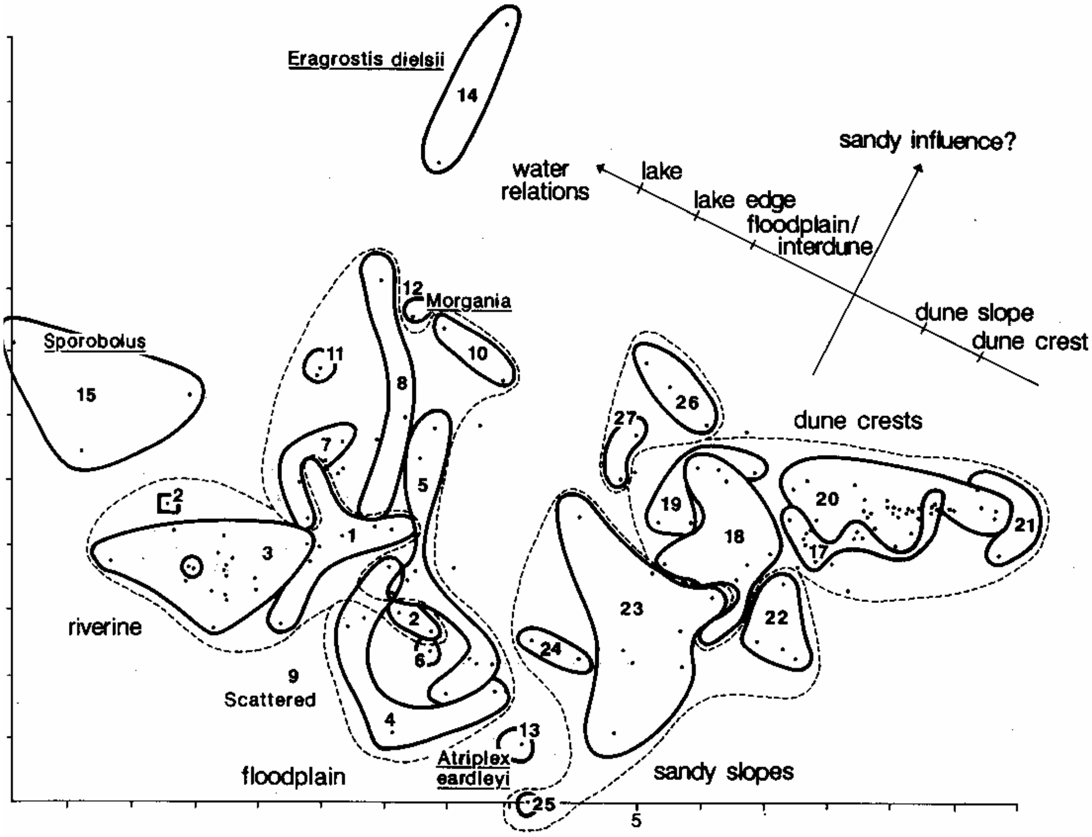

Fig. 2. An ordination figure of the perennial flora of the Coongie Lakes district, showing a two-dimensional arrangement of the 148 sites with the distance between the sites reflecting the dissimilarity in floristic composition. The vegetation associations, enclosed in solid lines, are described (as numbered) in Table 1. A putative environmental gradient (water relations) to account for the arrangement of associations is indicated.

The river redgum dominated riparian woodland (association 3) occurs as a narrow strand along the banks of the Kudriemitchie and Tirrawarra Waterholes. The vegetation is floristically and structurally diverse. Permanent water and vertical structural diversity (four distinct strata of perennial plants) explain the extraordinarily rich bird community. The Barking Owl, Golden-backed Honeyeater, Mallee Ringneck and Restless Flycatcher are notable rarer elements, while Red-rumped Parrots, White-breasted Woodswallow, Grey Shrike-thrush and several species of kite, dove and honeyeater are more conspicuous inhabitants. The well-formed litter layer ideally suits the needs of the small skink Morethia bou/engeri, legless lizard De/ma tincta and the red-naped snake *Furina diadema*. The arboreal gecko *Gehyra variegata* and skink *Cryptoblepharus plagiocephalus* are a common sight on tree trunks during night and day. Small mammals are represented poorly. The introduced house mouse *Mus musculus* is most common.

A similar but less rich community is the coolibah riparian woodland of the lakes and interlake channels. The first four birds mentioned above are encountered rarely; otherwise a similar suite of species occurs. Brown Treecreepers are especially common in coolibahs. The density of the breeding raptor population is highly significant. Gilbert's Water Dragon *Gemmatophora gilberti* and the arboreal pygmy-goanna *Varanus tristis* are rare reptiles found there. Occasionally the narrow-nosed planigale *Planigale tenuirostris* is encountered.

Some of the smaller tree species that add character to the riparian woodland are Queensland bean-tree *Lysiphyllum gilvum*, Broughton willow *Acacia salicina*, river coobah *A. stenophylla*, plum bush *Santalum lanceolatum* and the occasional stand of sour plum *Owenia acidula*, a member of the cedar family Meliaceae. This last species and the bean-tree are tropical elements.

Open to sparse coolibah woodlands are scattered through the district's floodplain environment, often associated with dry lake beds, or occurring as thin strands which mark previous high flood levels around the outer margins of floodplains. Diamond Dove, Blue Bonnet, Blackfaced Woodswallow and Southern Whiteface are typically encountered in this habitat, which supports a relatively rich bird community still, although densities are a lot less than those in the riparian woodlands.

Wherever lignum *Muehlenbeckia cunninghamii* is prominent (e.g. associations 3,5, 7 and 9) either as a shrubland (sometimes co-dominant with Queensland bluebush *Chenopodium auricomum* or old man saltbush *Atriplex nummulariaj*, or as a shrub layer under a woodland canopy, a characteristic suite of birds occurs. Chirruping Wedgebill, White-winged and Variegated Fairywrens are prevalent. Terrestrial mammals encountered include the stripe-faced dunnart *Sminthopsis macroura*, fat-tailed dunnart *S. crassicaudata* and the odd narrow-nosed planigale *Planigale tenuirostris*, while limited observations suggest that the dense lignum beds provide important refugial habitat for the irruptive long-haired rat *Rattus villosissimus*.

The two dunnarts and the rare Forrest's mouse *Leggadina forresti* are widespread over the range of floodplain environments as are the following reptiles: curl snake *Suta suta*, bearded dragon *Pogona vitticeps*, central netted dragon *Ctenophorus nuchalis*, lined earless dragon *Tympanocryptis lineata*, and tessellated gecko *Diplodactylus tessellatus*. However, whereas these species are generally restricted to the floodplain, the following habitat generalists are commonly encountered in both floodplain and dune environments - house mouse, the skinks *Ctenotus regius*, *Menetia greyi* and *Morethia adelaidensis*, Bynoe's gecko *Heterenotia binoei*, beaded gecko *Lucasium damaeum* and beaked gecko *Rhychoedura ornata*. The generalists still display subtle habitat preferences. For instance, although they commonly occur together, the stripe-faced dunnart favours more densely vegetated parts of the floodplain than the fat-tailed dunnart (Reid 1988a). Given their different size, jaw shape, time of breeding and potential fertility (the fat-tailed dunnart has five nipples and commences breeding a month earlier than the stripe-faced dunnart with eight nipples), they would seem to be able to partition their environment quite effectively as well as adopting different life history tactics (e.g. Lee et al. 1982).

Most of the floodplain carries a sparse, low vegetation of variable composition, dominated by ephemeral or short-lived perennial species. Cover and species composition change through the year and between years, with heavy rains producing a spurt of dense growth, the composition of which is determined by the season in which the rain falls. Grasses, *Boerhavia* spp, *Tribulus* spp, *Portulaca* spp and *Trianthema triquetra* dominate the summer-autumn landscape, while daisies, brassicas and *Zygophyllum* species are prevalent in winter·spring. Few birds are permanent residents of these open habitats - Richard's Pipit and Cinnamon Quail-thrush (on sandier parts) mainly, although Zebra Finch, Southern Whiteface, White-winged Fairy-wren and Black-faced Woodswallow are regularly encountered as well. After rain (or upon flooding) many more species move into these areas, namely songlarks, chats, quail and waterbirds.

An important and distinctive habitat in the district's range of floodplain environments is the densely vegetated normally dry lake-bed. Lake Apachirie, immediately west of Coongie is the best example. These lakes receive water from the Cooper only occasionally (perhaps one in three or four years) and are characterised by rich, friable, deeply cracking clays. The Coongie daisy Brachycome coongiensis grows here and the paucident planigale *Planigale gilesi* is largely restricted to this habitat (and the similar environment found around some of the outer margins of the main lakes and channels). The rare Flock Pigeon utilizes this habitat seasonally and is strongly suspected of breeding on the ground amidst the dense short cover (see Reid 1988b), which is favoured by the Emu for the same purpose.

Dune crests are dominated by the perennial tussocky sandhill cane-grass *Zygochloa paradoxa*, which is optimum habitat for the White·winged Fairy-wren and Eyrean Grasswren, the latter virtually restricted to this habitat. Dunes support a rich small mammal and reptile community, composed of the native sandy inland mouse *Pseudomys hermannsburgensis*, house mouse, the diurnal skinks *Ctenotus brooksi* and *C. leae*, the nocturnal, fossorial skinks *Lerista labialis* and *Eremiascincus fasciolatus*, the dragons *Diporiphora winneckei* and *Ctenophorus pictus*, the knob-tailed Gecko *Nephrurus levis* and the blind snake *Ramphotyphlops endoterus*, in addition to the habitat generalists referred to earlier.

Not all of these species can occur at anyone site, and some of the subtler habitat distinctions have been addressed (Reid 1988a). However, a lot more fieldwork would be required to gain a precise understanding of habitat partitioning within the dunes' reptile communities. The richest fauna is associated with the spinifex hummock grasslands, which are distributed patchily within Ihe dunefields, but are always associated with orange sands which are the coarsest and oldest in the district. Four animals appear to be restricted to this habitat: namely a species of ningaui *Ningaui* sp. aff. *ridei*, spinifex hopping-mouse *Notomys alexis*, centralian blue-tongue *Tiliqua multifasciata* and *Lerista xanthura*.

Shrubbier habitats are scattered through the dunefields, wherever the sandhill wattle *Acacia ligulata* (and occasionally other wattles, cassias and eremophilas) is prominent. The Diamond Dove, Variegated Fairy-wren, Singing Honeyeater and rare Banded Whiteface are particularly associated with these dune-slope open shrublands, and are joined in winter by the seasonal Red-capped Robin, while the highly nomadic Black Honeyeater occasionally invades the district when the *Eremophila* species (principally *E. longifolia*) are heavily in bloom.

Flocks of Budgerigah and Zebra Finch are a common sight in the dunes following summer rains, as they take advantage of seeding grasses (e.g. *Aristida* and *Enneapogon* spp.), and the ephemerality of the community structure (due primarily to the mobility of birds and the annual nature of the majority of the district's flora) is a striking feature of the dunefields and indeed of the whole district.

Finally the arid dunefield environment is an extremely important refuge for the entire district's dryland ground fauna. When the great floods inundate all of the floodplain in the district (an infrequent event, but perhaps occurring on average once each 30 years - see Mollenmans ef al. 1984), the only refuge for the terrestrial reptiles, mammals and birds is the dune. Recolonization of the floodplain following such a flooding remains to be documented, but would be of enormous ecological interest.

THE AQUATIC ENVIRONMENT

The Northwest Branch of Cooper Creek, including the Coongie area presents a great variety of wetland types. There are a number of axes along which this variety of wetlands may be described; an axis of duration of flooding from the ephemeral rain-filled interdune claypans to the deep permanent waterholes of the Northwest Branch channel; an axis of current velocity from the narrow fast-flowing interlake channels such as Ellar Creek to the calm spaces of the lakes themselves; an axis of shoreline complexity from the open lake beaches to the intricate capillary streams of Tirrawarra Swamp; an axis of aquatic macrophyte complexity from the dense matrices of the creek channel edges (with emergent lignum *M. cunninghamii*, submergent algae *Spirogyra* sp., floating attached *Ludwigia peploides*, floating unattached fern *Azolla filiculoides*) to the shelterless offshore waters of the lakes. Many such axes would have to be considered to describe the habitat diversity here, including all the shallow floodplain habitats such as flooded meadows, lignum swamps, flooded coolibah woodlands and samphire claypans. Further, there are temporal axes along which habitats should be distinguished. For example a flood peak may take five months to travel from Tirrawarra Swamp in the south to Lake Goyder in the north, so these habitats flood in different seasons, and the flood may be receding in Tirrawarra Swamp as it begins to rise in Lake Goyder.

Corresponding to this diversity of habitats, there is a diversity of aquatic fauna, little of it studied. Most of the material to follow has been drawn from the first intensive and protracted studies of the aquatic ecology of the area (Puckridge & Drewien 1988; Reid 1988a, b; Roberts 1988). The Coongie Lakes system shows an exceptional diversity of zooplankton; from December 1986 collections alone, 41 Rotifers, 12 Cladocerans and four Cope pods have been identified, the majority from river rather than lake habitats (Roberts 1988). This diversity is attributed in part to an overlap of tropical and temperate faunas. Puckridge & Drewien (1988) have begun a description of aquatic insects of the region. Most noticeable to the visitor are the dense populations of hemipteran bugs (notonectids and corixids) and aquatic beetles (dytiscids) in the open waters of the northern lakes, the caddis-fly larvae (Trichoptera) of the lake-edge *Cyperus gymnocaulos* beds, the rich fauna of dragonfly and damselfly larvae (Odonata) in the *L. peploides* fringe of the river channels, and the midge larvae (Chironomidae) teeming in the litter of newly flooded shores. Crustaceans are also abundant. Dense blooms of planktonic crustaceans, notably large *Daphnia*, occur in the northern lakes after flooding, and are preyed on by the hemipterans mentioned above (see also Reynolds & Geddes 1984). The prawn *Macrobrachium australiense*, an extremely widespread and abundant animal, is probably the major recycler of detritus in the system. The yabby, *Cherax destructor*, however, although widely distributed, is not abundant. In rain-filled pools, crustaceans such as the shield shrimp *Triops australiensis*, the clam shrimps (Conchostraca), and the fairy shrimps *Branchinella* species hatch from drought-resistant eggs and live through an accelerated life-cycle (Williams 1980). In dry creek-channels, the inland crab *Holthuisiana* *transversa* survives long droughts sealed in deep burrows (Macmillen & Greenaway 1978).

Gastropods are common and diverse (at least nine species). The large transparent bubble-shell *Austraopeplea lessoni* is abundant on the *L. peploides* river channel fringe, the smaller brown conical *Physastra gibbosa* inhabits the litter of the channel bottom, the ornate *Glyptophysa aliciae* is found in the *C. gymnocaulos* fringe of the northern lakes, and *Gabbia australis* is characteristic of ephemeral rain-filled pools. The larger of two bivalve species, the mussel *Velesunio wilsonii*, which is a feature of aboriginal middens in the area, is still abundant in the shallows of the lakes and channels. There is anecdotal evidence that *V wilsonii* is able to aestivate through several years of drought (Ch'ng Tan 1969). The tiny bivalve *Corbiculina australis* is also widespread, and the shells are common on the dunes.

Aquatic vertebrates include the water-rat *Hydromys chrysogaster*, which is widespread but not common, and can be seen on the lake shores carrying captured mussels back to feeding platforms on emergent trunks of flooded coolibahs. The large and unnamed Cooper Creek short-necked tortoise, *Emydura* sp., is common in both river channels and lakes. During the first rains of summer, hundreds may be seen floating downstream with their heads above water.

The fish community of the Coongie Lakes region is one of the most significant in the State. Whereas the River Murray fish community has been severely damaged by river regulation (Walker 1983; Cadwallader 1986), the Coongie Lakes community essentially retains its original composition and ecological cycles, and may serve as a benchmark by which to gauge the effects of alterations in other inland warm water rivers. There are only two exotics in the Cooper at present, the mosquito fish *Gambusia affinis*, and the goldfish *Carassius auratus*. The former is abundant and widespread, and well-known for its destructive impacts on native fish communities (Myers 1965; Lloyd *et al*. 1986). The latter is rare and its effects probably insignificant; however, the appearance of goldfish in such a remote river system as the Cooper indicates that more destructive introductions will follow unless there is more effective public education.

The Coongie Lakes region shares major species with the Murray-Darling system (bony bream *Nematalosa ereb*i, callop *Macquaria ambigua*, western carp gudgeon *Hypseleotris klunzingeri*, smelt *Retropinna semoni*, spangled perch *Leiopotherapon unicolor*) , but also has central Australian species (desert rainbowfish *Melanotaenia splendida tatei* and Welch's grunter *Bidyanus welchi*) and more widespread northern species (yellow fin tandan *Neosilurus glencoensis* and silver tandan *Neosilurus argenteus*) (Merrick & Schmida 1984). However, since the taxonomy of the Australian neosilurid catfishes is still under review, the indentifications of the Coongie Lakes specimens must be considered provisional.

The distribution of these species in the Coongie Lakes region is strongly influenced by the frequency and duration with which different habitats are flooded, and this diminishes along an approximately south-north axis. Bony bream and smelt are both the most abundant and widespread species, and are found in even the most northern lakes such as Goyder and Apanburra, sometimes in extreme conditions. Callop, mosquito fish and to a lesser extent Western carp gudgeon and silver tandan also venture into rarely flooded areas, but only in small numbers. However, Welch's grunter, yellow fin tandan, goldfish and - surprisingly - spangled perch (c.f. Llewellyn 1973) are both less abundant and less widespread, being confined principally to the permanent waters of the North-West Branch channel.

Flooding plays a major role in the life histories of the Coongie Lakes fishes. It creates extensive new wetlands for colonization, and provides food for young fish both by stimulating emergence and hatching of drought-quiescent invertebrates, and by replenishing nutrients which fuel algal blooms and a succession of aquatic microorganisms, crustaceans and insects (Maher & Carpenter 1984; Arumugam & Geddes 1987). The fish community responds to flooding in various ways. As in the Murray-Darling (Reynolds 1983), callop begin an upstream reproductive migration early in the flood. Adult bony bream and desert rainbowfish do not appear to undertake a spawning migration, and will spawn both in response to flooding and seasonally. Spangled perch, smelt and western carp gudgeon seem to be principally seasonal spawners, as reported for eastern Australia (Llewellyn 1973; Milton & Arthington 1985; Lake 1967). Neither breeding events nor larvae of the two catfish have been observed, but they may undertake upstream spawning migrations like some other neosilurids (Orr & Milward 1984).

Migration in response to flooding takes several forms. Mature adult callop (and perhaps the two catfish) move upstream to spawn. However there are also feeding and colonizing migrations which utilize the resources of newly flooded areas, and these, directed downstream or laterally, are undertaken almost entirely by juveniles, principally bony bream and callop. The lateral movements are from a permanent river channel or lake out onto the floodplain. Early in a summer flood, spectacular numbers of juvenile bony

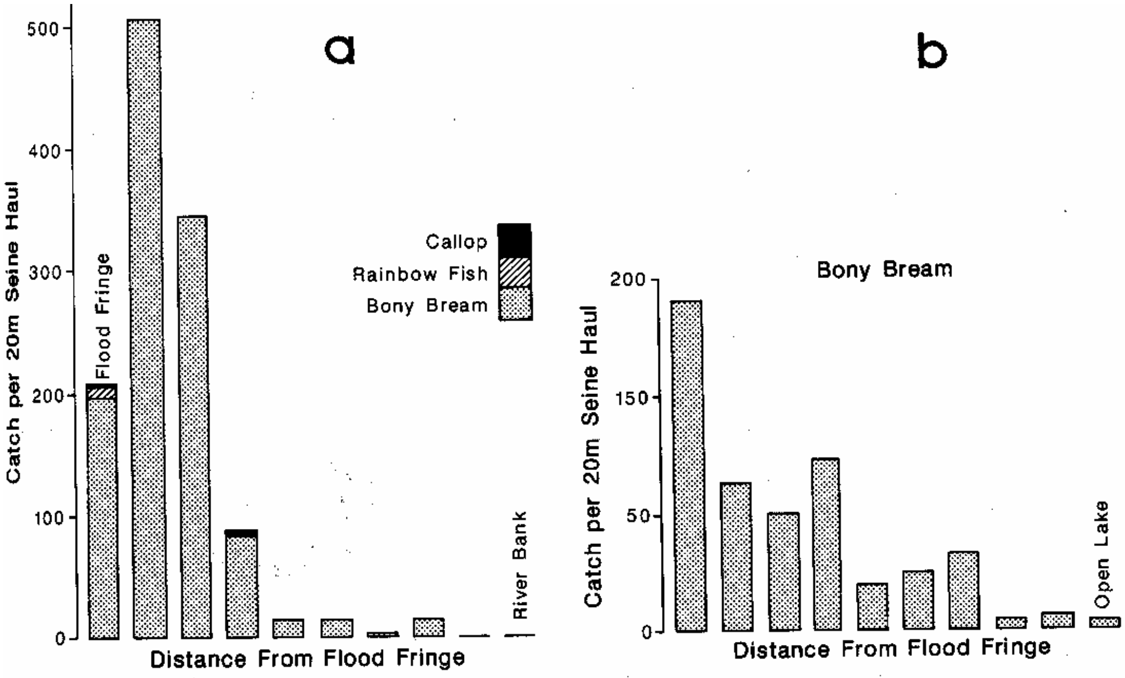

Fig. 3. Use of Cooper Creek — Coongie Lake floodplain by juvenile fish. a. North-West Branch Channel floodplain, March 1987. b. Coongie Lake floodplain, April 1987.

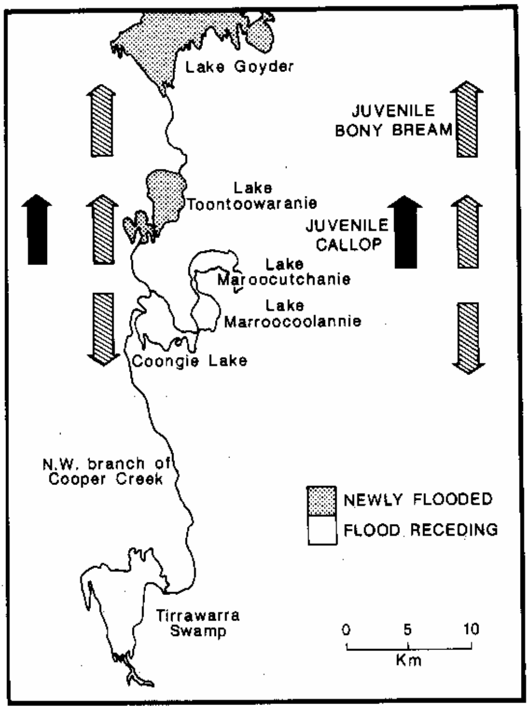

Fig. 4. Longitudinal migration of callop and bony bream juvenile fish through the Coongie Lakes system, Feb. 1988.

bream may be found out at the flood fringe (Fig. 3). In early winter, the floodplain may be used only in the late afternoon, when water temperatures in the shallows are high. Longitudinal migration takes place from the southern permanent waters to the newly flooded northern lakes. The northern migration of juvenile bony bream appears to continue steadily as long as there is substantial flow; callop juveniles, however, move north in a pulse, apparently having migrated from spawning grounds far upstream (Fig. 4).

When there are heavy local rather than regional rains, and water rushes into the river from the floodplain instead of vice versa, a colonizing migration of bony bream and silver tandan juveniles may occur out onto the floodplain against this flow. This phenomenon has been observed widely in inland Australia, particularly for spangled perch (Llewellyn 1973), and may account for the appearance of fish in unexpected places (Glover 1982).

The Coongie Lakes support a highly diverse and, at times, abundant waterbird population. To date 70 species have been recorded (Mollenmans et al. 1984; May 1986; Reid 1988b), and 36 of these have bred, while 15 species are nonbreeding migrants (mainly waders) from the Northern Hemisphere

Many of the species are rare (e.g. Glossy Ibis, Plumed Whistling Duck, Oriental Pratincole) or vagrant (Northern Shoveler, Lesser Yellow-legs) in South Australia, while the populations of Freckled Duck and Red-necked Avocet in the greater region are of national significance. Reid (1988b) has ranked the importance of the district's waterbird habitat on a par with Bool Lagoon in the South East.

The concentration of birds on the lakes can be spectacular. Approximately 5,000 Australian Pelican were present in early 1987 (Reid 1988b), and large breeding colonies occasionally gather on the island in Lake Goyder (e.g. Paine 1976). Duck numbers peaked at about 35,000 in September 1987 towards the end of the ten-month study of Reid & Gillen (1988), with Pink-eared Duck and Grey Teal contributing most to this total. The population of Black Swan on the lakes increased gradually over the study period from 1,000 to 2,000, with small numbers breeding at most times.

Almost 1,000 Freckled Duck congregated briefly on a southern bay of Lake Toontoowaranie in May 1987 (Reid 1988b). Smaller numbers of this threatened species occurred over the rest of the year. Very little breeding activity by the ducks was observed during the study, and no male Freckled Duck were seen in breeding condition in 1987. However, duck certainly breed in good numbers in some years (e.g. 1973- Rix 1974), and in June 1988, when water levels were half a metre higher than in the previous year, several nests and broods of Pink-eared Duck and Grey Teal were encountered; also many pairs of Freckled Duck appeared to be about to breed, with the males sporting their red bill bases, which they assume when ready to breed (Frith 1977).

Flooding, or perhaps more correctly, initiation of flow along the North West Branch, heralds an immediate breeding response in some of the district's water-birds. In particular, the response of Yellow-billed Spoonbills is dramatic. Within days of the flood front reaching Coongie in February 1987, pairs were courting and building their stick platforms in river red gums overhanging the Kudriemitchie Channel (Reid 1988b). Other species to commence breeding soon after the arrival of a flood pulse in 1987 and 1988 include Pied Cormorant, Darter, Rufous Night Heron, White-faced Heron and Dusky Moorhen.

An important factor appears to be the inundation of previously dry ground that occurs as the district's water level quickly rises with the arrival of the flood front. Crome (1986) has argued that this can trigger waterfowl to breed in the Murray-Darling system, and presented data to support the contention that the filling of previously dry wetlands, rather than the rise in water level itself (as stated by Frith 1977) was the proximate factor. Certainly a concentrated food resource is ideally required to sustain a large waterbird breeding event, and the shallow, vegetated margins (especially where lignum is prominent) found around parts of Lakes Coongie, Maroocutchanie, Toontoowaranie, and Goyder, as well as the backwaters along the channels, are important feeding and breeding grounds.

Intense rainstorms, which fill the numerous pans and swamps in the Coongie and surrounding districts, providing extensive alternative waterbird habitat, result in a dramatic decline in waterbird numbers on the lakes. Repeatedly in 1987, the withdrawal of waterfowl, in particular, from the lakes was observed following heavy rains (Reid 1988b). Numbers on the lakes would then steadily rise over the subsequent month or two as the rain-filled water bodies dried, often coincident with the arrival of a new pulse of water down the North West Branch.

Casual observers, arriving at Coongie Lake, may be disappointed to find little waterbird life on the vast body of water before them. The occasional pelican, Pied Cormorant, Caspian Tern, stray coot and a thin scattering of ducks may be all that meets the eye on the deeper, exposed waters. In winter a few Great Crested Grebe and Blue-billed Duck, rare visitors from southern Australia, are also found in this open-water habitat.

In contrast the greater habitat diversity within the lake shore environment and the shallow water enables a range of wading birds, waterfowl and fish eating species to gather where conditions are appropriate - in sheltered bays on windy days and in swampy, vegetated margins. Aggregations of birds are still patchy, however, probably reflecting the spatial patchiness of food resources, and spectacular concentrations are only infrequently encountered on Coongie Lake itself. Black-winged Stilts, Masked Lapwings and Blackfronted Plovers are common on these shores, while the occasional Brolga, egret, heron or spoonbill may also be seen stalking the wet grass and sedgeland. In the shallows, the ducks dabble, a raft of coot may drift into the open waters when approached, and a few Whiskered Tern will skim the water's surface occasionally, while flying in search of insects and small fish.

Waterholes provide a distinct habitat, supporting a wide range of species including Dusky Moorhen, Coot, Pelican, Yellow-billed Spoonbill and several duck species. The fringing coolibahs and redgums are important for tree nesting waterbirds, while with rising water levels, the backwaters and associated lignum flats become a rich foraging area for wading birds (e.g. Red-kneed Dotterel, Black-fronted Plover, Blackwinged Stilt, herons, spoonbills and ibis), Blacktailed Native-hen and, in some years, crakes.

The deep, permanent waterholes of the North West Branch provide the only drought refuge for the district's waterbirds, and therefore constitute a critically important habitat. However, because the southern lakes and shallower waterholes dry out so infrequently, they are important drought refuges in the frequent dry years, when the northern lakes and ephemeral water bodies in the greater district have all dried. At such times, the concentration of waterfowl on Coongie Lake is indeed spectacular (as in August 1979 - Reid 1988b). Also spectacular is the movement of huge numbers of inland ducks and other waterbirds to the sub-coastal waters of southern Australia, when drought takes hold of central Australia; Pinkeared Duck (Frith 1977) and Black-tailed Nativehen (Matheson 1978) are good examples.

Evaporative losses are high over the long hot summer (Allan 1988), and the muddy, receding lake margins can support thousands of small migratory sandpipers. These birds breed in the high latitudes of the Northern Hemisphere during the northern summer. It is likely that the majority of these waders stay only briefly in the Coongie District, while on passage to or from their 'wintering' feeding grounds in (sub-) coastal Australia.

The Coongie Lakes support the richest frog community known in Central Australia, and the distribution and patterns of activity of the eight species are of interest. All eight species occur along the permanent Kudriemitchie Waterhole, and the diversity decreases dramatically with distance from this waterhole. In the adjacent dunes, only *Neobatrachus centralis*, *Cyclorana platycephala* and *Crina deserticola* are found (Reid 1988a), while it is unlikely that the last named species intrudes far into the dunefields. An undescribed species of *Cyclorana*, *Litoria caerulea* and *L. latopalmata* were not found downstream of the inlet of Coongie Lake in 1987, while *Limnodynastes tasmaniensis*, *Litoria rubella* and *Crinia deserticola* are widespread through the lake system.

Breeding as evidenced by vocal activity was restricted to summer for six species. Interestingly the only frog with a basically temperate or Bassian distribution, *L. tasmaniensis*, called throughout the year, while *Crinia deserticola* ceased calling over winter (May to early August) in 1987.

While heavy rain at any time of year resulted in a burst of feeding activity of all the species, the greatest activity was observed in response to the torrential rains of December 1986 and February 1987 (Reid 1988a), and the density of frogs on the North-West Branch's floodplain at those times was extraordinary. The deafening chorus of seven or eight species, initiated by these rains, can only be described as a riotous cacophony, and it would be one of the most memorable experiences that the summer traveller, fortunate enough to be stranded at Coongie by an impressive electrical rainstorm, could hope to have.

What has been learned about the aquatic community of the Coongie Lakes region is just a beginning. It is important that this community remains pristine so that its unique features may be explored thoroughly. Since the lower reaches of rivers are dependent on their catchments, this means that the whole of the Cooper, from the headwaters to Lake Eyre, should be protected. As an example of an inland draining desert river system it is both distinctively Australian and of world significance.

ACKNOWLEDGEMENTS

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11: Vegetation

by R. T. LANGE & T. J. FATCHEN

INTRODUCTION

The whole of the north east deserts, far from the sea and lacking high mountains, has an extremely low, erratic and non-seasonal rainfall with very hot summers and mild winters (Chapter 6) consequence, the emergence and growth of herbaceous plants is episodic and infrequent, depending on chance combinations of water availability and suitable temperatures. Except in very limited localities, perennial plants must endure long spells of increasing water stress between effective rainfalls.

The effect of these conditions is to produce very meagre vegetation over relatively vast areas, with slightly more growth reflecting small advantages of line-scale habitat differences, such as depressions and drainage lines. Bare, exposed groundsurface predominates. 'In every direction', wrote Cannon (1921) about a vista near Oodnadatta, 'the wide-spreading plains and flat topped hills appear quite barren'.

This paucity of plant cover and bare or scarcely clad landscape is evident throughout the photographic record, for example Cannon (1921) and Crocker (1946), and even on occasions when extended rainfall results in vigorous plant growth, much of the ground remains bare (colour plates 24 & 25 in Ludbrook 1980).

Only at very restricted localities such as mound springs (Chapter 9) and along the braided courses of floodways entering the north east from Queensland, are plants afforded relief from acute water shortage for extended periods, independent of local rainfall. As shown in the colour plates of Gillen & Reid (1988), incursions of floodwater can result in extended, dense, permanent shrub and tree vegetation (their plate 6), abundant herbage meadow (their plates 9, 10, 18) and even waters with floating waterfern.

On an area basis, such situations are exceptional: miniscule in regional terms. Broadscale vegetation distribution across the north east generally follows landform and edaphic factors, the climate varying little over the region. This stressed in the volumes of Laut et al. al, where vegetational variation is tabulated against landform profiles.

For each part of the north east, Laut *et al*. used landform differences to divide landscapes into finescale units. These units were then aggregated contiguously into larger areas called environmental associations, by appeal to a common, usually geomorphological theme. Associations were then grouped contiguously into regions, again with reference to a common geomorphological theme. The north east is made up very unequally of two such regions. The main one is the Lake Eyre Basin environmental region, embracing 11 environmental associations. The other, the Central Tablelands environmental region, is represented only by its eastern margins.

Differences in landforms and soils cause the corresponding major differences in the kinds of vegetation found in the two regions. Laut et al. (1977) list the sorts of vegetation that are dominant or co-dominant in the units of the various environmental associations (Fig. 1). Hummock Grassland (H2) is the outstanding dominant of Lake Eyre Basin environmental associations, where chenopod shrubland is rarely dominant. The situation in the eastern margins of the Central Tableland region is the reverse.

Table 1 lists the particular plant species Laut *et al*. (1977) used to designate the principal vegetation types of the north east. The list gives an initial impression of those species that most strike the eye, in the various localities.

In the following section a general overview of botanical literature about the north east is given. A semi-historical approach has been taken, but particular reference is made also to studies which provide maps and descriptions, and those with quantitative analysis.

The third section considers a few specific situations in relative detail, illustrating the sorts of impressions and conclusions that have been reached by workers who took the trouble to sample and analyse the vegetation of particular places.

OVERVIEW OF THE LITERATURE

The botanical literature for the region displays several changes in emphasis from the mid-19th

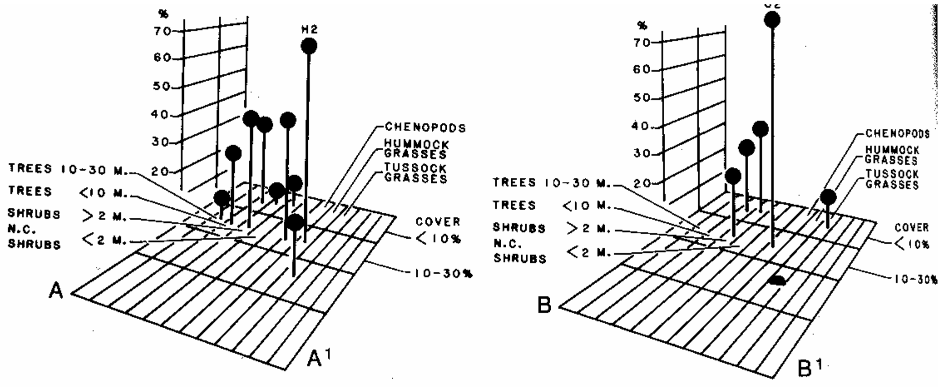

Fig. 1. The baseplane represents the 'structural formations' categories of Australian vegetation, with shift in the growth habit of the dominant species from tall trees (A), grading down to herbs (A^1), and in corresponding projective canopy cover from greatest (B) to least (B^1). NC = non-chenopod. The lefthand diagram summarises dominance or co-dominance of vegetation types on the Central Tablelands associations in the north east; the righthand diagram refers to Lake Eyre Basin associations.

Table 1. PLANTS USED BY LAUT *et al.* (1977) AS CHARACTERISTIC OF VEGETATION IN THE ENVIRONMENTAL ASSOCIATIONS OF THE NORTH EAST. CTA = Central Tableland associations in the N.E.; LEBA = Lake Eyre Basin environmental associations. Scores represent the approximate proportion (out of a possible 10) of environmental associations from which the species was named as a character-species or group.

	CT	LEBA		CTA	LEBA
Eucalyptus microtheca	7	5	*Dodonaea* spp.	3	0
Eucalyptus camaldulensis	7	5	*Heterodendrum oleaefolium*	3	0
Aristida contorta	1	7	*Acacia salicina*	2	1
Zygochloa paradoxa	1	7	*Acacia tetragonophylla*	1	2
Acacia cambagei	6	3	*Atriplex rhagodioides*	2	1
Eremophila spp.	6	3	*Acacia ramulosa*	2	0
Cassia spp.	6	2	*Acacia cyperophylla*	0	2
Triodia basedowii	1	6	*Atalaya hemiglauca*	0	2
Halosarcia - Sclerostegia	4	5	*Lysiphyllum gilvum*	0	2
Aristida browniana	1	5	*Eragrostis* spp.	0	2
Enneapogon spp.	5	1	*Maireana* spp.	0	2
Sclerolaena (Bassia) spp.	5	1	*Eragrostis australasica*	1	1
Chenopodium auricomum	1	5	*Hakea leucoptera*	1	1
Atriplex vesica ria	5	0	*Acacia victoriae*	1	0
Acacia aneura	4	4	*Atriplex* spp.	0	1
Acacia ligulata	3	4	*Atriplex spongiosa*	0	1
Atriplex nummularia	2	4	*Casuarina cristata* ssp. *pauper*	1	0
Astrebla pectinata	4	1	*Dodonaea attenuata*	1	0
Maireana aphylla	4	1	*Eremophila freelingii*	1	0
Maireana astrotricha	4	1	*Grevillea* spp.	1	0
Hakea spp.	1	4	*Melaleuca glomerata*	1	0
Nitraria billardieri	3	3	*Myriocephalus* spp.	0	1
Sclerostegia tenuis	2	3	*Rumex vesicarius**	0	1
Frankenia spp.	1	3	*Sporobolus actinocladus*	1	0
Acacia spp.	3	0	*Sporobolus mitchellii*	0	1
Acacia brachystachya	3	0	*Tripogon loliiformis*	1	0

* introduced

Century to the present. Since the emphasis in research controls to a great extent the utility of the information gained, the following overview follows the 'streams' of investigations which can be discerned over the short history of research rather than simply cataloguing literature by topic and geographic area.

19th Century Botanical Exploration

Early botanical research in the north east was an adjunct to physical exploration. From the beginnings in 1844 to the early 20th Century, the emphasis was on a 'search for the new': the collection of new species and their categorisation. Questions of plant geography and the nature of the vegetation were considered only in very general terms, if at all. The vegetation was given little attention other than in the very broad sense of evaluating the suitability (or, in most instances, the unsuitability) of land for agriculture.

Taxonomic exploration is dealt with in more detail, and for a wider area, by Black (1960) and Willis (1981), from which the following is a digest. The first botanical reports and collections in the north-east of SA came from Charles Sturfs explorations 1844-1846. Sturfs collecting area included Cooper's Creek, the Great Stony Desert and the eastern margins of the Simpson Desert. The taxonomist Robert Brown, examining the relatively small collection (100 species), complained that the emphasis was on 'new or striking' plants (Willis 1981).

In 1858, the party of A. C. Gregory, in search of Ludwig Leichhardt, collected along the Coopers and Strzelecki Creeks to the northern Flinders Ranges. On the western margins of the north east, exploratory expeditions under Babbage and Warburton (1858) to Lake Eyre South and Stuart Creek, and John McDoual1 Stuart (1859) north to Oodnadatta, provided further collections. All of these collections were examined by Ferdinand Mueller, whose enthusiasm, encouragement, financial support and active collection contributed greatly to botanical knowledge for central Australia generally. Mueller also examined various collections from Coopers Creek and about Lake Eyre South in the late 1870s and 1880s. An early synthesis of collections for the Lake Eyre Basin was given by Tate (1889). The Elder expedition of 1891-1892, under David Lindsay, provided some further collection again on the western margins.

The 20th Century Plant Geographers and Ecologists

All the preceding expeditions were primarily exploratory, with a view to describing the physical landscape. Vegetation was described only in the most general terms (e.g. as in Gregory 1906 for Lake Eyre surrounds), and botanical collection was a discretional adjunct. The botanical emphasis was taxonomic (collection, identification and listing, with habitat information either missing or only given in very general terms) and we can follow further examples of this stream into the 20th Century: Black (1917) for the Strezelecki-Coopers Creek area, Cleland et al. (1925) for the area north of Coopers Creek, and Cleland (1930) for the south-west margins of the region. Plant checklists remain an important first step in examining the vegetation: although now they tend to be incorporated into broader accounts, listings with notes such as those of Symon (1969) for the Simpson Desert and Symon (1984) for Dalhousie Springs continue to extend knowledge of the region.

Towards the end of the 19th Century, emphasis in botanical exploration began to shift from the purely taxonomic. W. A. Horn's expedition to central Australia in 1894 had scientific observation and reporting as its primary objective. From this expedition, Ralph Tate (in Spencer 1896) gave the first account of plant communities in relation to habitat applicable to central Australia (and impinging on the northwestern corner of the region of interest). Tate commented that having 'little hope of the discovery of botanical novelties, ... I determined very early on the journey to concentrate my efforts in the direction of studying the facts and problems of geographic distribution'. (cited in Willis 1981).

Tate thus ushered in a second stream of investigation, of a geographical rather than taxonomic bent. With the appearance of ecology as a recognised discipline, the emphasis increasingly was placed on relationships between plant communities and their physical environment in both space and time as well as wider distributional questions. The geographical stream dominated research in the region up to the late 1960's, and continues to be a major component of management-oriented studies.

There are two key differences between the geographical stream and subsequent, analytical approaches which were to be applied from the late 1960s. First, investigators sought to classify vegetation. For this they relied on subjective definitions of what might represent a plant community, with the inevitable corollary of different observers defining different communities to describe similar vegetation, and frequently having difficulty determining where one community stopped and the next started.

Second, most investigators used the concepts of primary and secondary succession as their conceptual framework. To a great extent, Wood (1937), whose community descriptions and mapping extend to the south-east corner of the region, was responsible for the promotion of a successional framework with emphasis on 'climax' communities. Despite his subsequent recantations (Wood 1939; Crocker & Wood 1947), concepts of primary succession and the notion of 'climax' vegetation remain entrenched in the literature (e.g. in Specht 1972).

Because investigators of the geographic stream tended to describe, classify and, especially, map very large areas, their later papers remain the most useful in providing a rapid and reasonably detailed appreciation of the region. Partly for this reason, they are still the most frequently quoted in management or planning documents (for examples see Pipelines Authority of South Australia 1981, Roxby Management Services 1982, extensive references in Laut *et al*. 1977). They also provide the main base for synthetic descriptions of vegetation on a larger scale, as in Specht (1972) in the South Australian context and Beadle (1981) in the Australian context.

The early reports, for example Cannon (1921) for the western part of the region, were rather anecdotal, but subsequently there appeared considerable detail on species composition of plant communities, and on the physical environment, particularly soils, with which communities appeared to be associated. In Jessup (1951), whose mapping extends to the gibber plains about and to the west of Lake Eyre South, soils are treated in detail, while the vegetation is described in terms of a series of associations for which the main data presented are species listings. Jessup, unusually for the time, also presents some quantitative data and analysis to do with chenopod shrub densities under grazing. It is revealing that the information is provided as an appendix to the soil and vegetation descriptions and cannot be readily reconciled with his mapped associations.

Elsewhere in the region, Ratcliffe (1936, 1937) described the soils and vegetation of the eastern margins of the Simpson Desert and the Channel Country. Skerman (1947) dealt with soils and vegetation of Coopers Creek in Queensland, immediately adjoining the region. Crocker (1946) described the soils and vegetation of the Simpson Desert, thus filling the major gap in general knowledge of the region's vegetation left by the 19th Century reports. A quarter of a century later, the vegetation of the eastern Simpson Desert was still being described, by Boyland (1970), in a manner almost identical to that of Crocker (1947), and Crocker's paper remains the most useful introductory description (discussed below).

From the late 1940s interest also focussed on wider biogeographical problems. Crocker & Wood (1947) examined the distributions of the regional plant communities in relation to past climatic fluctuations. Despite considerable subsequent changes in our understanding of the sequence of Pleistocene arid cycles, Crocker & Wood's main arguments still appear valid (Crocker 1959; Fatchen & Barker 1979a). They consider that, in periods of extreme aridity, the MacDonnell Ranges (NT) and the Diamantina-Coopers Creek system provided arid refuges, from which reo invasion of much if not most of the north east took place in less arid periods. On a wider scale, Eardley (1948) drew comparisons between the plant geography of the Simpson Desert and other major sandridge deserts of the world. More recently, Buckley (1981a) provides a comparison of the Simpson Desert with the southern Kalahari.

The early taxonomic stream did not altogether disappear. Collection and nomenclatural work continued (as it does to the present, often at an accelerating rate), but major botanical exploration of new areas, in the 19th Century sense, was limited to the first scientific expedition to the Simpson Desert (1939), for which Eardley (1946) examined the material.

Analytical Approaches Post-1960

Increased availability in the late 1960s of multivariate statistical techniques (and of the computers needed to use them) led to a less subjective approach to vegetation description and analysis. In contrast to the geographic stream, subjectivity in observation and classification was replaced by non-subjective sampling and quantitative data, with statistical testing of associations between species, or between plant populations and the physical environment. Especially, plant communities in the sense of the subjective associ· ations beloved of the geographers tended to be ignored, other than as a simple means for setting the broad context. The closer and more objective scrutiny made possible by the new techniques, when applied to areas already described by the geographical stream, showed much of the vegetation to be continuously varying, not neatly divided into discrete and non-interacting associations. (Fig. 2).

For the north east, almost all work in this stream has applied to the Simpson Desert only. Wiedemann (1971) re-examined vegetation in the Simpson Desert, concluding that it was best considered as a continuum rather than as the series of associations described by Crocker (1946). Similar studies with similar conclusions can be found in Fatchen & Barker (1979b) and Buckley (1982a, b). More recent work of a similar nature elsewhere in the region has appeared in a few management-oriented studies, discussed below. The analytical emphasis has also been applied to broad-scale geographic questions, for example variation in species' distributions across the Simpson Desert (Fatchen & Barker 1979a, Buckley 1981b).

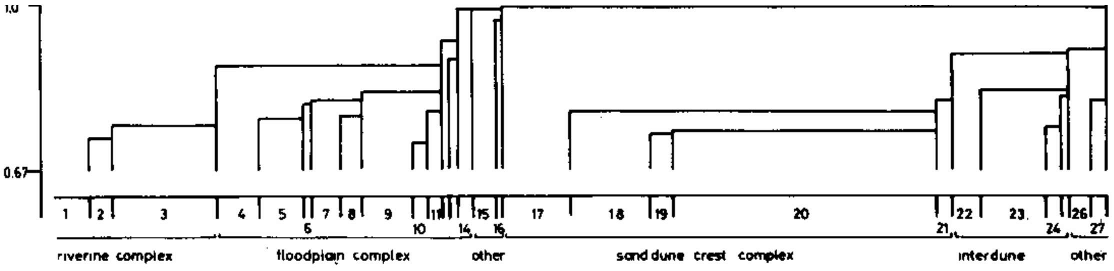

Fig. 2. Dendrogram showing the variety of vegetation of the Coongie Lakes district, simplified from Gillen & Reid (1988). Table 1 pp. 122 names the 27 associations by reference to the prominent plants that give the associations their visual character.

Management-Oriented Approaches Post-1970

Research since the early 1970s has been largely directed to land management, reflecting the increased public consciousness of needs for biological conservation, non-destructive land use and limitation or amelioration of development impact. The last involves legal requirements of increasing complexity which have only appeared in the last decade.

The information available has increased greatly as a consequence of this raised consciousness, although one might query whether knowledge has increased at the same rate. Much of the recent work might be seen as a retreat away from the analytical to the geographical stream, with strong reliance on subjectively defined plant associations described in equally subjective structural terms, or by floristic listings. In this category come most of the reports directed toward biological conservation. These include the Nature Conservation Society publications on the far northeast (Foale 1982), which provides the extensive but generalised vegetation mapping and description of Lewis (1982), and on the mound springs (Greenslade et al. 1985). As well, there are some publicly available consultancy reports such as Mollenmans et al. (1984) for the Cooper's Creek environmental association. A heartening exception is the report of Gillen & Reid (1988) for the Coongie Lakes area, with a renewed emphasis on objective rather than subjective description and classification of vegetation.

Attempts at integrated description of large portions of the region, aimed at providing a basis from which land management decisions might be made, resulted in a sometimes curious blend of earlier streams and new technologies. For determining their environmental associations, Laut *et al.* (1977) combined use of satellite imagery with an essentially geographic approach to land description, with the vegetation very much a secondary consideration and usually derived from one of the earlier authors (e.g. Crocker 1946; Jessup 1951). Similar techniques, but with an ecological emphasis and some reference to the analytical as well as the geographical research stream, have since been applied to the channel country by Graetz (1980) and to the Simpson Desert and surrounds by Graetz et al. (1982) and Purdie (1984). All have land classification and mapping as the primary aim, all provide concise general descriptions of vegetation and maps of their various land units, and all produce differing final views of the region.

Information on vegetation given in environmental impact statements (EISs), National Park management plans and similar documents tends to be derivative. Information is drawn from whatever sources are available, with additional original, and usually rather localised, survey performed only where gaps are obvious. Again, authors from the earlier geographic stream are frequently referenced. The information may also be highly variable in quality. The formal, normally published EIS being an edited document, detail on vegetation may only be available from unpublished 'supporting documents' of very limited availability.

Close & Williams (1982) give an outline of vegetation to the west of Lake Frome, part of the region for which there is still little information. Further information on the Cooper Basin vegetation is in Environmental Research & Planning Group (1980) and SANTOS (1981, 1983). A vegetation transect from the Moomba gasfields to the Flinders Ranges is reported in Pipelines Authority of South Australia (1981). National Parks & Wildlife Service (1984) summarises vegetation for the Simpson Desert, and Graetz & Pech (1982) examine problems of monitoring man-made impacts in the Desert. Vegetation descriptions and maps in Roxby Management Services (1982, 1983) extend into the region as far as Lake Eyre South. Vegetation on mound springs is reported in Roxby Management Services (1984).

Gaps in Information

Compared with the remainder, the southeastern portion about Lake Frome remains largely undescribed other than in the generalised mapping of Specht (1972) and Laut *et al*. (1977). Away from favoured exploration routes, without major stream systems, of subdued topography and lacking the glamour associated with the more remote Simpson Desert, the only prompting for vegetation description appears to have been its mineral potential (Close & Williams 1982). Research in the 1920s associated with the Koonamore Vegetation Reserve did reach into this area (Fatchen 1978) but remains unpublished.

A more subtle gap in our knowledge is the lack of information on processes controlling or affecting the vegetation. The majority of the reports cited describe vegetation either in static terms, or, where dynamics are considered, in terms of subjectively inferred and highly doubtful successional sequences and changes. This perhaps is a logical outcome of surveys taken in isolation, at a single time. Yet for areas where successive surveys have been made (such as the Simpson Desert with Crocker 1946; Fatchen & Barker 1979a; Graetz et al. 1982; Purdie 1984; or the Lake Frome area with Fatchen 1978) major changes can be detected, with or without the influence of domestic stocking.

Lack of understanding of the processes controlling vegetation in the region presents particular difficulties for land managers, and for those charged with determining potential impacts of development or changed land use. Generally, one cannot predict future changes in vegetation without knowledge of the processes involved, and this knowledge cannot be gained from once-only surveys.

SELECTED ILLUSTRATIVE CASES

The Simpson Desert and the gibber downs - Crocker (1946)

The similar dunefields of the Simpson and Strzelecki Deserts dominate the region. The paper by Crocker (1946) on the Simpson Desert remains the most appropriate introduction to these dunefields. It is remarkably comprehensive, considering that it was based mainly upon one rapid transect across the centre of the desert in 1939. It is a good example of the manner in which contributors from J. G. Wood's school at the Botany Department, University of Adelaide, were documenting South Australian vegetation and, as such, is a good example of the geographical stream of research discussed above.

Crocker (1946) is also a major source of information on the vegetation of the gibber plains and downs. These usually bare, poorly vegetated and stony expanses seem to have raised little enthusiasm amongst those examining vegetation: apart from Crocker's paper, detailed descriptions are limited to those of Jessup (1951), with relatively slight treatment in other studies (e.g. Foale 1982).

Crocker separated the vegetation of the Simpson Desert and surrounds into 12 well-described associations, and produced a generalised vegetation map of the entire desert and its borders at the mapping-unit level of three 'edaphic complexes', into which the 12 associations were grouped. More recent research (Wiedemann 1971; Fatchen & Barker 1979b; Buckley 1982a, 1982b) indicates that a number of Crocker's associations in at least one of these edaphic complexes are actually intergrading positions along a continuum of vegetation, and not the wholly distinct vegetation entities which might be inferred from Croc· ker's descriptions. Nevertheless the associations serve as a useful summary of dunefield and associated vegetation, provided the possibilities of overlap between associations are remembered.

Table 2 reproduces Crocker's summary of the 12 associations, their habitats, and the edaphic complexes into which he grouped them. The first edaphic complex, *Triodia basedowii-Zygochloa paradoxa*, consists of the five associations of sandy desert habitats, ranging from the deep, unstable sands of the dune crests to the shallower sands of the interridge corridors and sand plain. One of these associations is restricted to the northern edge of the desert well beyond the north east of S.A. The remainder are:-

(a) *Zygochloa paradoxa* association

Throughout the desert the main sandridge crests are unstable and largely devoid of vegetation. *Z. paradoxa* (sandhill canegrass), a sand-binder over 1 m tall, is the most distinctive crest species. Other perennials are *Ptilotus* and *Sida* species; annuals include grasses such as *Eriachne aristidea* and forms such as *Salsola kali*. (Fig. 3).

(b) *Triodia basedowii* association

The 'spinifex' *T basedowii* occurs in the major part of the desert in sandy inter-ridge areas, and on lower dunal slopes as dense tussocks. It is the most frequently met and most obvious member of a group of species in these habitats, but is not the uniformly present species that Crocker believed (Fatchen & Barker 1979b). Various tall shrubs also may be present - *Hakea leucoptera*, *Grevillea* and *Eremophila* species. *Acacia ligulata* (sandhill wattle), occasionally encountered by Crocker, appears to have become a major plant of this association over the last two decades (Graetz et al. 1982; Purdie 1984).

Table 2. THE VEGETATION ASSOCIATIONS, HABITATS AND EDAPHIC COMPLEXES OF THE SIMPSON DESERT AND SURROUNDS, (AFTER CROCKER 1946)

Association	Habitat	Edaphic complex
(a) *Zygochloa paradoxa*	Unstable sandridge crest	*T basedowii*
(b) *Triodia basedowii*	Interdune corridors and lower dunal flanks	*Z paradoxa*
(e) *Nitraria billardieri*	Interdune near Lake Eyre	
(d) *Triodia basedowii* *Grevillea juncifolia* *Eucalyptus pachyphylla*	Sandplain (NT only)	
(e) *Acacia cambagei - Atriplex vesicaria*	Eastern interdune areas; mostly Queensland	
(f) *Acacia peuce Sclerolaena*	Gibber Downs (N.T. only)	*A pectinata -* *A vesicaria -* *Sclerolaena*
(g) *Astrebla pectinata Sclerolaena*	Gibber Downs	
(h) *Atriplex vesicaria Sclerolaena*	Gibber Downs	
(i) *Eucalyptus microtheca*	Fringing river channels and floodplains	E. microtheca – A nummularia
(j) *Atriplex nummularia*	Floodplains	
(k) *Chenopodium auricomum*	Floodplain swamps	
(l) *Muehlenbeckia cunninghamii*	Floodplains and swamps	

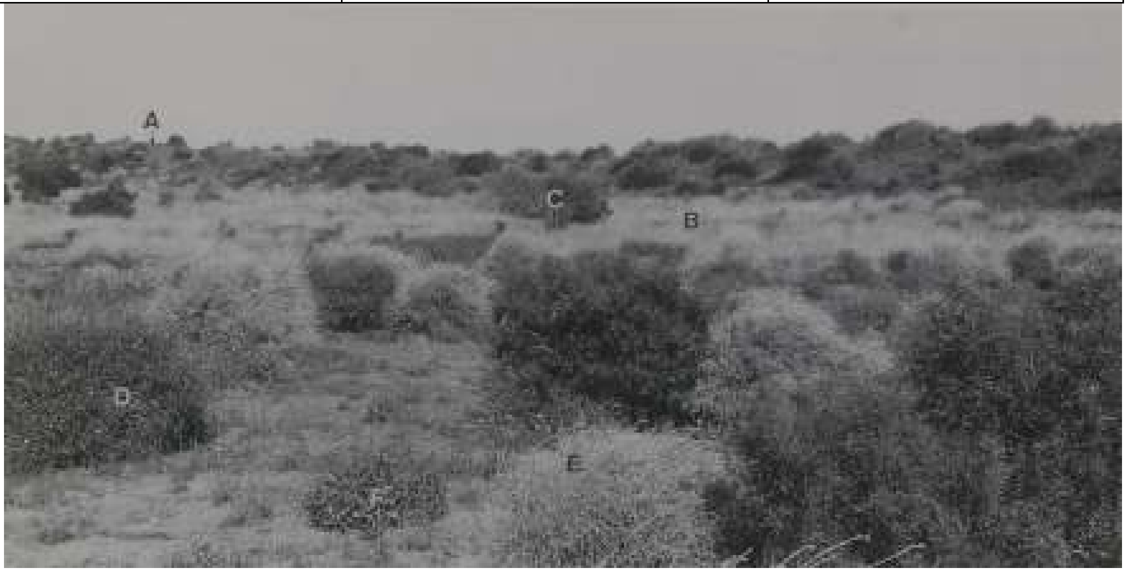

Fig *3* Sandridge vegetation in the Strzelecki Desert. Partially bare dune crest with sandhill canegrass (*Zygochloa paradoxa*) (A) and the annual buckbush (*Salsola kali*) & *Crotolaris eremea*; slope and interdune with 'spinifex' or porcupine grass (*Triodia basedow*ii) (B) with occasional sandhill wattle (*Acacia ligulata*) (C). Annuals on sand in foreground: buckbush (Salsola kali)(D), Crotalaria eremea (E), Nicotiana velutina (F)

(c) *Nitraria billardieri* association

In the sandhills about Lake Eyre the soil is gypseous and saline. The preceding association is replaced by *Nitraria billardieri* (nitre bush) and in places *H. leucoptera* (needlebush) occurring with a very depauperate associated flora.

(d) *Acacia cambagei* - *Atriplex vesicaria* association

Mainly in southern Queensland, this association extends partly into the north east. Interdune areas are partially wooded with the low tree *A. cambagei* (possibly a misidentification of *A. georginae*- Purdie 1984) with areas of the saltbush *A. vesicaria*.

The second of Crocker's edaphic complexes is the *Astrebla pectinata* - *A. vesicaria* - *Sclerolaena* complex of the gibber flats, stony downs and lower stony rise habitats. There are three component associations, one of which is not represented in the north east. The two remaining associations are *Astrebla pectinata* (Mitchell grass) - *Sclerolaena* and *Atriplex vesicaria* (saltbush) - *Sclerolaena*. These associations are very variable: Jessup (1951) recognises several, rather than just two, for gibber areas about Lake Eyre South alone. (Fig. 4).

Northeast of Lake Eyre, *A. pectinata* occurs but less prominently than in Queensland. Instead, the principal gibber downs grasses are *Enneapogon polyphyllus*, *E. avenaceus*, *Sporobolus actinocladus*, *Iseilema vaginiiflorum* and *Tripogon loliiformis*. Chenopod shrubs are locally important and include *Maireana appressa*, *M. pyramidata*, *M. astrotricha*, *M. pentagona* and *A. vesicaria* as well as biennial species of bindyi (S*clerolaena*) species, for instance *S. divaricata*, *S. intricala* and *S. lanicuspis*. During periods of ephemeral growth numerous herbaceous species are present, particularly composite herbs *Helichrysum* and *Helipterum* species. Samphire (*Scleroslegia tenuis* and related species) is common on gibber downs: Crocker noted in particular its presence north of Oodnadatta contrasting with its absence on the eastern gibber about Goyders Lagoon The *Eucalyptus microtheca* - *Atriplex nummularia* edaphic complex is the third of Crocker's major groupings, comprising the vegetation of floodplains and that fringing river channels (Fig. 5). Crocker recognised four associations in the complex:-

(a) *Eucalyptus microtheca* association
(b) *Atriplex nummularia* association
(c) *Chenopodium auricomum* association
(d) *Muehlenbeckia cunninghamii* association

Extensive floristic lists for this vegetation are given by Crocker (1946). He noted that, of the association dominants, *E. microtheca* (coolabah) fringed the channels and appeared on the floodplains of all rivers flooding into the Simpson Desert. Beyond the fringing coolabah, *Atriplex nummularia* was common (old man saltbush) (Fig. 6). *Muehlenbeckia cunninghamii* (lignum) dominated swamp communities and *Chenopodium auricomum* (Queensland bluebush) was associated with the levees and floodplains of rivers on the north east desert borders.

Fig 4 Silcrete gibber downs northeast of Innamincka. Mitchell grass (*Astrebla pectinata*) perennial tussock grassland (A) with ephemeral or biannual cover of various cheopods forbs and annual grasses (A). The bulk of this cover is usually absent. Gidgee (*Acacia cambage*) low open woodland in broad drainage lines (B) (Phote J Gillen

Fig 5 Fringing vegetation on the Cooper Ck channel, Innamincka causeway. Large red gum (*Eucalyptus camaldulensis* var *obtusa*) fringing stream (A). Tall mixed woodland of coolabahs (*E. microtheca*), red gum, *Acacia salicina* and *Eromphila bignonflora* (B) alternating with lignum shrubland (C) and grassland or sedgeland (*Cynodon dactylon*, *Cyperus* spp.) (D) on levees (Photo J Gillen)

Fig 6 Floodout area associated with Strzelecki Creek. Foreground of mixed grasses and forbs (A): *Eragrostis setifolia*, *Dactyloctenium radulans*, *Enneapogon* spp., *Sclerolaena bicornis*, *S intricate*, *Senecio gregorii*. Back ground of shrubland of old man saltbush (*Atriplex nummularia* (B) and lignum (*Muehlenbeckia cunninghamii* (C). Scattere coolabahs (*Eucalyptus microtheca*) (D). Photo J Gillen

The Coongie Lakes District - Gillen & Reid (1988)

The most penetrating analyses from the north east refer to the Coongie Lake district, an area about 60 km long x 10-20 km wide, on the northwest branch of the Cooper Creek. Gillen & Reid (1988) describe the Coongie Lakes as an island of comparative vegetative luxuriance within a rippling sea of sand dunes, part of a humid and productive strand placed incongruously in a desert setting.

In this system where wetland and desert are juxtaposed, a mosaic of channels, floodplains, swamps and lakes presents a diversity of plant habitats making the Cooper Creek Environmental Association heterogeneous.

Gillen & Reid collected incidence and abundance data for plant species in 148 sampling sites distributed between Lake Toontoowaranie in the north and Mundooroonie in the south. Thirty sites were chosen to include as many readily identifiable habitats as possible, distributed as widely as practicable given difficulties of access. The remaining 118 were scattered arbitrarily.

Of the various ways in which the data were treated, those summarised here concern 84 species of perennial and biennial plants, ignoring annuals. The purposes of the analyses were, first, to distinguish the different plant communities present and their affinities in an objective, quantitative way, and second, to demonstrate their habitat relationships. For the first purpose, site similarities were calculated (using Czekanowski distance as the similarity measure) between all pairs of sites in turn, on the basis of the abundance scores of all 84 species. The resulting sites x sites distance table was then extracted to produce a dendrogram. This dendrogram, shown in abridged form in Fig. 2, distinguishes the variety of vegetation types encountered at any chosen level of similarity, and expresses their affinities with each other.

Such an approach contrasts with the subjective erection of associations as discussed for the preceding example: associations can be and are defined, but how many such depends on the level of similarity demanded, and affinities between one association and another can be objectively defined. From Fig. 2, vegetated sites divided first into two suites of almost complete dissimilarity, those of the sands of dune and interdune, versus those of floodplain and riverine areas. Each of these suites was then divided almost as strongly into two separate subsuites, sites of the dunal crests versus interdunal sites, and sites of the floodplains versus riverine localities.

Within each of these four major groupings, 'complexes' of Gillen & Reid, 27 associations of plants were distinguished, each separated from the others by a Czekanowski distance of approximately 0.65 at least. Table 1, Coongie Lakes, lists these associations, named for the prominent species that give them their visual character.

Gillen & Reid used detrended correspondence analysis (DCA) as a means for exposing habitat relationships. The significance of this procedure lies in the well established notion, that controlling environmental variables commonly show corresponding distributions. In the DCA of the 27 associations, water relations are affirmed as a controlling environmental theme. This might seem a self-evident outcome for a system of streams and lakes, and quite capable of satisfactory illustration by subjective criteria (e.g. as in Mollenmans *et al*. 1984) rather than a resort to complicated analysis, however objective. But several noteworthy features emerge when details of the analyses are examined, which could well be missed on a purely subjective appraisal.

For instance, the Riverine Complex includes sites which are not riparian, but which are located well away from lake or channel margins. These involve coolabah woodland which occurs sometimes near the junction of floodplain and dunefield. Again, the Interdune Complex does not embrace all interdune sites in the district, but only those influenced by a sandy substrate; the others fallon floristic analysis into the Floodplain Complex. Instances such as these illustrate how subtle features such as subsoil texture or hydrological contact can cut across predominant landform in determining vegetation type. Gillen & Reid elaborate on such subtleties which complicate the system and introduce much intergradation.

The Mound Springs

Mound springs (Chapter 9) provide the most intriguing plant habitats of the north east, being minute 'islands' of permanent wetlands, of relatively fresh water, in the most arid part of the continent. The spring vegetation has received little close scrutiny until very recently, despite their intrinsic interest (Harris 1981). Published reports are still rather limited, and are not always readily reconciled with each other. Casperson (1979) provided an initial but very general appreciation of the vegetation on springs. The subsequent major reports dealing at least in part with vegetation come from a brief survey by the Nature Conservation Society of SA in 1978 (Greenslade et al. 1985) and an impact assessment survey (Zeidler & Ponder 1989). Each is limited in geographical extent: springs between the Peake and Denison Ranges and Marree, springs from Lake Cadibarrawirracanna to west of Marree, and springs at Dalhousie respectively.

We cannot discuss the vegetation of the springs generally because the springs themselves are not uniform entities. The Dalhousie Springs complex is unique, in the sheer volume of its water flow, the extent of its wetlands (Chapter 9), and the scrub or even forest of *Melaleuca glomerata* associated with its wetlands (Mollenmans 1989) (Fig. 7). Springs between Dalhousie and Lake Eyre South have major differences in water quality compared with those east from Lake Eyre South: these differences influence the physical nature of the springs (Chapter 9) and may affect the nature and the dynamics of the spring vegetation. As well, physical location of springs may strongly influence the vegetation: vegetation on relatively transient springs in frequently flooding watercourses, as are the majority of those discussed in Roxby Management Services (1984), could well be expected to perform differently from vegetation on stable mounds not subject to flooding, as is the case with many of the springs discussed in Greenslade et al. (1985).

The springs have the following characteristics in common. First, the aquatic habitats they provide, even with the relatively extensive Dalhousie spring group, are miniscule in any but the most local context. Vents may be as small as one or two metres in diameter, and individual vent outflows larger than a hectare are unusual.

Second, the springs permit the retention of relict species, even though these species may be confined to a relatively small proportion of the springs available. The endemic *Eriocaulon carsonii* is known only in a few of spring groups about Hermit Hill, west of Marree (discovered as recently as 1978 - Symon 1985b), one spring group southeast of Marree, and one spring group in southwestern Queensland, but is extinct in the type locality near Louth, NSW. The species appears to be a tropical relict, as its family is essentially tropical (Jessop 1981) and the genus well represented in the Australian tropics. As well, there are several species for which the main distributions are in temperate regions and which would not be expected in the north east without permanent waters. These include the common duckweed, *Lemna disperma*, and blady grass, *Imperata cylindrica*, recorded only at Dalhousie Springs (Symon 1984; Mollenmans 1989). Others are the 'cutting grass', *Gahnia trifida*, and spikerush, *Baumea juncea*, in several of the spring groups surveyed by Symon (1985b), populations of which are far distant from the species' main distributions on the south-eastern seaboard Third, despite the presence of relict species, the springs have a very limited specific flora of aquatic or semi-aquatic plants (Symon 1984; Roxby Management Services 1984; Symon 1985a, b; Mollenmans 1989). For the 250 spring vents and tails discussed in Roxby Management Services (1984), the spring-specific flora comprises only a dozen or so species including

Fig 7 One extreme of mound spring vegetation. *Melaleuca glomerata* (A), *Phragamites australia* (B) and *Typha domingensis* fringing the very strong flow at Dalhousie Springs. Naturalised date palms (Phoenix sp.) present (Photo T Fatchen)

Fig. 8. The other extreme of mound spring vegetation. Monospecific sward of Cyperus laevigatus (A) covering a vent with a minute water flow near Lake Eyre South. Similar vents dominated by Phragmites australis in background (B). (Photo D. Whiting)

the endemic and relict species discussed above. The flora of spring surrounds is relatively rich by comparison, but generally comprises species of watercourses, floodplains and saline soils which are present in the region away from springs and which, although the springs may influence their distribution and abundance, are not as directly reliant on the spring waters as are the springspecific semi-aquatics.

Fourth, the springs provide more than simply water to the plants in them. Symon (1985a) and Roxby Management Services (1984) both provide evidence that artesian bores, despite apparent similarities with artesian springs in the same area, do not support all the species associated with springs and in particular do not support the endemic and relict species. This clearly must relate to differences in water chemistry, flow and temperature, although the tolerances of the spring-specific flora remain unknown.

The most intensive examination of vegetation on springs is described in Roxby Management Services (1984). Vegetation was sampled for species incidence and relative abundance in some 250 spring vents, tails and bores, in 34 spring groups extending from near Marree to Lake Cadibarrawirracanna. The depauperate nature of the spring vegetation is highlighted by results for species richness and species diversity from this sample, and the influence of spring densities (the number and spacing of vents in a spring group) is also indicated.

The maximum number of species scored in any sampling unit was seven. Median species richness of semi-aquatic plants for the relatively species-rich springs in the large spring groups about Hermit Hill (some 80 km west of Marree) was only three to four species, reducing to one to two in smaller spring groups and on bore drains. Species diversity showed a similar pattern of higher mean diversity in larger spring groups and lower mean diversity in smaller groups and bore drains, with the latter two containing numerous sampling units of zero diversity (monospecific stands), usually of the sedge *Cyperus laevigatus* (Fig. 8). Species richness appeared to be largely independent of wetland area but correlated closely with the number of individual spring vents (regardless of size) in a spring group.

The data were also analysed by principal components analysis (PCA) in a nodal analysis (in the sense of Noy-Meir 1971) from which the extracted principal components can be related to a particular environmental influence. The PCA permitted separation of the influence of spring derived wetland from the putatively similar influences of flooding and major streams.

Species identified through PCA as the 'core' spring flora for this region were the narrow endemic *Eriocaulon carsonii*, the sedges and rushes *Baumea juncea*, *Cyperus gymnocaulos*, *C. laevigatus*, Fimbristylis dichotoma, *Gahnia trifida* and *Juncus krausii*, the reed Phragmites australis and the grass Sporobolus virginicus. With the exception of S. virginicus all are semiaquatic species requiring relatively fresh water: *S. virginicus* appears on mound fringes and on waning springs. The bull rush *Typha domingensis* was not found to be a member of this core group, being almost totally absent from springs in this region though present at bore outlets. This is in marked contrast to the Dalhousie area, where the species is a major component of spring vegetation (Mollenmans 1989), and further underlines the difficulties in attempting to consider all the mound springs as a single bloc. Other species often regarded also as 'spring' species, in particular the various samphires (*Halosarcia* and *Sarcocornia* spp.) were found to be associated either with hypersaline springs or saline watercourses, or with drainage influences generally. They were not associated with the relatively fresh-water mound springs.

Similarity analyses analogous to those already discussed for the Coongie Lakes were applied in the expectation that successional processes, with such a limited flora, should be revealed in a consistent pattern of species composition: waning springs being grouped by their possession of one combination of species, relatively new springs by another combination, and unusual and endemic species grouping together in a similarity analysis. Expectations were not met. Instead, a rather bewildering variety of species combinations appeared which could not be fitted into any rational successional scheme. Indeed, results suggested that random colonisation and extinction processes were largely responsible for the species composition rather than any orderly sequence of species. Further support for this notion comes from Symon (1985b), who indicated that neighbouring and apparently otherwise identical vents could carry totally different vegetation, with different species dominating. Orderly and predictable species' successions do not therefore appear to be occurring.

Such a finding has as its corollary that the springs under study must be highly dynamic, providing continued opportunities for colonisation regardless of competitive differences between the spring species which could normally be expected to result in an eventual competitive exclusion. Further, the dynamics must be on a relatively small time scale, of the order of years rather than the geological time scales usually put forward for spring development, mound accretion and flow decline (e.g. in Greenslade et al. 1985). It is to be hoped that investigations to test these hypotheses will continue. Even without further investigations, this study in particular emphasises our lack of knowledge on the dynamics of vegetation in the north-east, despite a now reasonable knowledge of its composition, distribution and habitat relations.

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12: Aboriginal People

by L. A. HERCUS

INTRODUCTION

'This place was full of [Aboriginal) people one time. When I was a little girl they were everywhere:- Kuyani, Thirrari, Pirlatapa, too many! I am the only one left now.' These were the words of old Alice, the last Kuyani, speaking at Marree in 1968. Today there is no full Kuyani nor anyone who can speak the Kuyani language, but fortunately there are many other people of Aboriginal descent originating from the north east of South Australia. They live mostly in the few townships that are in the general vicinity of their original territories, in Pt Augusta, Marree, Oodnadatta and Birdsville. At one time they were indeed everywhere, as Alice said, they had total occupation of the area, they made use of every possible resource, there was no wasteland, no empty country, no 'desert', everything 'belonged' both in practical terms and in mythology.

Even 20 years ago there were still Aboriginal people working and living on most of the stations and maintaining a link with their country. Today, with the decline of station employment, the area is almost totally empty of Aboriginal people, except in the townships. This is the latest stage in a general movement of people away from their traditional lands, a movement that has been studied in detail by Gale (1966). Apart from the flow of population to centres there has also been, until recent years, a steady numerical decline in the population (Jones & Sutton 1986). From the earliest days of contact and throughout the first two decades of this century it was dramatic and devastating. This was brought home with poignancy by Basedow who visited the north east on a medical expedition just after the influenza epidemic of 1919. He states in his 1920 report, speaking of what is now the Oodnadatta track:

> 'Although the western Aluridja groups and their western neighbours, the WongaPitchas, are still represented by goodly numbers, the population along the more civilised central tracts has suffered alarming losses. The recent influenza epidemic was disastrous, having in many centres like Herrgott Springs and Oodnadatta, almost completely annihilated the resident groups. We were surprised also to note the appalling decrease in the numbers at Anna Creek, once a veritable stronghold of the local tribe .. .'

Old Alice was referring to a much earlier time, when Aboriginal people were 'everywhere'. This was when she was a little girl, in the 1880s, long before Basedow's expedition. Even then the drift and, in some cases, the forced move away from traditional lands had started: people were moving to stations to live on rations, and many people from the eastern half of the Lake Eyre Basin had gone to the great Lutheran mission at Killalpaninna which was set up in 1866. However in the 1880s a high proportion of Aboriginal people in the north east of South Australia remained living traditionally on their own lands

THE LANGUAGES OF THE NORTH EAST DESERTS

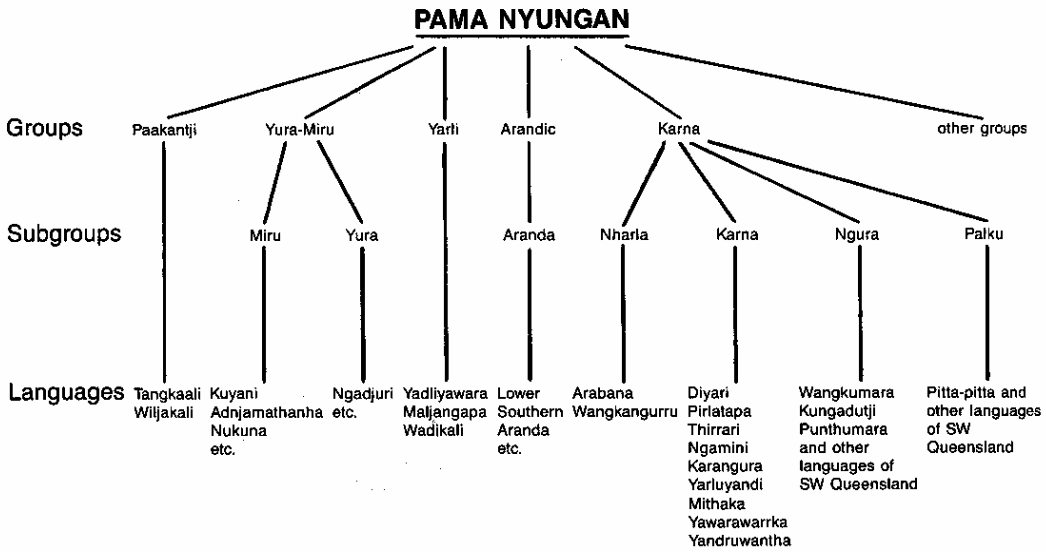
Relationships between the languages

The people who once occupied the north east deserts belonged to a number of different linguistic groups of the one big language family which covers most of Australia, Pama Nyungan. These groups are divided into subgroups. From one subgroup to another these languages were not mutually comprehensible, still less from one group to another. Table 1 summarises the relationships between the languages of the area.

The table implies that the languages of the Eastern Lake Eyre Basin were closely related to each other: Pirlatapa, Diyari, and the languages of the adjacent areas all belonged to the same subgroup, namely the Karna subgroup of the Karnic group. Wangkangurru belongs to a different subgroup, usually labelled Nharla, from the Arabana word for 'man' which is nharla. Maljangapa, Wiljakali and Ngadjuri are not closely related, and belong to three separate groups.

The true language situation was much more complex: there were many similarities amid the diversity. Though people might use different

Table 1. SKETCH OF THE GENETIC RELATIONSHIPS BETWEEN THE LANGUAGES OF THE LAKE EYRE BASIN AND ADJOINING AREAS.



words, there were many similar grammatical and semantic structures that belonged to languages of different groups. Typical of such a 'Lake Eyre Basin' semantic structure was the use of a word meaning 'fruit' which served as an adjunct to names of body parts and other nouns to imply something small and round, hence 'fruit of the eye' meant 'iris of the eye' in Wangkangurru, Diyari, Kuyani and adjacent languages. The structure was identical, although Wangkangurru said kardi, Diyari said tandra and Kuyani said kaka for 'fruit' (Austin et al. 1976), so 'iris of the eye' was

*milki-kard*i in Wangkangurru
miltja-ardi in Arabana
milki-tandra in Diyari
mina-kaka in Kuyani

An example of the diffusion of a grammatical structure is the use of an 'altruistic' (Austin calls it 'benefactive') form of the verb; an affix is added to the stem of transitive verbs to imply that the action is performed on behalf of somebody else. In Arabana-Wangkangurru, as also in Pitta-Pitta (Blake 1979) this affix is *-la*, in Diyari it is *-yirrpa*, *-ipa*, and in Yarluyandi *-pa* (Austin 1981). Thus in Wangkangurru one can say:

athu paka-yira 'I am digging (for yams).'
I dig- PRESENT

athu paka-la-yira 'I am digging (for yams) for somebody else.'
I dig- ALTRUISTIC -PRESENT

similarly in Pitta-pitta (Blake 1979):
mari- to get, *mari-la* 'to get for somebody else'
in Diyari:
kurlka 'to save'
kurlkakurlka-yirrpa- 'to save for somebody else.'

These similarities were not regular in any way, sometimes features appear to have crossed from one subgroup or even group to another. Other features were limited in their geographical extension: there was no overall pattern, no single focal geographical point, but probably a series of areas where linguistic diffusion took place (Hercus 1987). Thus *ng-* is often lost at the beginning of nouns in Arabana-Wangkangurru. It is never lost in Diyari:

Arabana	Diyari	English
apalka	*ngapitha*	dream
apitji	*ngapiri*	father

Yandruwantha and Yawarawarrka are geographically further from Arabana than is Diyari. Nevertheless these two languages have kinship terms where initial *ng-* has been lost, hence Yandruwantha apari, Yawarawarrka apadi 'father'. Special kinship pronouns are used in ArabanaWangkangurru, and only a limited set exists in Diyari and Yarluyandi. Only Yawarawarrka has a consonant cluster *-tk-* as in *mitka* 'lake' (Breen MS).

No doubt at least part of the reason for the complex network of linguistic diffusion was that the population of the whole area was linked by a network of similar social structures: all had a matrilineal moiety system and similar but not identical kinship organisations. This has been described in detail by Elkin (1938-9) and more recently by Scheffler (1978). There were also strong links in trade and exchange (McBryde 1987) as well as mythological and ritual associations.

Fate of the Languages

The disruption of traditional society led to an expansion of linguistic knowledge: people who had originally been monolingual, or only had a slight knowledge of neighbouring languages, found themselves living in close proximity to speakers of other Aboriginal languages in the townships, on stations and particularly at the Killalpaninna mission. Therefore many persons born in those environments in the late nineteenth century were multilingual.

Reuther, writing at the turn of the century (Reuther, microfiche edition 1981) was able to work with living languages and has left a vast store of data. He did not aim to do specific linguistic work, but if it were not for him much information would have been lost. As this century progressed, spoken knowledge of the traditional languages declined dramatically. Karangura was the first to disappear: there are reasons for believing that it became extinct in the first decade of this century. Al/the other languages gradually died in the twenties and thirties. They died in the sense that they were supplanted by English and ceased to be the main means of communication of a distinct group. They ceased to evolve, they were no longer being passed on in their entirety to the next generation, they were no longer a dynamic vehicle for thought. They died, but they did not all die out: they remained in the memory of individual older people and only became totally extinct with the death of these last speakers.

Wadikali became extinct in the thirties with the death of Ned *Palpilina*.

Pirlatapa was lost in 1967 with the death of Fred Johnson, an Adnjamathanha centenarian who in his youth had acquired an excellent knowledge of the language, and who was able to make a short recording in 1966.

Wiljakali became extinct with the death of Dougal Macfarlane in 1967.

Thanks to the dedication of the last knowledgeable speakers it was still possible in the sixties and early seventies to carry out a thorough linguistic investigation of the remaining languages. These studies were obviously undertaken only just in time, they have extended over years and are continuing. S. A. Wurm, pioneering this work in 1957, had collected valuable data on **Maljangapa**, later supplemented by L. Hercus before the death of the last speaker, George Dutton, in 1969. J. G. Breen has worked extensively on the Innamincka dialect of **Yandruwantha**, on **Yawarawarrka** and **Ngamini**. P Austin has made a detailed study of **Diyari** and **Thirrari**. L. Hercus has worked on **Arabana-Wangkangurru**, **Yarluyandi** and **Kuyani**. B. Schebeck was able to record some **Yadliyawara** and some **Kungardutji**. This language was recalled only by one old Yawarawarrka man, Bob Parker. It was originally spoken in Queensland not far over the border from Haddon's Corner.

All of us made use of tape-recorders: the voices of the old people speaking and explaining these languages are there for the future.

Concern about the future is justifiable because by now, Ngamini, Kungardutji, Yadliyawara, Kuyani, and Yandruwantha have become extinct. There are only memories of vocabulary in Yarluyandi and Yawarawarrka: nobody can form a sentence. There is only one speaker of Thirrari:

Ben Murray aged 96. There are two speakers of Diyari and a few elderly speakers each for Arabana and Wangkangurru. Despite the valiant efforts of some Arabana people to introduce Arabana to primary school children at Marree, it is clear that the languages of the north east deserts are on the brink of total extinction.

TRADITIONAL LIFE

Because of the vast scope of the subject I will discuss the lifestyle and follow the fortunes of only two of the groups of people of the north east deserts: the Wangkangurru of the Simpson desert and the Yawarawarrka of the Sturt Stony desert. From the comparison between these two groups we may gain indications that apply to the whole area.

Boundaries

Over recent years there has been some criticism of earlier writers, particularly of Howitt (1904) Elkin (1933) and Tindale (1974), who thought in terms of clear-cut tribal boundaries. The more fluid situation in the Western Desert has

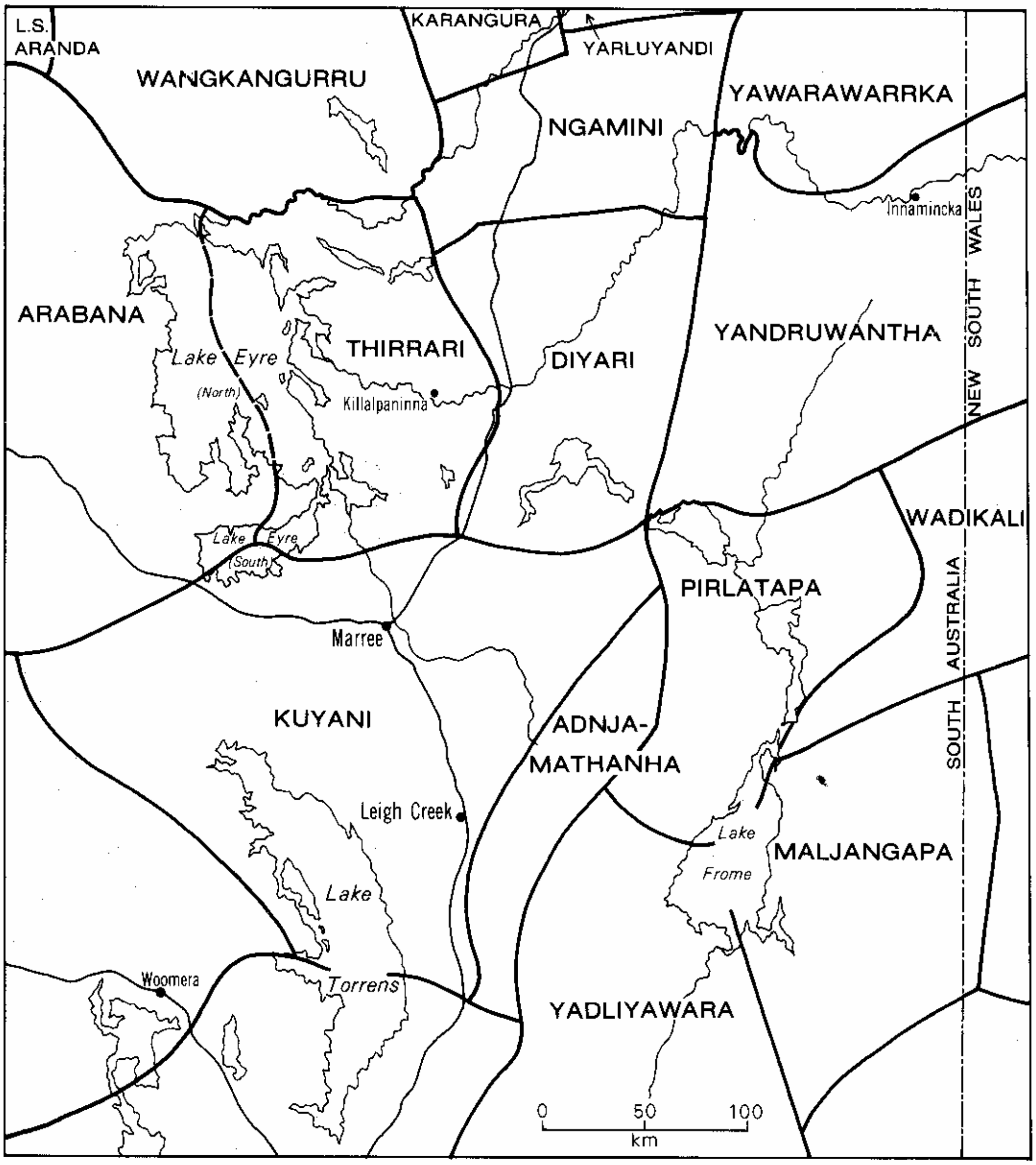


Fig. 1. Tribal boundaries in the north east deserts region.

brought about the idea that there were no real boundaries in the Lake Eyre Basin (Morphy 1972). The views of Howitt, Elkin and Tindale about this area cannot simply be ignored: they were there when traditional systems were much more in place. However it has become evident that traditional territorial boundaries were far more sophisticated than was originally thought. This increased understanding has come about gradually, and is mainly due to the important paper by Stanner (1953) and the 1973 discussions of Peterson (1976). The situation is particularly intricate in the north east where there were complex social and cultural links. Wangkangurru people did not talk about 'boundaries', there is in fact no such word in the language. They thought of the matter positively in terms of who 'owned' an area. They were conscious of a series of places where their territory 'cut out' and somebody else's began. Another way of talking about it was to say that one was 'sorry' because 'that is the end of the country'. This 'cutting out' was viewed in some areas as quite definite, but sometimes it was viewed as more gradual, the neighbouring people may have had 'a right in' an area, i.e. they could come there freely for ceremonies without this being considered an act of aggression. This applied for instance to the Alkaowra Flood Flats, where the lowest channels of the Finke join the Macumba. This area was owned jointly by Lower Southern Aranda and Arabana: Wangkangurru people could also 'join in'. Rights for foraging were strict. Tindale (1974:24) makes it clear that 'trespassing to hunt was one of the main causes of fights between tribes'. There were also intricate internal rules governing where people were allowed to forage. Amongst the Arabana and Wangkangurru men usually went out north from any camp and women south and there were severe punishments for any infringements. The view of territory in the north east deserts was thus not one of boundaries but of a series of places with a complex system as to who had access to them (Fig. 1).

People knew in meticulous detail who owned land: this is clear from all the comments made by traditional people on the subject. In a conversation (26.1.67) two very senior men, Mick McLean (Wangkangurru) and Tom Sagot (Lower Southern Aranda) spoke to L. Hercus about some specific 'boundaries':

M. 'Irlalanha (waterhole) is back from Kumparanha sandhill. That's Arabana country .. .'
L. 'So the border between Arabana and Aranda goes from the Todmorden road across to Macumba?'
M 'South of Macumba just a bit. Then Arabana run right across to that creek (the Macumba) then. There is Wangkatjaka (a subgroup of Wangkangurru) along the Kallakoopah, the whole lot .. .'
L. . 'Arakapaninha (hill).'
M. 'That is all my country (i.e. Wangkangurru).'
L. 'Where do Aranda come in there?'
'M. You got to find Macumba Ck west side, we are east side altogether.'

While showing us sites along the lower Diamantina Mick McLean pointed out Thupuwarrunha

Fig 2 Linda Crombie standing near the remains of a hearth by the Kadlalumba Well in the Simpson Desert, Aug 1987. The eact location of this well was rediscovered by Vlad Potenzy, Abotiginal Herittage Br 1987

'White Smoke', a waterhole on the Diamantina a few miles upstream from New Karlamurina. This, he said, was the last waterhole in Wangkatjaka country and the site for a spell that was said to enable Wangkatjaka clever men to alter the course of the river. Above that the country belonged to the Ngamini, and relations with them were often hostile (see also Horne & Aiston 1924). Similarly when travelling on the Birdsville Track and approaching Mungerannie from the south, different senior Aboriginal people would say on separate occasions: 'This is M*aruPilakani* ("The Wide Plain"). You see the point of that sandhill that runs out into the plain? This is where Diyari cut out and Ngamini start.' People were acutely aware of the fact that there could be changes: thus the Ngamini were frequently accused of being expansionist, and there is clear evidence of Western Desert people displacing Lower Southern Aranda to the west of Oodnadatta (Tindale 1974). This awareness of historical changes did not alter the profound sense of land-ownership.

Life at the Wells

The Wangkangurru *mikiri-nganha* 'Wangkangurru people from the wells' also called themselves 'Wangkangurru *mungathiri-nganha*' 'from the high sandhills' as distinct from the Wangkatjaka or Wangkangurru *karla-nganha* 'from the creek' (the Kallakoopah and the lower Diamantina). The Wangkangurru *mikiri-nganha* were permanent residents of the Simpson Desert.

The most important historical account of the Simpson Desert wells and of the people camped near them comes from David Lindsay in his report of the 1886 expedition. There is further information in the work of Horne & Aiston (1924). Thanks to Maudie Naylon and Mick McLean we have first hand accounts of life in the Simpson desert, before the turn of the century, when Wangkangurru people still inhabited their lands. The Simpson Desert Wangkangurru lived in the desert on a continual basis in spite of the absence of permanent surface water. It was their home. After rains they would range all over the area, around claypans and swamps. Mick McLean described how they prolonged their supply of surface water by building dams across the deeper claypans to retain water; Kimber (1986) gives a similar account. Once even this supply was exhausted they would camp near the mikiri 'native wells'; by combining all sources of information we know now that there were at least 18 of these, of varying popularity and varying quality of water (Fig. 2). The Wangkangurru *mikiri-nganha* belonged to two different local groups, an eastern and a western one. Lindsay's guide Paddy who came from a western well, Murraburt (*Mara-pardi*), did not know the people on the eastern side of the desert.

Fig. 3. The late Frank Crombie near the Wolporican Well, Simpson Desert, August 1987. The exact location of this well was rediscovered by Denis Bartell, 1983.

The Wangkangurru *mikiri-nganha* lived and died at the wells, which provided the only source of water in dry periods (Figs 3, 4). Practically all the wells have burial sites eroding out of nearby dunes: Wangkangurru people buried their dead in shallow graves in the sand. This differed from the Yawarawarrka who followed the customs of more easterly people (Berndt 1964) in building mounds with tree-trunks and soil.

From looking at the minute fragments of animal bones that carpet the ground around the mikiri wells Peter Clark deduced that the main source of meat was small marsupials, bettongs, Caloprymnus, and Lagorchestes and others, as well as dingoes, carpet snakes, emus and other birds (Hercus & Clark 1986). Mick McLean speaking in Wangkangurru described life at the Balcoora well, where he and other children passed the time playing and catching desert chats for food, while the older people went out hunting and foraging:

'We had meat and we were satisfied. We weren't really worrying about food, not like today when people eat every five minutes ... We had plenty of water. There were a lot of humpies there and we all got water from the well, we had a big camp there.' The mode of life was not very different in western Yawarawarrka country except that permanent water came from soakages rather than wells. Life on the larger waterholes on the Cooper

Fig 4 The Beelaka Well is in the shallow depression. The location was rediscovered by Denis Bartell, 1983

had been described in brilliant detail by Ben Kerwin speaking about his early life at Innamincka to J. G. Breen (1986). People there had a more varied diet than in the sandhills and certainly more leisure.

Myths and Songs

The knowledge of myths and songs was the most treasured possession of traditional people. This knowledge provided not only an interpretation of the landscape, it gave meaning to life. The significance of totemic mythology has been described many times, but it is particularly well explained by Stanner (1953).

The expression 'History Time' was used in the north east deserts for the concept of 'Dreamtime'. The Ancestors of the History Time are associated with prominent features of the landscape, they traversed the land in their travels and various happenings on these journeys are reflected in the landscape. This, however cannot be viewed simplistically. There is not a one to one relationship between the myth and the land: one single myth may refer to two different areas, and one single prominent place may have a number of myths associated with it. Some Ancestors are major Cult Heroes, they travel afar and their adventures are celebrated in long song cycles and ritual, often in more than one language. Thus the Urumbula describes the return journey of Malbunga, the Native Cat Ancestor and his group from Pt Augusta to Alice Springs. This song cycle is entirely in Aranda. Each group through whose territory the myth passed, had its own section, and there would be great meetings where the whole cycle would be performed (Strehlow 1970). Similarly the Mindiri Emu ritual and song cycle united all the people from the Wadrawadrinna Waterhole southwest of Innamincka as far as the Lower Cooper. A Duck Egg cycle belonged to all the Cooper people including those further up on the Wilson River. A Wangkumara man, the late George McDermott, could still 'call all the country', he could intone all the names of the sites for this cycle, which formed part of an increase ritual. As he put it: 'If your mob didn't come to the ceremony, your country would miss out.' Some major Ancestors had several 'lines' of travel. The Two Men, the Nail-tailed Wallaby and the Desert Rat-Kangaroo, travelled from their home at Mararu in the central Simpson desert first to the southwest and then to the southeast to teach people about circumcision, and there are major song cycles belonging to this, linking different people. Similarly there is a number of lines of song of the Ancestral Rain linking Arabana and Lower Southern Aranda country, and linking the Wangkangurru to their eastern neighbours. Mick McLean, the last Wangkangurru Rainmaker could sing all these. Ngamini people had yet another Rain cycle. Mick McLean explained this as follows: 'Clouds go anywhere, don't they! So did the Rain in the History Time'. The major myth of the Two Boys from Dalhousie is also associated with the Rain: this myth traverses the Simpson Desert.

The Two Boys took with them the feathers of many small birds and gave them to Karangura people on the west side of Goyder Lagoon for ceremonial decoration. They thereby started the Warrthampa cult, which linked the Wangkangurru with their eastern neighbours: the *Warrhampa* was for the people of the Diamantina what the *Mindiri* was for the people of the Cooper.

There is no doubt about the importance of the major cults. There were however many minor Ancestors, their story might 'only go a short way', and have only a few songs, if any. They could also playa small role in the adventures of major Cult Heroes. The following summary of the Mosquito History is given to illustrate the importance of such minor myths.

The Mosquitoes

There are some porous-looking rocks in the bed of Boy Creek in Arabana country where it leaves the tableland, close to Lake Eyre. This is the home of the Mosquito Dreaming, *Yuwinja*. In the myth the Rainbow Brothers were returning from the *Wiljaru* Secondary Initiation ceremony at Mt Midlarguna. As they approached the bend of Boy Creek near the hills called Purrthakanha 'They have been bitten', the Rainbow Brothers were attacked by the Mosquitoes and their ally the Marchfly, who is still represented by a pointed rocky hill. The Brothers ran to some small sandhills which now have little vegetation: the Rainbow Brothers had pulled out all the bushes to try to beat off all those swarming insects. The Brothers, bleeding from numerous bites and screaming ran as fast as they could. They got away and returned to their home further south at Blanket Waterhole, the lowest waterhole on the Neales before it reaches Lake Eyre. This was called *Pilparu-palthiyangunha*, 'Split by Lightning', because the whole camp was ultimately destroyed. The huge circular boulders around the waterhole represent the dead Rainbow people.

This Mosquito myth is only a minor part of Arabana mythology: there seems to be nothing much to it. It has however to be seen in context.

a. This myth gave good entertainment value; the story-teller enjoyed the antics of the frenzied Rainbow Brothers.
b. The story gave life and meaning to the countryside around Boy Creek.
c. Minor rituals were associated with the Mosquito rocks: people used to go there to sing chants intended to rid the countryside of mosquitoes, or to make mosquitoes swarm all over their enemies.
d. The Mosquito myth had significance for material culture: at the back of one of the hills that form part of Purrhakanha 'They have been bitten' is a red ochre mine. The ochre is said to have come from the drops of blood of the Rainbow Brothers.
e. The Mosquitoes only travelled a few miles, but there was a wider History importance in that all the participants in the Mosquito myth had links not only with the Rainbow Brothers but through them to one of the major cults, the *Wiljaru*. It was the profusion of minor myths like the Mosquitoes myth that gave such wealth and diversity to the History Time.

EUROPEAN CONTACT

Wangkangurru and Yawarawarrka people were at opposite extremes with respect to European contact: The Simpson Desert was not taken over by Europeans, Wangkangurru people left it voluntarily. The Yawarawarrka however experienced dispossession and persecution right from the beginning of the contact period.

Wangkangurru

Wangkangurru people must have heard tales about the coming of the Europeans by the later eighteen sixties. Small groups of Wangkangurru men certainly found out about the newcomers at first hand when they went on their traditional ochre expeditions to Parachilna in the Flinders Ranges (Hercus 1985). The bulk of the population however had never seen Europeans. There came a rude awakening when (probably in the early eighteen eighties), some eastern Wangkangurru people went to a great *Warrthampa* ceremony which was to be performed at the Kalidawarry waterhole near Lake Muncoonie in southwestern Queensland: Practically all who took part were murdered by the police in retribution for the death of a white man (Hercus 1986).

The first European to travel through Wangkangurru country was J. W. Lewis who led an expedition along the lower Kallakoopah, the country of the Wangkatjaka group of the Wangkangurru. He described the area as 'simply frightful' (Threadgill 1922). He established a camp at what he called Tommy's well, which must have been close to or at a place called *Waltawaltanha*. He set off a little way up the creek. He was not encouraged by what he saw:

> 'Tommy's well is undoubtedly permanent and fresh, but the country around it is abominable; to take a view from any slight elevation of the bare sandhills, sandcliffs and utter want of vegetation is sufficient to create thirst, without having to travel over it.'

He then went further east through Wangkatjaka country along the Warburton. This was in 1874-5.

It took over a decade for the first European traveller to reach the Wangkangurru of the Simpson desert. This was David Lindsay, who with the help of a Wangkangurru guide named Paddy visited nine of the wells in the Simpson Desert in January 1886. He came there to check the water resources of the wells to see whether the area was suitable for pastoral development. Fortunately the area was not taken up, though some sections added to the Cowarie lease in the eighteen eighties extended a long way into the desert. Whatever may have been his intentions, Lindsay conducted himself well towards Wangkangurru people; moreover - unlike most other explorers - he did not impose new names on the wells or on any other features of the country he traversed. Through the links with the outside world and presumably also through Lindsay it eventually became known in the Simpson Desert that Europeans were not all evil, and that there were good things to be had, such as regular supplies of food at stations and missions. So people gradually began to leave (Hercus 1985); the last groups departed in 1899-1900. It was at Poonarunna that Mick McLean's group first saw bullocks and were given European food, bread and jam, which they did not at first like, as well as clothes, which they initially found most unpleasant, constricting and itchy. They never returned to the desert on a permanent basis, though some older people made nostalgic visits, and the mikiri country was left uninhabited.

The Simpson Desert Wangkangurru were the last people in the Lake Eyre Basin to come into immediate contact with Europeans, they were also the most traditional and the most persistent as regards their own language and culture. When it came to staying at Killalpaninna mission or at centres like Birdsville the bulk of the Wangkangurru were the last to come in and the ones most ready to move off. Because of their attachment to traditions their old men were naturally the most interesting people for anyone to talk to about the old ways, even more so than the Wangkangurru from the Kallakoopah and the lower Diamantina. Therefore the works on the traditions of the Lake Eyre Basin, such as Horne & Aiston (1924), are largely based on what was learnt from Simpson Desert Wangkangurru people. The great work undertaken by the Reverend Reuther at the turn of the century at the Killalpaninna Mission gives vast materials on the languages and traditions of the eastern Lake Eyre Basin. It is based mainly on Diyari, as Killalpaninna was in Diyari country, but it also shows a tremendous input from Wangkangurru people. The last survivors of those born in the desert, Mick McLean *Irinjili* (c. 1888-1977) of Pt Augusta and Maudie Naylon *Akawiljika* (c. 1885-1981) of Birdsville recorded a vast corpus of mythology and song in Wangkangurru for the present writer.

Yawarawarrka

Yawarawarrka people were particularly unfortunate in their early contacts with Europeans. Settlement followed exploration in tremendous haste, and amid a display of greed that has few parallels. The activities of station-managers like J. W. Wylie who was at Coongie from 1881, and the notorious Johnnycake Miller are well known (Farwell 1950; Tolcher 1986): they fenced Yawarawarrka people out of their own lands and poisoned or shot anyone that returned. Yawarawarrka country was the scene of a large scale massacre, recalled vividly in oral tradition for almost

Fig 5 A Yawarawarrka grave near Cordillo Downs. Chippie Flash is showing it to a younger man

a century by people throughout the eastern Lake Eyre Basin. It happened probably not long after the *Warrhampa* massacre, in the eighteen eighties on the western edge of Yawarawarrka country at Cooncherie Point, a great ritual centre, where the point of the Cooncherie sandhill forms a peninsula, jutting out into the waterhole. A large number of people, not only Yawarawarrka, but also Karangura, Diyari, Yarluyandi and Ngamini had assembled there for the *Mindiri* emu ritual. The entire group, men, women and children, were cut off at the narrow point of the peninsula and shot, and the bodies were burnt: all this to avenge the theft of a young bullock. Only three men escaped, one by feigning death and two by diving into the waterhole (Hercus 1986). The remaining Yawarawarrka people sought refuge in the more easterly section of their country at Cordillo (Fig. 5), but they were soon to be displaced from there also. Some fled to Killalpaninna mission, while others ultimately settled at Innamincka, among Yandruwantha people, and others went still further afield to Tibooburra and Silverton in N.SW. The whole area from around Coongie to Araburry was abandoned completely and became known as *Ngura-warla* 'empty camp' (Breen 1971). This name, spelt 'Ngura-wola' by Tindale, has sometimes mistakenly been regarded as a tribal name. The area abandoned included some of what was originally Kungadutji country as well as Yawarawarrka. Deep attachment for the country ultimately brought just a few back to Yawarawarrka land, to Lew Reese's station 'Minnie Downs' on the Apamurna waterhole in the first decade of this century.

The Yawarawarrka name is *Ngapa-mana*, which means 'bad water' and refers to the fact that the waterhole was brackish, as were the soakages in the creek. Frank Crombie, a Wangkangurru man who was reared on this station at the time of the First World War, described in detail how, for practically nothing but their rations, both old and young were made to work from dawn to dusk, including an old Yawarawarrka woman named Judy and old Peter Parker Waya-waya, the ritual leader of the western Yawarawarrka (Fig. 6). Lew Reese was not hostile to Aboriginal traditions and there was even one final Yawarawarrka Mindiri emu ceremony held nearby on the shores of the huge claypan called Lake Etamunbanie (*Ita-manpa-ni* 'Go over that way!', named from an incident in the Emu History). There was an initiation, probably in the early twenties, at *Thirriljanha* 'Shining' an area of flat ground on the *Ngapa-mana* waterhole as it broadens out towards the edge of the lake. This site belongs to the Two Men of the Initiation

Fig 6 The remains of Waya=waya humpy at Ngapa-mana

History and was a major initiation place, both in the mythology and in actuality. This was the last flicker of revival of independent Yawarawarrka traditions.

Later initiations of Yawarawarrka men took place only at the Innamincka *Irpanji* (circumcision) site. The last ceremony there was in 1941, with Yandruwantha and Wangkumara people from Queensland. The men in charge were Lazy George, a Wangkumara, and Charlie' Murray who was Yawarawarrka. After this all rites were discontinued, even at Innamincka.

Today there is not a single Yawarawarrka person on traditional Yawarawarrka land, but there are, in Birdsville, Quilpie and Pt Augusta, descendants of those who escaped to Innamincka: these descendants have a particular attachment not as much to Yawarawarrka country as to Innamincka where they were brought up. The tragedy of the displacement and decline of the population of the north east deserts was brought home by Murtee Johnnie, the only survivor of the Strzelecki Desert Yandruwantha (as distinct from the Innamincka group). Murtee outlived the rest of his people by decades. He was nearly a hundred years old when I saw him for the last time. He was blind and crippled, and was being well cared for at the Wami Kata Home in Pt Augusta. Yet he would always pack and repack his suitcase, saying: 'I want to go back to my own country, **my** country with the red sandhills.'

Much of the information in this chapter comes directly from former inhabitants of the north east deserts. The author is particularly indebted to the late Mick McLean *Irinjili* and Maudie Naylon *Akawilijika*.

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13 Mammals

by C. M. KEMPER

INTRODUCTION

Early knowledge stems from collecting during exploration along Cooper Creek and in the Lake Eyre region, and was associated with construction of the telegraph line between Marree, Oodnadatta and the NT. border. P. M. Byrne (after whom the kowari, *Dasyuroides byrnei*, is named) was an enthusiastic collector at the Charlotte Waters telegraph station in the early part of the century. But, it wasn't until the 1930s, when H. H. Finlayson studied the mammals of the Lake Eyre Basin (Finlayson 1933, 1935, 1936, 1939a,b), that any part of the area was studied comprehensively. Finlayson (1961) returned in the 1950s and reported the decline or absence of many of the species formerly present. In the past 20 years some studies (Aitken 1968; Dept of Environment & Planning 1984; Davey et at. 1985) simply have compiled existing information, while others (Watts & Aslin 1974; Foale 1982; Mollenmans et at. 1984; Reid & Gillen 1988) have reported field observations.

The mammal fauna is rich by arid zone standards, with 46 native and ten introduced species recorded (Table 1). This richness possibly is due to the diverse nature of the habitats. The gibber plains, sand-hill country, river floodplains and fringing woodlands, and stony tablelands all support mammal species. It is unfortunate that many of the mammals that have inhabited the region formerly are now locally, and some entirely, extinct. Most of the locally extinct species are medium-sized e.g. bandicoots, bilbies, hare wallabies, rat-kangaroos and bettongs. Occasionally there are reported sightings of supposedly 'long-gone' species, and it should be noted that new species of small mammals have been discovered in the last decade.

MAMMALS IN MAJOR GEOGRAPHIC ZONES

Seven major geographic zones (Fig. 1) representing different landforms and vegetation types, are found in the north east of South Australia. Some (e.g. Marree, and Lake Frome) are more or less uniform whereas others (watercourse woodlands and Lake Eyre) are diverse in nature.

Table 2 shows the number of species recorded for each of the major geographic zones. This varies between 45 for the watercourse woodlands of the Cooper and Strzelecki Creeks and Diamantina River, and six for the Simpson Desert. It should be noted that several factors, including survey efforts, may account for the differences in species richness.

Watercourse habitats provide an oasis for scientists and consequently have been relatively well studied. Conversely, areas such as the Simpson Desert, are very inaccessible and inhospitable and so have never been seriously surveyed for mammals. Further collecting there will undoubtedly uncover many of the 17 species recently recorded by Gibson & Cole (1988) in the NT. portion of the Simpson Desert.

Despite the differences in collecting effort between some areas, it seems plausible that watercourse habitats would support more mammal species. They have grassy floodplains, trees and standing water, at least intermittently. The floodplains provide food for herbivorous and granivorous rodents which in turn are food items for the marsupial predators. Large trees provide roosting sites for bats (seven species are recorded from the watercourses) and, in the past, nesting hollows for the now locally extinct brushtail possum, *Trichosurus vulpecula*. Permanent water provides a suitable environment for the water-rat, *Hydromys chrysogaster*, and a moister environment in general, with abundant insect life to feed the bats and insectivorous marsupials.

One final factor should be taken into consideration when interpreting the species' counts in Table 2. The long, thin nature of the watercourse zones substantially increases the edge effect and thus the chance of animals from other zones 'spilling over' into them.

NATIVE MAMMALS

Forty-six species of native mammal have been recorded - one monotreme, ten dasyurids, the marsupial mole, four bandicoots, one possum, seven macropods,11 bats, 11 rodents (Table 1).Ten are believed to be either locally or entirely extinct.

Table 1. MAMMAL SPECIES RECORDED FROM THE NORTH EAST OF SOUTH AUSTRALIA. Museum specimens lodged at the South Australian, Queensland, Western Australian and Australian Museums. Other records are from various literature sources. *According to Wood Jones (1923-25) a specimen is in SAM. but it now cannot be located.

Common Name	Scientific Name	Museum Record	Other Record	Regional Status
MONOTREMES				
short-beaked echidna	*Tachyglossus aculeatus*		x	rare
DASYURIDS				
kultarr	*Antechinomys laniger*	>1960	x	uncommon
mulgara	*Dasycereus cristicauda*	>1960	x	rare
kowari	*Dasyuroides byrnei*	>1960	x	uncommon
quoll	*Dasyurus sp.*			extinct
wongai ningaui	*Ningaui ridei*	>1960	x	rare
paucident planigale	*Planigale gilesi*	>1960	x	uncommon
narrow-nosed planigale	*Planigale tenuirostris*	>1960	x	rare
fat-tailed dunnart	*Sminthopsis crassicaudata*	>1960	x	common
striped-faced dunnart	*Sminthopsis maeroura*	>1960	x	common
Ooldea dunnart	*Sminthopsis ooldea*	>1960	x	rare
MARSUPIAL MOLE				
marsupial mole	*Notoryctes typhlops*	<1940		rare
BANDICOOTS AND BILBIES				
pig-footed bandicoot	*Chaeropus ecaudatus*	SAM?*	x	extinct
golden bandicoot	*Isoodon auratus*		x	extinct
greater bilby	*Macrotis lagotis*	1941-60	x	extinct?
lesser bilby	*Macrotis leueura*	<1940	x	extinct
POSSUMS				
common brushtail possum	*Trichosurus vupecula*	<1940	x	extinct
MACROPODS				
burrowing bettong	*Bettongia lesueur*		x	extinct
desert rat-kangaroo	*Caloprymnus campestris*	<1940	x	extinct?
western grey kangaroo	*Maeropus fuliginosus*	<1940		rare
eastern grey kangaroo	*Maeropus giganteus*	>1960	x	rare
red kangaroo	*Maeropus rufus*		x	uncommon
euro	*Maeropus robustus*		x	rare
crescent nailtail wallaby	*Onychogalea lunata*		x	extinct
BATS				
little red flying fox	*Pteropus scapulatus*	>1960	x	rare
yellow-bellied sheathtail-bat	*Saccolaimus flaviventris*	>1960	x	uncommon
Gould's wattled bat	*Chalinolobus gouldii*	>1960	x	common
chocolate wattled bat	*Chalinolobus morio*		x	rare
Finlayson's eptesicus	*Eptesicus finlaysoni*	>1960	x	rare
inland eptesicus	*Eptesicus baverstoeki*	>1960	x	common
lesser long-eared bat	*Nyetophilus geoffroyi*	>1960	x	common
western broad-nosed bat	*Scotorepens palstoni*	>1960	x	rare
little broad-nosed bat	*Scotorepens greyii*	>1960	x	common
little mastiff-bat	*Mormopterus planiceps*	>1960	x	common
white-striped mastiff-bat	*Tadarida australis*	>1960	x	common
RODENTS				
water-rat	*Hydromys chrysogaster*	>1960	x	uncommon
Forrest's mouse	*Leggadina forresti*	>1960	x	uncommon
greater stick-nest rat	*Leporillus conditor*	<1940	x	extinct
spinifex hopping-mouse	*Notomys alexis*	>1960	x	uncommon
fawn hopping-mouse	*Notomys cervinus*	>1960	x	rare
dusky hopping-mouse	*Notomys fuscus*	>1960	x	rare/common
plains mouse	*Pseudomys australis*	>1960	x	rare

Bolam's mouse	*Pseudomys bolami*	>1960		rare
desert mouse	*Pseudomys desertor*	>1960		rare
sandy inland mouse	*Pseudomys hermannsburgensis*	>1960	x	common
long-haired rat	*Rattus villosissimus*	>1960	x	rare/common
INTRODUCED SPECIES				
house mouse	*Mus domesticus*	>1960	x	common
European rabbit	*Oryctolagus cuniculus*		x	common
dingo/wild dog	*Canis tamiliaris*	>1960	x	common
fox	*Vulpes vulpes*	>1960	x	uncommon
cat	*Felis catus*	>1960	x	common
donkey	*Equus asinus*		x	rare
wild horse	*Equus caballus*		x	common
European cattle	*Bos taurus*		x	common
Arabian camel	*Camelus dromedarius*		x	uncommon
wild pig	*Sus scrofa*	>1960	x	rare

Table 2. NUMBER OF MAMMAL SPECIES RECORDED IN SEVEN GEOGRAPHIC REGIONS OF NORTH EAST SOUTH AUSTRALIA. See Fig. 1 for explanation of regions. Additional records are from literature and personal communications. Numbers in parentheses are introduced species, included in totals.

	SiD	StD	WW	CG	LEO	M	LF
Specimen Records	2	12	31	17	18	12	11
Additional records	4	5	14	4	7	7	3
Total	6(5)	17(4)	45(10)	21(4)	25(6)	19(5)	14(4)

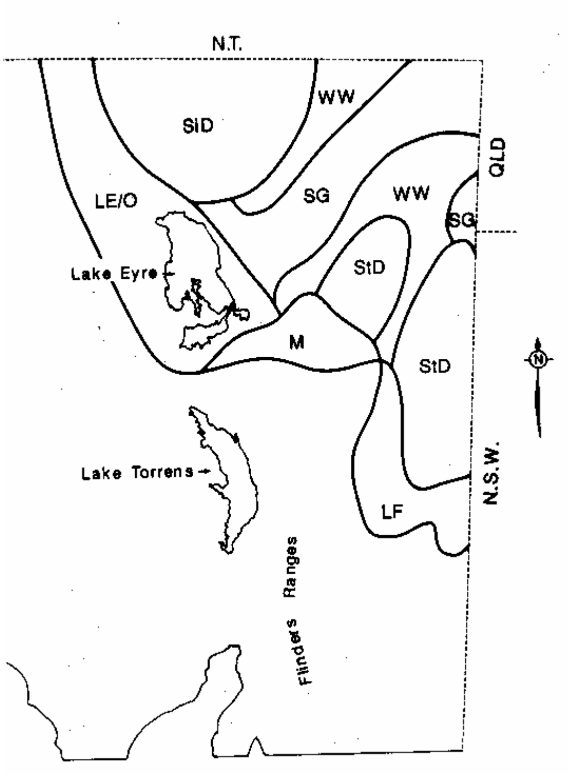

Fig 1 Major geographic zones based on a map of vegetation formations produced by Woods & Forests Dept SA in 1980 SiD=Simpson Desert, StD-Strezlecki Desert, WW=Warecourse woodlands, Cg=Central grasslands, LE/O-Lake Eyre/Oodnadatta region, M=Maree region, LF=Lake Frome

The short-beaked echidna is rare there, and indeed over much of the Australian arid zone. The most recent sighting was made along Cooper Creek near Innamincka in the 1970s (Reid & Gillen 1988). Finlayson (1936) considered it always uncommon and noted that, although found in a variety of habitats, it seemed more common in stony country.

Of the dasyurid marsupial species, two (the fattailed, *Sminthopsis crassicaudata*, and the stripefaced, *S. macroura*, dunnarts), are common in a variety of habitats. The Ooldea dunnart (*Sminthopsis ooldea*) apparently occurs only in the west, around Oodnadatta. All three species have the ability to store fat in the tail. Gibson & Cole (1988) recorded the lesser hairy-footed dunnart

S. youngsoni in the NT. sector of the Simpson Desert but it remains unknown from SA. The kultarr, *Antechinomys laniger* (Fig.2), is a small, attractive dasyurid with a tufted tail. When travelling at high speed, it bounds on all four feet in a ricochetal action. The kultarr can be confused with hopping-mice (*Notomys spp.*) until closer inspection reveals rows of sharp teeth, instead of the large upper and lower gnawing incisors typical of rodents. The kowari, *Dasyuroides byrnei* (Fig. 3), and the mulgara, *Dasycercus cristicauda*, are two, medium-sized dasyurids with bushy tails. Both are considered rare/uncommon but, because population abundance may vary considerably from year to year depending on resources (Gibson & Cole 1988) and because they are cryptic animals, it may be difficult to ascertain their true status. Live mulgara were recorded in 1990 from the Mt Dare/Dalhousie area and the kowari has been collected and sighted several times within the last five years. In the NT. sector of the Simpson Desert the mulgara is uncommon but widespread.

Fig. 2. *Antechinomys laniger*, the kultarr, lives in open country and shelters in logs, stumps, beneath bushes or in other animals' burrows. Photo: R. Miller.

There is some confusion as to whether the western quoll, *Dasyurus geofroii*, ever lived in the north east deserts. Finlayson (1933) recorded that Aboriginal people talked of a 'spotted' animal on the Barcoo (lower Cooper) but later (1961) dismissed the possibility that the western quoll ever lived in the area. Spencer (1896) describes a specimen taken at Crown Point, N.T., 100 km north-west of Mt Dare Homestead. Two species of S.A. planigale are found in the north east deserts. Both are restricted to areas of cracking clay soils, usually associated with watercourses, claypans or gibber plains. Reid & Gillen (1988) showed that they could inhabit the same location, separated by subtle differences in the environment.

Fig. 3. *Dasyuroides byrnei*, the kowari, is a medium· sized dasyurid marsupial weighing up to 140g. It eats insects, small vertebrates and carrion.

Another very small dasyurid, the wongai ninogaui (*Ningaui ridei*), was first found in the north east in 1987 by Reid & Gillen (1988). Since *Ningaui* species live in spinifex and sandy habitats it is likely that the wongai ningaui will be found in the Simpson Desert. These tiny marsupials, planigales and ningauis, were unknown to early collectors (e.g. Finlayson 1933, 1961) and have come to light only since the advent of pitfall trapping in the 1960s. Byrne collected the marsupial mole, *Notoryctes typhlops*, in the general vicinity of Oodnadatta. Considering its preference for sand-hills, it is likely that this cryptic species will be found in the Simpson Desert sooner or later.

Before European settlement, the golden bandicoot (*Isoodon auratus*), pig-footed bandicoot (*Chaeropus ecaudatus*), greater bilby (*Macrotis lagotis*) and lesser bilby (*M. leucura*) occurred in the north east deserts (Kemper in press). With the possible exception of the greater bilby (Fig. 4), none remains. Recent investigations by S. Carr (pers. comm.) have established that the greater bilby still occurs in the Birdsville district. The pigfooted bandicoot (now extinct) apparently never was common in the arid zone (Aitken 1983).

The brushtail possum, *Trichosurus vulpecula*, once was common in the river red gums along the Cooper and Diamantina, with thousands of skins being taken in the early days (Tolcher 1986). By the 1930s Finlayson reported that it was extremely rare. The brushtail possum spends a .good deal of time feeding on the ground and perhaps disappeared for much the same reason as the bandicoots.

Fig. 4. *Macrotis lagotis*, the greater bilby, was once common in the north east but it is now considered extinct there. There are extant populations just across the border, in Queensland.

No species of macropod, including the red kangaroo (*Macropus rufus*), is common. Before the turn of the century the burrowing bettong, *Bettongia lesueur*, probably was fairly abundant but is now extinct there. There is some speculation that the brushtail bettong, *B. penicillata*, may have had a wide distribution in the arid zone (Burbidge et al. 1988) and so occurred in the north east. Another small macro pod (the desert rat kangaroo, *Caloprymnus campestris*), is known only from the Diamantina and adjacent grasslands. Originally described in the 1840s, Finlayson reported it plentiful on the stony plains of what is now Clifton Hills Station, in the 1930s. No positive reports have been made since that time although occasional sightings of a small macropod kindle the hope that the species is extant. However, the elusive animals could be burrowing bettongs or desert rat-kangaroos. Rock wallabies have been mentioned as possible inhabitants of the western edge of the north east but the reports have not been substantiated.

Of the 11 bat species recorded, seven are primarily tree-roosters and would find abundant places to shelter along the major river courses. The chocolate wattled bat, *Chalinolobus morio*, and Finlayson's eptesicus, *Eptesicus finlaysoni*, are two species which inhabit caves. Their distribution in the north east probably is restricted to the west and south. The little red flying-fox, *Pteropus scapulatus*, is an inhabitant of northern Australia, but several vagrants have been recorded in South Australia (Reardon & Flavel 1987). Another occasional and possibly seasonal visitor is the yellow-bellied sheath tail-bat, *Saccolaimus flaviventris*. It appears almost every Easter at Dulkaninna Station (S. Bell pers. comm.) and there are sporadic records elsewhere from March to May.

Rats and mice occur throughout the north east. Some species, such as the plains mouse (*Pseudomys australis*) and the long-haired rat (*Rattus villosissimus*), may become abundant following good rains (Finlayson 1939b); many a camper has been pestered by the gnawing of the long-haired rat during plagues. Between plagues (the last was in 1974-76) this species is reduced to small populations associated with the Diamantina and Cooper drainage systems, Although Finlayson (1939b) recorded the plains mouse to be abundant during the early 1930s, it is now considered very rare, but was recorded in good numbers in the Mt DarelDalhousie region in 1990.

Forrest's short-tailed mouse, *Leggadina forresti*, is a species which does not form plague populations. It is widespread but most commonly found on hard or stony substrates. In contrast to the solitary behaviour of Leggadina, hopping-mice (*Notomys* spp.) live in communal burrow systems. Three species live in the north east and, with our limited knowledge, seem to have different habitat preferences. Both *N. alexis* and *N. fuscus* (Fig. 5) live in the sandy country. *N. fuscus prefering* tussock grassland as opposed to *Triodia*; *N. cervinus* is an inhabitant of gibber plains. All hopping-mice use bipedal locomotion when travelling at high speeds, a tactic probably employed to escape predators. Another interesting feature of the hopping-mice is that they can live without free water, so are well adapted to desert life. *Hydromys*, the water-rat, is at the other end of the water-conserving spectrum. It lives near permanent water, in which it swims and finds its food

Fig. 5. *Notomys fuscus*, the dusky hopping-mouse, lives in tussock grassland and *Triodia* country. During the day, when it is inactive above ground, it shelters in deep burrows. Photo: H. Aslin

of fish and shellfish. It is known from the Diamantina and Cooper rivers (Finlayson 1939; Reid & Gillen 1988).

The greater stick-nest rat, *Leporillus conditor*, was once an inhabitant of the breakaway country around Lake Eyre and Oodnadatta. In 1907 a captive colony from the Lake Eyre region built the sticknest now on display at the South Australian Museum. The large stick-nests are the only reminders of its former existence on mainland Australia (Copley 1988).

One species of mouse listed in Table 1, Bolam's mouse (*Pseudomys boami*), is not a true inhabitant since it is found only at the southern part of the study area, near Lake Frome.

INTRODUCED MAMMALS

Ten species of mammal have been introduced by man (Table 1). While their effects on the native fauna are imperfectly known it is believed that some may have had adverse effects, either directly or indirectly. The dingo has been hunted and fenced out of southern areas but remains abundant north of the dog fence. The two other introduced predators, the cat and fox are wide-spread and at times abundant. The fox is less common north of the fence, apparently because it is preyed upon and competes with the dingo (P. Bird pers. comm.). All of the introduced predators eat rabbits as well as native animals and their abundance is controlled by the abundance of prey items. Rabbit numbers fluctuate considerably, from a few to several thousand per square kilometre. Plague proportions were reo corded in 1975 and 1988. Introduced herbivorous mammals have effected enormous changes to the natural vegetation. The wild pig is rare in the north east but more abundant in the channel country of south-west Queensland. Concern has been expressed that it could become a problem along the waterways of the Cooper and Diamantina because of the suitability of these habitats.

The camel is restricted to sandy areas of the western Simpson Desert, extending down to Lake Eyre, and the Strzelecki Desert around Moomba and Innamincka (Animal and Plant Control SA pers. comm.). The donkey is found on stony soils in the Oodnadatta/Mt Dare region and in the vicinity of Murnpeowie Station in the far north of the Flinders Ranges (P. Bird pers. comm.). The house mouse, *Mus domesticus*, is common and widespread.

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14. Birds

by J.R.W. REID, F. J. BADMAN & S. A. PARKER

INTRODUCTION

The deserts of the north east support a relatively rich avifauna, which includes a wide variety of waterbirds, many colourful land birds and the State's one endemic species, the Chestnut-breasted Whiteface.

The avifauna, while perhaps depauperate in comparison with those of the forested and wooded biomes of the southern, eastern and northern periphery of Australia, comprises more species than that of any other truly arid region for which data exist (Parker 1980b; Reid 1988a). This richness stems largely from the presence of two major river-systems (the Cooper and the Diamantina-Warburton) and the consequent diversity of often specialised wetland and dryland habitats.

Apart from the landforms associated with the major watercourses and their floodplains, two other major landform groups (see Laut *et al. 1977)* have a strong influence on bird distributions within the region: the sandy deserts, typified by the Simpson and Strzelecki dunefields, and the stony or gibber deserts. Certain birds are characteristic of these two landform or habitat groups, although the number of species involved is far less than that associated with the major watercourse systems.

Salt lakes constitute important if highly ephemeral aquatic habitat, while other distinctive landforms or features provide additional habitat for birds *e.g.* the natural mound springs (Badman 1985) and the artificial artesian bore-drains (Badman 1987a). These point water-sources are major foci for bird activity *(e.g.* Badman 1987a), as are, to a lesser degree, the myriad cattle troughs and tanks in the pastoral areas. A surprising percentage of birds inhabiting Australian deserts *(ca* 47% *fide* Schodde 1982a) depends on the availability of free water.

While many birds are generalists, occurring widely through the region, others are of more restricted occurrence because of specialised habitat preferences, while yet others enter the region seasonally (as breeding or non-breeding migrants), or opportunistically (nomads) as conditions allow - generally in response to rainfall and flooding.

Breeding can be highly episodic (Reid 1988a), although a spring breeding pulse at least is probably an annual occurrence (Schodde 1982a; F.J.B. unpubl.), and some species *(e.g.* Australian Raven - Rowley 1983) can apparently breed only from early winter to early summer.

Accurate information on both the movements and breeding cycles is limited, largely because of the sparse human population and the virtual absence of resident ornithologists. Few ornithological observations made over a long period have been documented. Of most value have been those of Badman (1979, 1987a, in press), Badman & May (1983) and May (1984, 1986), while L. R. Reese of Minnie Downs (an abandoned homestead on present-day Pandie Pandie Station) made an invaluable contribution with a series of published bird-notes in the 1920s and 1930s.

Here we review the literature, and analyse distribution patterns. Limitations of space do not permit individual treatment of the 225 species reliably recorded: these are listed with a few annotations in Table 1. We then describe some intriguing strategies employed by Australia's arid zone birds (taking examples from the north east) that also illustrate features common to desert life, namely ephemerality, rapid community-shifts, rapid life-cycles, drought evasion, drought resistance, and 'plasticity'. Schodde (1982a) presents a more detailed review of these strategies.

English names are used in the body of the text, except where taxonomic discussion necessitates the use of scientific names. Taxonomy and nomenclature follow Parker (1985).

ORNITHOLOGICAL HISTORY

Captain Charles Sturt and his party were the first Europeans known to have penetrated the region and to have made observations on its natural history. Notable among their specimens was the first recorded Night Parrot, collected by John McDouall Stuart near Lake Goyder on 15 October 1845 (Forshaw *et al.* 1976). The distinguished early naturalist and collecter F. W.

Table 1. ANNOTATED LIST OF SPECIES FOR WHICH THERE ARE ACCEPTABLE RECORDS FROM THE NORTH EAST OF SOUTH AUSTRALIA.

Key to Annotations

* Precedes those 13 species referred to in text which are much more plentiful or of more regular occurrence in adjacent regions to the east, south and west.

1. Habitat Preference. U: ubiquitous or present in a wide range of habitats; W: woodland and tall shrubland, often associated with watercourses or floodplain features but including mulga and gidgee stands; D: dunefield; G: gibber and stony tableland; A: aquatic or usually in the vicinity of water; S: shrubland (e.g. lignum, chenopod, sandhill wattle); 0: open plains and swales; P: playas; -: habitat specialised (e.g. artesian bore, township) or poorly known.
2. Abundance in Appropriate Habitat. C: from regularly encountered in low numbers to plentiful; U: uncommon and occasionally encountered; R: rare; I: infrequent or vagrant visitor; P: rare, being confined to periphery of region; D: declined to (near) extinction within region.
3. Breeding Status and Mobility. B: breeding confirmed; N: breeding not reported and considered unlikely to breed; -: no information (nor judgement) on breeding status; ?B: evidence for breeding; W: winter visitor predominantly; S: summer visitor predominantly; '(W/S)': regular influx in season indicated; M: wide-ranging, mobile species that may be migrants or nomads into, through and within the region.

SPECIES	ANNOTATIONS		
	1.	2.	3
Emu *Dromaius novaehollandiae*	U	C	B,M
Great Crested Grebe *Podiceps cristatus*	A	R	N,W
Hoary-headed Grebe *Poliocephalus poliocephalus*	A	C	B,M
Black-throated Grebe *Tachybaptus novaehollandiae*	A	U	B,M
Australian Pelican *Pelecanus conspicillatus*	A	C	B,M
Darter *Anhinga melanogaster*	A	U	B
Great Cormorant *Phalacrocorax carbo*	A	C	B
Little Pied Cormorant *Phalacrocorax melanoleucos*	A	U	B,M
Little Black Cormorant *Phalacrocorax sulcirostris*	A	C	B
Pied Cormorant *Phalacrocorax varius*	A	C	B
Great Egret *Ardea alba*	A	C	?B
Little Egret *Ardea garzetta*	A	R	N,M
Intermediate Egret *Ardea intermedia*	A	R	N,M
White-faced Heron *Ardea novaehollandiae*	A	C	B
Pacific Heron *Ardea pacifica*	A	C	B,M
Cattle Egret *Bubulcus ibis*	A	I	N
Nankeen Night Heron *Nycticorax caledonicus*	A	C	B
Yellow-billed Spoonbill *Platalea flavipes*	A	C	B
Royal Spoonbill *Platalea regia*	A	C	B,M
Glossy Ibis *Plegadis falcinellus*	A	C	B, (8)
Sacred Ibis *Threskiornis aethiopicus*	A	U	N
Straw-necked Ibis *Threskiornis spinicollis*	A	C	B,M
Magpie Goose *Anseranas semipalmata*	A	0	
Plumed Whistling-Duck *Dendrocygna eytoni*	A	U	B,M
Black Swan *Cygnus atratus*	A	C	B
Freckled Duck *Stictonetta naevosa*	A	U	B,M
Mountain Duck *Tadorna tadornoides*	A	C	B
Chestnut Teal *Anas castanea*	A	I	N
Northern Shoveler *Anas clypeata*	A	I	N
Australasian Grey Teal *Anas gracilis*	A	C	B,M
Blue-winged Shoveler *Anas rhynchotis*	A	U	-,M
Pacific Black Duck *Anas superciliosa*	A	C	B
Hardhead *Aythya australis*	A	C	B,M
Wood Duck *Chenonetta jubata*	A	C	B
Pink-eared Duck *Malacorhynchus membranaceus*	A	C	B,M
Musk Duck *Biziura lobata*	A	U	B,M
Blue-billed Duck *Oxyura australis*	A	R	?N,W
Collared Sparrowhawk *Accipiter cirrhocephalus*	W,D,S	U	B,M
Brown Goshawk *Accipiter fasciatus*	W,D,S	U	B,(W)
Wedge-tailed Eagle *Aquila audax*	U	C	B
Swamp Harrier *Circus approximans*	A	U	B,M

Spotted Harrier *Circus assimilis*	U	C	B,M
Black-shouldered Kite *Elanus caeruleus*	U	U	B,M
Letter-winged Kite *Elanus scriptus*	U	U	B,M
Whistling Eagle *Haliastur sphenurus*	U(A,W)	C	B
Black-breasted Buzzard *Hamirostra melanosternon*	U(W)	U	B
Black Kite *Milvus migrans*	U	C	B,M
White-bellied Sea-Eagle *Haliaeetus leucogaster*	A	R	B
Little Eagle *Hieraaetus morphnoides*	U(W)	C	B
Brown Hawk *Falco berigora*	U	C	B,M
Nankeen Kestrel *Falco cenchroides*	U	C	B,M
Grey Falcon *Falco hypoleucos*	U	R	B,M
Little Falcon *Falco longipennis*	U(W)	U	B
Peregrine Falcon *Falco peregrinus*	W	I	N
Black Falcon *Falco subniger*	U	C	B,M
Stubble Quail *Coturnix novaezelandiae*	U	C	B,M
Swamp Quail *Coturnix ypsilophora*	O	I	N
Brolga *Grus rubicundus*	A,O	U	B,M
Australian Bustard *Ardeotis australis*	U	U	B,M
Red-chested Button-quail_ *Turnix pyrrhothorax*	0	I	N
Little Button-quail *Turnix velox*	U	C	B,M
Coot *Fulica atra*	A	C	B
Dusky Moorhen *Gallinula tenebrosa*	A	U	B
Black-tailed Native-hen *Gallinula ventralis*	A	C	B,M
Banded Landrail *Gallirallus philippensis*	A	I	N
Purple Swamphen *Porphyrio porphyrio*	A	C	B
Australian Spotted Crake *Porzana fluminea*	A	C	B,M
Baillon's Crake *Porzana pusilla*	A	R	N,M
Spotless Crake *Porzana tabuensis*	A	U	-,M
Southern Stone-curlew *Burhinus grallarius*	A,W	R	?B
Plains Wanderer *Pedionomus torquatus*	0	I	N
Painted Snipe *Rostratula benghalensis*	A	I	N
Mongolian Plover *Charadrius mongolus*	A	I	N,S
Red-capped Dotterel *Charadrius ruficapillus*	A(O)	C	B,M
Oriental Dotterel *Charadrius veredus*	0	I	N,S
Black-fronted Dotterel *Eiseyornis melanops*	A	C	B
Red-kneed Dotterel *Erythrogonys cinctus*	A	U	B,M
Inland Dotterel *Peltohyas australis*	G,O	U	B
Lesser Golden Plover *Pluvialis fulva*	A	I	N,S
Grey Plover *Pluvialis squatarola*	A	I	N,S
Masked Plover *Vanellus miles*	A	C	B
Banded Plover *Vanellus tricolor*	O,A	C	B,M
Banded Stilt *Cladorhynchus leucocephalus*	P	U	B,M
White-headed Stilt *Himantopus leucocephalus*	A	C	B
Red-necked Avocet *Recurvirostra novaehollandiae*	A	C	B,M
Common Sandpiper *Actitis hypoleucos*	A	R	N,S
Turnstone *Arenaria interpres*	A	I	N,S
Sharp-tailed Sandpiper *Calidris acuminata*	A	C	N,S
Knot *Calidris canutus*	A	I	N,S
Curlew Sandpiper *Calidris ferruginea*	A	U	N,S
Pectoral Sandpiper *Calidris melanotos*	A	R	N,S
Red-necked Stint *Calidris ruficollis*	A	C	N,S
Long-toed Stint *Calidris subminuta*	A	R	N,S
Latham's Snipe *Gallinago hardwickii*	A	R	N,S
Grey-tailed Tattler *Heteroscelus brevipes*	A	I	N,S
Black-tailed Godwit *Limosa limosa*	A	R	N,S
Little Curlew *Numenius minutus*	A	I	N,S
Whimbrel *Numenius phaeopus*	A	I	N,S
Lesser Yellowlegs *Tringa flavipes*	A	I	N,S
Wood Sandpiper *Tringa glareola*	A	R	N,S
Greenshank *Tringa nebularia*	A	U	N,S
Marsh Sandpiper *Tringa stagnatilis*	A	U	N,S

Terek Sandpiper *Xenus cinereus*	A	I	N,S
Oriental Pratincole *Glareola maldivarum*	O,A	I	N,S
Australian Pratincole *Stiltia isabella*	O,A	C	B,(S}
Whiskered Tern *Chlidonias hybridus*	A	C	B,M
White-winged Black Tern *Chlidonias leucopterus*	A	N,S	
Caspian Tern *Hydroprogne caspia*	A	C	B
Gull-billed Tern *Gelochelidon nilotica*	A,(G}	U	B,M
Silver gull *Larus novaehollandiae*	A	C	B
Feral Pigeon *Columba livia*	-	I	N
Diamond Dove *Geopelia cuneata*	W,D,S	C	B
Peaceful Dove *Geopelia placida*	W	C	B
Crested Pigeon *Ocyphaps lophotes*	U	C	B
*Common Bronzewing *Phaps chalcoptera*	W,S	R	
Flock Pigeon *Phaps histrionica*	U	U	B,M
*Major Mitchell *Cacatua leadbeateri*	W,S	I	B
Galah *Cacatua roseicapilla*	U	C	B
Little Corella *Cacatua sanguinea*	U	C	B
Red-tailed Black Cockatoo *Calyptorhynchus magnificus*	W	R	B,M
Cockatiel *Nymphicus hollandicus*	U	C	B,M
Red-winged Parrot *Aprosmictus erythropterus*	W	D	?B,M
*Ring-necked Parrot *Barnardius zonarius*	W	C	?B
Budgerigah *Melopsittacus undulatus*	U	C	B,M
"Bourke's Parrot *Neophema bourkii*	W,(G}	U	B
Blue-winged Parrot *Neophema chrysostoma*	U	U	N,W
Scarlet-chested Parrot *Neophema spendida*		I	N
Bluebonnet *Northiella haematogaster*	W,(O}	C	B
Night Parrot *Pezoporus occidentalis*	P,O,S	R	?B,M
Red-rumped Parrot *Psephotus haematonotus*	W	C	B
Mulga Parrot *Psephotus varius*	W	P	
Fan-tailed Cuckoo *Cacomantis flabelliformis*	W	I	N
Horsfield's Bronze Cuckoo *Chrysococcyx basalis*	U	C	B,M
*Black-eared Cuckoo *Chrysococcyx osculans*	W,S	R	N,M
Pallid Cuckoo *Cuculus pallidus*	U	C	B,M
Channel-billed Cuckoo *Scythrops novaehollandiae*	W	D	B,S
Barking Owl *Ninox connivens*	W	U	?B
Boobook Owl *Ninox novaeseelandiae*	W,S	U	-,M
Barn Owl *Tyto alba*	U	C	B,M
Grass Owl *Tyto capensis*		I	
Owlet-night jar *Aegotheles cristatus*	W	C	B
"Spotted Nightjar *Eurostopodus argus*	U	U	B,M
Tawny Frogmouth *Podargus strigoides*	W	C	B
Fork-tailed Swift *Apus pacificus*	U	R	N,S
Red-backed Kingfisher *Halcyon pyrrhopygia*	W,D	C	B,M
Sacred Kingfisher *Halcyon sancta*	W	U	N,?S(M)
Dollarbird *Eurystomus orienta lis*	W	I	N
Rainbow Bird *Merops ornatus*	U(A}	C	B,S
Singing Bushlark *Mirafra javanica*	G,O	U	?B,(S}
White-backed Swallow *Cheramoeca leucosternum*	U	C	B
Fairy Martin *Hirundo ariel*	U	C	B,M
Welcome Swallow *Hirundo neoxena*	A	U	B,M
Tree Martin *Hirundo nigricans*	W	C	B,M
Clamorous Reedwarbler *Acrocephalus stentoreus*	A	U	B,M
Brown Songlark *Cincloramphus cruralis*	U	C	B,M
Rufous Songlark *Cincloramphus mathewsi*	W	C	B,M
Little Grassbird *Megalurus gramineus*	A	U	B,M
Chestnut-crowned Babbler *Pomatostomus ruficeps*	W,S	C	B
*White-browed Babbler *Pomatostomus superciliosus*	W,S	U	B
Grey-crowned Babbler *Pomatostomus temporalis*	W	P	
Grey Grasswren *Amytornis barbatus*	S	R	B
Eyrean Grasswren *Amytornis goyderi*	D	C	B
Thick-billed Grasswren *Amytornis textilis*	S(G}	U	B

Variegated Wren *Malurus lamberti*	S,W	C	B
White-winged Wren *Malurus leucopterus*	U	C	B
Rufous-crowned Emu-wren *Stipiturus ruficeps*	D	U	B
Inland Brown Thornbill *Acanthiza apicalis*	W,S	P	
*Yellow-rumped Thornbill *Acanthiza chrysorrhoa*	W	R	
Chestnut-rumped Thornbill *Acanthiza uropygialis*	W,S	U	B
Southern Whiteface *Aphelocephala leucopsis*	W,S	C	B
Banded Whiteface *Aphelocephala nigricincta*	D,S	C	B
Chestnut-breasted Whiteface *Aphelocephala pectoralis*	G(S)	R	B
Western Fieldwren *Calamanthus campestris*	S	U	B
Redthroat *Pyrrholaemus brunneus*	W,S	R	
*Weebill *Smicrornis brevirostris*	W	R	
Red-browed Pardalote *Pardalotus rubricatus*	W	C	B
Striated Pardalote *Pardalotus striatus*	W	U	B,(W)
Spiny-cheeked Honeyeater *Acanthogenys rufogularis*	W,S	U	B,(W)
Pied Honeyeater *Certhionyx variegatus*	W,S	R	N,M
Black Honeyeater *Sugomel niger*	W,S	R	B,M
Grey Honeyeater *Conopophila whitei*	W	I	N
Painted Honeyeater *Grantiella picta*	S	I	N
Yellow-throated Miner *Manorina flavigula*	W	C	B
White-plumed Honeyeater *Meliphaga penicillata*	W	C	B
Singing Honeyeater *Meliphaga virescens*	U	C	B
Golden-backed Honeyeater *Melithreptus laetior*	W	R	B
*White-fronted Honeyeater *Phylidonyris albifrons*	W,S	I	N
Gibberbird *Ashbyia lovensis*	G,O	U	B
White-fronted Chat *Ephthianura albifrons*	O,S	I	B
Orange Chat *Ephthianura aurifrons*	U	C	B,M
Yellow Chat *Ephthianura crocea*	A	R	B
Crimson Chat *Ephthianura tricolor*	U	C	B,M
Brown Treecreeper *Climacteris picumnus*	W	C	B
Jacky Winter *Microeca leucophaea*	W	R	-,?W
*Hooded Robin *Melanodryas cucullata*	W	U	-,M
Red-capped Robin *Petroica goodenovii*	W,S	U	B,(W)
Grey Shrikethrush *Colluricincla harmonica*	W	C	B
Crested Bellbird *Oreoica gutturalis*	W,S	U	-,?M
*Rufous Whistler *Pachycephala rufiventris*	W	U	N,W
Restless Flycatcher *Myiagra inquieta*	W	R	?N,(W)
Grey Fantail *Rhipidura fuliginosa*	S,W	U	N,W
Willie Wagtail *Rhipidura leucophrys*	W,S,A	C	B,(W)
Magpie-lark *Grallina cyanoleuca*	A,W	C	B,M
Cinnamon Quailthrush *Cinclosoma cinnamomeum*	G,D,O	C	B
Chirruping Wedgebill *Psophodes cristatus*	S	C	B
Chiming Wedgebill *Psophodes occidentalis*	W	U	
Apostlebird *Struthidea cinerea*	W	P	
Black-faced Woodswallow *Artamus cinereus*	U	C	B
White-breasted Woodswallow *Artamus leucorynchus*	W(A)	C	B
Masked Woodswallow *Artamus personatus*	U	C	B,M
White-browed Woodswallow *Artamus superciliosus*	U	U	B,M
Black-faced Cuckooshrike *Coracina novaehollandiae*	W	C	B,M
Ground Cuckooshrike *Pteropodocys maxima*	W	U	B
White-winged Triller *Lalage sueurii*	U	C	B,M
Little Crow *Corvus bennetti*	U	C	B,M
Australian Raven *Corvus coronoides*	W	C	B
*Grey Butcherbird *Cracticus torquatus*	W	R	
Pied Butcherbird *Cracticus nigrogularis*	W	P	
Australian Magpie *Gymnorhina tibicen*	U	C	B
Olive-backed Oriole *Griolus sagittatus*	W	I	N
Mistletoebird *Dicaeum hirundinaceum*	U	C	?N,W
Richard's Pipit *Anthus novaeseelandiae*	U	C	B
Zebra Finch *Poephila guttata*	U	C	B,M
House Sparrow *Passer domesticus*		U	B
Starling *Sturnus vulgaris*	W	I	N

Andrews, accompanying the J. W. Lewis expedition of 1874-75, encountered the Night Parrot along the Cooper and around the margins of Lake Eyre, and obtained further specimens. On the same trip Andrews also collected the first specimens of the Eyrean Grasswren, a species not positively recorded again for almost 100 years (May 1977a; Parker *et al.* 1978). In 1863, Samuel White undertook ornithological exploration along the lower reaches of the Cooper; Parker (1980a) has documented White's most notable discoveries there, including breeding records of Plumed Whistling-Duck, Letter-winged Kite and Flock Pigeon and a specimen of the Channelbilled Cuckoo. Lyons (1902) visited Lake Eyre in 1901 as a member of Prof. Gregory's expedition and published a few bird notes.

The first thorough documentation of the region's bird life was made by Captain S. A. White (son of Samuel), ornithologist on the South Australian Museum expedition led by E. R. Waite in 1916. The party traversed the Strzelecki and Cooper creeks as well as the stony country to the north of Marree. White (1917a,b) recorded 103 species on this trip.

The next 20 years saw ornithological progress over most of the region. J. Neil McGilp documented observations made in the Lake Callabonna district, incorrectly referred to by McGilp in his writings as the Lake Frome District (McGilp 1919, 1921, 1923), and was instrumental in the discovery of a huge breeding colony of Banded Stilts on Lake Callabonna (McGilp & Morgan 1931). Whitlock (1924) traversed the westernmost parts of the region during his unsuccessful search for the Night Parrot, while Cleland (1925) presented an annotated species list for the easternmost districts north of Lake Callabonna. Parsons (1921), Nicholls (1924) and Morgan (1930) made observations along the Birdsville Track. L. R. Reese, a pastoralist in the Far North, communicated regularly with the South Australian Ornithological Association; his bird lists and notes extracted from 19 letters were published in the *South Australian Ornithologist (1924*1936) and principally covered the corner of the State west to the Diamantina River and south to the Coongie and Goyder Lagoon districts.

Little ornithological activity ensued for the next 35-40 years (Brandon 1951; Glover 1957; Miller 1961), but in the past 15-20 years ornithologists have 'rediscovered' the north east, recognising the richness and variety of its avifauna. The vast expanse of the South Australian section of the Simpson Desert had to await ornithological exploration until this latter period (May 1977a,b, 1984; Parker *et al.* 1978; Badman 1979), while important contributions relating to the wider region include Rix (1972, 1974), Cornish & Ellis (1974), Black (1975), Cox & Pedler (1977), Pedler & Ragless (1978), Parker (1980b), Cox (1982), Badman & May (1983), Reid (1984, 1988a), Badman (1985, 1987a,b, in press) and May (1986). This recent flurry of activity has resulted in six records new for the State - Grass Owl and Grey Grasswren (Cox 1976) Rufous-crowned Emu-wren (Parker *et al.* 1978), Northern Shoveler (Close & Jaensch 1981), Yellow Chat (Black *et al.* 1983) and Lesser Yellowlegs (Reid 1988b) - and the rediscovery of 'lost' species such as Eyrean Grasswren and Rufous crowned Emu-wren (May 1977a; Parker *et al.* 1978), Night Parrot (Parker 1980b) and Golden-backed Honeyeater (Badman in press). In addition came recognition of the significance of the region for bird conservation *(e.g.* Reid & Vincent 1979, Parker 1980b; Foale 1982; Mollenmans *et al.* 1984; Dept Lands 1986; Reid & Gillen 1988).

HABITATS AND PATTERNS OF DISTRIBUTION

In their study of the Mt Dare district Davey *et al.* (1985) recognised three basic terrains: stony dissected tableland, floodplain and floodouts, and dunefields'j Purdie (1984) recognised three corresponding major 'land zone complexes' in the Simpson Desert. Mollenmans *et al. (1984)* adopted a similar classification for the Cooper Creek region, but recognised claypans and saltlakes as a fourth category.

Relatively few species occur throughout the north east. Most are restricted by habitatrequirement to particular areas. Thus, patterns of avian distribution can often be explained on the basis of habitat. However, because of their mobility, some birds may be encountered beyond their preferred habitat(s); thus, habitat preferences indicated in the following subsections (and Table 1) should not be regarded as definitive.

A biogeographic approach is also instructive. Pairs of closely related allopatric taxa include Chiming and Chirruping Wedgebills, Western and Grey Shrikethrushes, and Port Lincoln and Mallee Ringnecks. In each of these three cases the first bird occurs eastwards to the western margin of the region (e.g. Blakers *et al.* 1984); the Chirruping Wedgebill occurs widely over the rest of the region (Ford & Parker 1973; Reid 1984), the Mallee Ringneck is confined to the upper portion of the Cooper Creek (Reid 1984), while the Grey Shrikethrush is present along the Diamantina as well as the Cooper. This east-west replacement of related taxa is a striking feature of avian distribution patterns in the north east, and is apparently a consequence of the Eyrean Barrier

(Ford & Parker 1974; Schodde 1982a); Parker (1980b) provides further examples.

Within the four broad habitat-groups defined above, many discrete habitats can be recognised on the basis of vegetation and landform. Distinctive bird communities occur in each habitat, though the composition may vary from one district to another (partly due to the broader biogeographic patterns mentioned above).

Various habitat classifications have been used. May (1984, 1986) adopted the most systematic approach for his studies in the Simpson Desert (12 habitats) and Innamincka Station (14 habitats) respectively. Badman (1987a) compiled a detailed account of birds encountered at bore-drains, one of the specialised habitats that cannot be assigned to any of the broad groups. A more general (and community-oriented) approach was used by Reid (1984, 1988) and Badman (in press) in their studies of the avifauna of various parts of the Cooper Creek, while Davey *et al. (1985)* indicated habitat preferences for species occurring in Witjira National Park (16 habitats identified).

In the next section, drawing upon the above syntheses and primary data-sources together with our own personal observations, we discuss dryland species that show pronounced preferences in habitat.

Salt Lakes

No species is restricted to salt lakes. When dry, as they usually are, these harsh environments support few birds. The characteristically saline or gypseous sandy surrounds are often vegetated with a low open chenopod shrubland, frequented by such species as the Brown Hawk, Orange Chat and the ubiquitous Richard's Pipit, Whitewinged Wren and Black-faced Woodswallow.

A wide variety of waterbirds has been recorded on salt lakes filled by rains or floodwaters *(e.g.* McGilp 1923). In the latter event the water can be fresh, supporting huge populations of fish (Pedler & Ragless 1978), which in turn can attract large numbers of pelicans, cormorants, terns and gulls (Badman in press; I. A. May pers. comm.). Waterfowl and the small shore-waders also may be common, while large breeding concentrations occasionally develop, such as with pelicans on Lake Eyre (Parker *et al.* 1979) and Banded Stilts on Lake Callabonna (McGilp & Morgan 1931).

Gibber and Dissected Tableland

Several species are largely restricted to stony terrains (Fig. 1): Chestnut-breasted Whiteface, Thick-billed Grasswren, Inland Dotterel, Bourke's Parrot, Singing Bushlark, Western Fieldwren and Gibberbird; the first two species are confined to them. Each species favours particular habitats within this broad category.

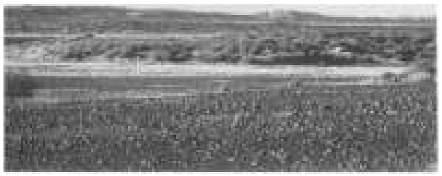

Fig. 1. Sparsely vegetated gibber plains, home to the Gibberbird and Inland Dotterel, and intruding sand dunes clothed with sandhill canegrass, habitat for the Eyrean Grasswren (Photo P. Canty).

The whiteface, fieldwren and grasswren are encountered in areas (often undulating, and predominantly in the southwestern part of the region) carrying a moderate cover of taller chenopod shrubs. The dotterel and Gibberbird favour the barer stony plains, whereas the bush lark occurs seasonally (summer-autumn generally) in grassy pockets (clay lenses, gilgais and swamps with mitchell grass *Astrebla pectinata* being particularly favoured) scattered through the gibbers in the north-eastern part of the region (Lawson & Parker 1976). Bourke's Parrot inhabits minor watercourses lined with coolibah *Eucalyptus microtheca,* red mulga *Acacia cyperophylla* and gidgee A. *cambagei,* and is generally seen in the far west of the region (Badman 1979, 1981), and in the tablelands north of Innamincka (Reid 1984, 1988a).

Major watercourses are a focus for bird activity within the gibber landscape. Along them a wide range of species is encountered, including Diamond Dove, Little Corella, Galah, Red-backed Kingfisher, Owlet-night jar, cuckoos, robins, wrens, honeyeaters, Southern Whiteface, Chestnutrumped Thornbill, Red-browed Pardalote, Mistletoebird, Grey. Butcherbird, Pied Butcherbird, Australian Magpie and corvids. This richness contrasts sharply with the generally sparse birdlife on the surrounding gibber slopes and plains.

Other interesting species of the gibber complex include Australian Bustard (grassy creek-flats) Flock Pigeon (floodouts) Cinnamon Quail-thrush and, in the winter months, the Blue-winged Parrot, a visitor to inland Australia from its wooded breeding grounds in south-eastern Australia and Tasmania (Parker 198Gb).

Dunefield

The entire known range of the Eyrean

Grasswren is circumscribed by the limits of the Simpson, Tirari and Strzelecki Deserts (Schodde 1982b). The species' economy is tied to the sandhill cane-grass *Zygochloa paradoxa* (Parker *et al.1978;* Parker 1980b), which it uses for food, shelter and nesting. Another member of the family Maluridae (Australo-Papuan wrens) is the Rufous-crowned Emu-wren, whose presence in the north east has only recently been detected (May 1977b, Parker *et al.* 1978). There, the species is apparently confined to the Simpson Desert, associating particularly with lobed spinifex *Triodia basedowii,* the dominant plant of dune slopes and sandy swales (National Parks and Wildlife Service 1984; Purdie 1984).

The Banded Whiteface is found throughout the Simpson and Strzelecki deserts, generally where taller shrubs *(e.g. Acacia ligulata)* are prominent. It also strays onto the gibbers where such taller shrubs occur. Other species favouring the shrubbier parts of the dunefields include the Redcapped Robin (mainly a winter visitor); Singing Honeyeater, Variegated Wren and occasionally Chirruping Wedgebill and babblers (Chestnutcrowned in the Strzelecki and White-browed in the Simpson). The Redthroat also occurs in the Simpson (May 1984), in gidgee-dominated swales in the eastern portion, and in *Acacia* spp. *Eremophila longifolia* communities in the western portion of the Desert.

White-winged Wrens are the most abundant residents within the dunefield environment, while the attractive White-backed Swallow is a common sight either overhead or at its burrow in the side of a dune or sandy bank. The Cinnamon Quailthrush is widespread, although nowhere plentiful, and even under the driest conditions a walk along sparsely vegetated swales will disturb the occasional Richard's Pipit or Black-faced Woodswallow. The Australian Magpie also is encountered frequently, though the desert populations are far less tame than those of southern districts. In contrast, Brown Hawks can be approached closely.

Major Watercourses and Floodplains

Birdlife along the major watercourses is prolific, especially in the river red gum woodlands of'the Upper Cooper (Fig. 2), to which the Barking Owl and Mallee Ringneck *Barnardius zonarius barnardi* are restricted. Other species confined to the Cooper Creek system are Red-rumped Parrot, Jacky Winter, Brown Treecreeper and Golden-backed Honeyeater.

Species encountered commonly in the coolibah and red gum woodlands that line the region's major watercourses are referred to in Chapter 10 although community composition differs with the river system. For example, Red-tailed Black Cockatos are recorded along the Diamantina and Fke Rivers (Badman 1979, I. A. May pers comm), but no longer occur along the Cooper (Reid 1984).

Fig. 2. Fairy Martin - gathering mud with which it builds colonial mud nests, usually attached to river red gums, coolibahs or human structures such as culverts. (Photo J. Gillen).

Generally, birdlife along the Cooper and Diamantina is more similar than that encountered along the western drainage lines.

The diversity and density of birds declines rapidly with distance from the major channels and fringing woodland (Reid 1984), but several other important floodplain habitats can be identified. The Grey Grasswren is confined to a few dense lignum beds on the Diamantina and Cooper systems (Cox 1976; Badman in press), while the extensive tracts of samphire and the samphirelike *Sclerolaena intricata* may be important for the rarely seen Night Parrot (Parker 1980b). Floodouts, margins of swamps and lakes, and the normally dry, ephemeral lake-beds along the two river systems often carry a surprisingly lush and dense herbland/low shrubland, frequented by Flock Pigeons, Emus, quail, songlarks and a range of other species (and may constitute important habitat for the Night Parrot).

The region's floodplains support a highly significant and striking population of raptors. Breeding densities, calculated along the Strzelecki Creek, are among the highest in the world (Mace 1981). Especially significant is the occurrence of Grey Falcon, Black-breasted Buzzard and Letter-winged Kite, together with numbers of the usyally sparse Little Eagle and Black Falcon. Also of interest is the repeated occurrence of White-bellied Sea-Eagle in the Coongie Lakes region (Reid 1988a; M. Steel pers. comm.).

The Cooper and Diamantina flow into South Australia virtually every year, and are graced with permanent waterholes. The reliability of flow is considered to account for the richness of the

Fig. 3. Black-fronted Dotterel - a common, small wader found on temporary pools and margins of lakes and channels. (Photo J. Gillen).

floodplain's avifauna, and for that of the entire region. The presence of water in an otherwise arid region has allowed the development of the structurally diverse riparian woodland habitats along the major channels, as well as providing the essential resource for the many species dependent on free water (Fig. 3). Structurally diverse vegetation is correlated positively with a high diversity of bird species (Krebs 1978). Another important factor is the value of river red gums and coolibahs in providing shelter and roosting and nesting sites; both trees readily develop hollows used by many birds *e.g.* parrots, some birds of prey and nocturnal birds, Sacred Kingfisher and Brown Treecreeper (Reid 1984). These riparian woodlands are the preferred habitat for the majority of the dryland birds, while the many and varied wetland habitats associated with the two river systems support the great majority of the waterbirds.

The major rivers appear to have played a significant role in shaping the present-day avifauna, as attested by several distinctive and restricted riparian populations. For instance, in the Mallee Ringneck *Barnardius zonarius barnardi,* Bluebonnet *Northiella haematogaster,* Grey Shrikethrush *Colluricincla h. harmonica* and Jacky Winter *Microeca l. leucophaea,* the north east populations are distinctively paler than those elsewhere, so much so that the last three are sometimes recognised as separate subspecies *(N. h. pallescens,* C. *h. anda,* M. *l. barcoo).* In addition the Cooper's Creek-Strzelecki Creek populations of the Red-rumped Parrot *Psephotus haematonotus* are not only paler but markedly different in hue, and are recognised as constituting a well-marked subspecies *P. h. caeruleus* Condon, 1941 (Parker 1980b). In three of the abovementioned species-groups, vicariant taxa occur in the far west of the region: Port Lincoln Ringneck *B.* z. *zonarius,* Mulga Parrot *Psephotus varius* and Western Shrikethrush C. *h. rufiventris,* while the red-vented form of the Bluebonnet, *N. h. haematogaster* is found to the south-west (Badman 1979), south and east (Blakers *et al.* 1984). Also, populations of *Barnardius zonarius, Psephotus haematonotus, P. varius* and *Colluricincla harmonica* occur in the North Flinders Ranges, from where they penetrate the southern parts of the north east along watercourses emanating from the ranges *(e.g.* Tindlepena Creek). Undoubtedly these watercourses, with their riparian corridors, continue to be important routes in this vast arid region.

An Impoverished Dryland Avifauna?

Reid (1984) observed that several species absent from or scarce in the north east occurred in adjacent regions, citing the examples of Weebill, Yellow-rumped Thornbill and Whitefronted Honeyeater. Badman's collation (in press) of records of these species has supported the observation. Reid (1988) gave other examples (such as Major Mitchell, Hooded Robin and Grey Butcherbird), and suggested two reasons for their absence or scarcity: the lack of mallee and mulga habitats within the region, and the prevailing openness of Sturts Stony, Simpson and Strzelecki deserts. He concluded that the consequent dearth of shrubby habitats accounted for the absence or limited occurrence of many species. A possible correlated factor is the greater aridity (reflected by average annual rainfall) compared with that of neighbouring regions.

Species absent from the region or confined to its extreme margin are Mulga Parrot, Splendid Wren, Inland Thornbill, Varied Sittella, Whitebrowed Treecreeper, Brown Honeyeater, Greyfronted Honeyeater, Grey-crowned Babbler and Pied Butcherbird. Most of them are encountered regularly in mulga habitats of adjacent regions. Thirteen more (asterisked in Table 1) are scarce in the north east, and many are encountered commonly in mulga and associated habitats. Furthermore, some others (e.g. Chestnut-rumped Thornbill, Crested Bellbird and Spiny-cheeked Honeyeater), without necessarily being scarce in the north east, are less plentiful there than in adjacent regions.

Of the 22 species referred to above, 19 occur regularly in the North Flinders Ranges, 21 regularly in southwest Queensland and northwest New South Wales, and 20 in northwest South Australia (data primarily from Blakers *et al. 1984).* Fewer species are encountered more regularly in the region to the north of the Simpson and Strzelecki deserts. The southern and western boundaries of the north east closely approximate the limits of regular occurrence of the suite of species under discussion, and are considered biogeographically significant. However, the northern and eastern boundaries are political, with more natural boundaries occurring further east and north where extensive stands of mulga are encountered.

WATERBIRDS IN THE NORTH EAST

The substantial areas of wetland in the north east fed by the major river systems of the Lake Eyre Drainage Basin set this region apart from any other arid region in Australia. The regional waterbird populations are at times stunning for their variety and sheer numbers. Major, if irregular and unpredictable, breeding episodes also are characteristic of the shallow, ephemeral, nutrientrich wetlands typical of the region (Reid & Gillen 1988), although some species apparently breed regularly in response to the initiation of flow e.g. Yellow-billed Spoonbill (Reid 1988a; Chapter 10) and probably the Darter, cormorants and herons. These contrasting reproductive strategies, the ephemerality of waterbird populations, their nomadism and their rapid response to the advent of suitable conditions illustrate the complexity of avian responses to life in an arid environment. Apart from those few species which can exist year round on the permanent waterholes (such as the Yellow-billed Spoonbill), the waterbirds of the region are classic drought-evaders.

As the State's other major areas of wetland in the south east, along the River Murray and in the Adelaide district have been and continue to be drained, polluted and hydrologically altered, the virtually pristine habitats of the north east are becoming increasingly important for many of the State's waterbirds (Reid & Vincent 1979). Together with adjacent parts of the Channel Country in Queensland, the wetlands are breeding strongholds for such Australian endemics as Freckled Duck, Black-tailed Native-hen and Red-necked Avocet *(e.g.* Parker 1980b; Parker *et al.* 1985; Reid 1988a). Within South Australia, the northeastern populations of Glossy Ibis, Plumed WhistlingDuck, Grey Teal, Pink-eared Duck, Brolga and Gull-billed Tern are also highly significant.

If strictly coastal and estuarine species are ignored, only three of the State's non-vagrant waterbirds have not been recorded in the north east: Little Bittern, Brown Bittern and Lewin's Rail. Eighty species have been recorded, not including the non-aquatic Southern Stone-curlew, Oriental and Inland Dotterel, and Oriental and Australian Pratincole.

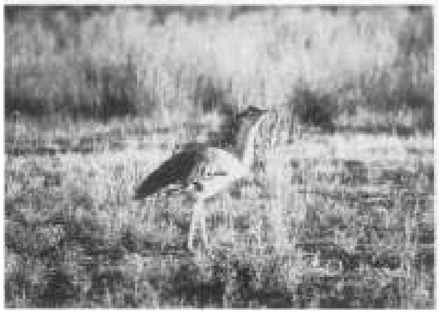

Fig. 4. Australian Bustard - a threatened Australian species. Generally uncommon, but local concentrations occur after heavy rains to feed in patches richly covered with grasses and forbs. (Photo J. Gillen).

After a prolonged drought very little surface water remains in the region. Consequently, the number of waterbirds is minimal, the vast majority having either perished or moved out. Subsequently, in response to major flooding caused by heavy rains upstream, or torrential local downpours, huge influxes occur (Badman in press). Whether wetlands are filled directly by rain or by flows along the river systems has a bearing on the waterbird response. Red-necked Avocets bred extensively on temporary rain-filled pools in the Cooper Creek region in the autumn and winter of 1987 and 1988 (Reid 1988a, unpubl.); at the same time, flows down the Cooper triggered an immediate breeding response at Coongie from Darters, Pied Cormorants, Yellow-billed Spoonbills and Dusky Moorhens (Reid 1988a; Chapter 10). Ducks and the Gull-billed Tern were observed to breed under both sets of conditions (Reid 1988a, unpubl.).

The variety of birds on the generally larger riverfed wetlands is far greater than on the rain-filled swamps, reflecting differences in habitats and food resources. For instance, obligate fish-eating species (Pelican, Darter, cormorants and Caspian Tern) rarely frequent the rain-filled pools, which are devoid of fish. A fascinating interplay between these two types of habitats has been observed by Reid (1988a) in the Coongie district. A pronounced withdrawal of waterfowl from the Coongie Lakes to the temporary swamps, following local heavy rains, was witnessed several times in 1987. Similarly, a flock of several thousand avocets had built up over late summer 1987 on the somewhat saline and quickly receding Lake Goyder; they dispersed to breed following the torrential downpour in mid-February of that year (Reid 1988a).

The artificial bore-drains and natural mound spring swamps such as Dalhousie carrying tall dense reed beds support a distinctive avian community (Badman 1987a), with Brolga, small crakes and waders, Clamorous Reedwarbler and Little Grassbird being characteristic inhabitants.

STRATEGIES FOR A DESERT ENVIRONMENT

Nomadism

More than one half of the birds inhabiting the arid zone in Australia were considered nomadic or migratory by Schodde (1982a), who also asserted that 'of all behavioural traits suited to life in deserts,' nomadism is 'by far the most important'. Nomadism is an appropriate strategy for a region in which rainfall can be very patchy or localised; nomads can quickly find areas where rain or flooding has generated a flush of plant growth and insect activity. Examples are Little Button-quail, Flock Pigeon, Budgerigah, Cockatiel, Rufous Songlark, Crimson Chat, Masked Woodswallow, Zebra Finch and a wide range of waterfowl.

May (1984) kept daily lists of birds over a long period of observation in the Simpson Desert. Under drought conditions in August 1982, his daily list ranged from 12 to 30 species, whereas in August 1976 it ranged from 40 to 60. Similar observations have been made by a number of workers in the region (e.g. McGilp 1923; Reid 1984, 1988; Badman in press). Bird communities shift rapidly in response to changing conditions as a consequence of the high level of nomadism within the region's avifauna, this dynamism being characteristic of desert bird communities, especially those of the waterless dunefields and gibbers. In comparison, the more predictable environments of the riparian woodlands support a richer and more stable and predictable suite of birds.

Eruptive patterns of behaviour, exemplified by the Letter-winged Kite and Black-tailed Nativehen, represent an extreme form of nomadism. These species can undergo population explosions rapidly in response to particularly favourable conditions. The kite responds to plague-like increases of its primary prey, the Long-haired Rat *Rattus villosissimus,* and may breed continuously while the rats remain abundant (Blakers *et al.* 1984). When the rat populations crash, the kites may disperse throughout the Continent (Parker 1980b) before the species' range contracts to the Channel Country of southwestern Queensland and north east South Australia. Between eruptions the population is low and highly fragmented, located in refuges.

Torpor

When entering torpor, animals become immobile and drop their body temperature, thereby lowering their metabolic rate. In this condition the body's use of water and energy is reduced greatly, and thus topor is regarded as a mechanism for conserving water and energy (Schodde 1982a), though torpid animals are encountered mainly in winter when energy maintenance is more likely to be a problem than excessive water-loss. Amongst Australian birds, this strategy has been reported so far in the Emu, Spotted Night jar, White-backed Swallow, Banded Whiteface, Red-capped Robin, Crimson Chat, White-fronted Honeyeater and Mistletoe-bird, (Ives 1973; Schodde 1982a); it deserves further study.

Terrestriality

Ground-feeding and strictly terrestrial birds constitute almost one half of the avifauna of the arid zone (Schodde 1982a). This figure, higher than that for other Australian biomes, is explained by both the greater prominence of bare ground and the limited extent of tall (and therefore vertically structurally diverse) vegetation.

Birds typically inhabiting open gibbers (Inland Dotterel, Australian Pratincole, Cinnamon Quailthrush, Richard's Pipit and Gibberbird) are strictly terrestrial, feeding, roosting and nesting on the ground. The Flock Pigeon and Night Parrot too are strictly terrestrial. This is unusual among pigeons and parrots, of which 20 species occur in the north east; the other 18, while principally ground-feeders, have retained their arboreal nesting and roosting habits. The Ground Cuckooshrike, like other cuckoo-shrikes, nests and roosts in trees or tall shrubs, but differs from other members of the family in its ground-feeding habits.

Breeding strategies

Much has been written on the reproductive strategies employed by Australia's desert birds (reviewed by Schodde 1982a). Several early workers (such as McGilp 1923, who detailed breeding records from the Lake Callabonna district) were struck by the ability of many species to breed seemingly at any time of year as favourable conditions arose. More recent analyses led Schodde (1982a) to conclude that there was a consistent spring breeding season in nearly all species and a minor one in autumn, with a significant winter pause (but see below); he also considered that autumn breeding became important only when summer rains had broken a drought that had suppressed the usual spring breeding. It seems likely, incidentally, that the double breeding season widespread in the interior of Australia is made possible by the fact that these central regions enjoy rains from overlapping weather systems - monsoonal rains from the north in summer and more normal rains from the south in winter.

Observations over ten years in the Lake Eyre region (F.J.B. unpubl.) support Schodde's contention that, for landbirds at least, spring breeding is the rule. However, widespread autumn breeding was observed in 1987 and 1988 (Reid 1988, unpubl.), both times following a prolonged spring breeding season (1986, 1987). Moreover, in 1987 and 1988, the spring breeding season commenced in June and several species bred in the short intervening period between the more pronounced ones *(ct.* Schodde, above).

Schodde (1982a) observed that highly mobile, nomadic birds tended to be opportunistic breeders, whereas sedentary species tended to be regular spring breeders. The two corvids conform to this pattern: the sedentary Australian Raven is strictly a late winter-spring breeder, whereas the Little Crow breeds opportunistically However, many resident species will breed at other times of the year. For example, the Eyrean Grasswren was recorded breeding at Coongie in FebruaryMarch (Reid 1988a) and May-June(Reid unpubl.), *pace* Schodde (1982b), who asserted it to be strictly a spring breeder (see also the strong circumstantial evidence for breeding of this species in autumn 1976, in the Simpson Desert, *fide* Parker *et al.* 1978). Other species not considered strongly nomadic but which can breed opportunistically include Richard's Pipit, Cinnamon Quailthrush, White-winged wren, Variegated Wren, Thick-billed Grasswren, Western Fieldwren, Gibberbird and Magpie-lark (Reid 1988, unpubl.).

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15: Amphibians and Reptiles

by M. J. TYLER, A. EDWARDS & G. R. JOHNSTON

INTRODUCTION

As perhaps is the case for many groups of organisms, progress in the study of the amphibians and reptiles of the area has a fortuitous element. This is particularly so for the frogs which are neither visible nor audible in dry weather, and roads to the area commonly are impassable during the wet conditions when the frogs are active on the surface. In consequence real progress has occurred mostly when collectors have been in the field when climatic conditions were ideal. That event occurred in 1987 during the Coongie Lakes biological survey undertaken by J. Reid and his colleagues. They encountered a deafening chorus of six species of frogs including one new to the fauna of the State (see Chapter 10).

We note from records associated with the collections of the South Australian Museum that the majority of species now known from the area was recorded there for the first time in the past 25 years.

In assembling a list of the herpetofauna of the north east we are aware that current data are deficient. Thus we include 25 species that are likely to occur there but whose presence requires confirmation in the form of voucher specimens. The specific identity of a further three species remains unknown, and is the subject of current investigations.

In the following text we have selected a few species for particular comment, principally to demonstrate the diversity of information available.

For further information on the herpetofauna of the area we provide an annotated appendix of selected references.

Hylidae

Well known as the water-holding frog, *Cyclorana platycephala* (Fig. 1) has an extensive geographic range within central Australia, and includes most of the north east (Tyler 1990). The capacity of this species to store water in its bladder and reabsorb it during drought has attracted a great deal of interest. There has been further fascination in the habit of some Aboriginals to locate the frogs, excavate them and drink the bladder water.

The existence of a second species of *Cyclorana* in S.A. was discovered during the recent biological survey of Coongie Lakes. Its identity remains uncertain but it seems most closely related to *C. cultripes* which is widely distributed in the Northern Territory.

Fig. 1. The waterholding frog *Cyclorana platycephala* (M. Davies).

Leptodaetylidae

The small frog let *Crinia deserticola* is an example of a recent leptodactylid species recently added to the State fauna. Its entire geographic range extends in an arc from the eastern edge of the Kimberleys in the NT. through to soutwest Queensland and northwest New South Wales. In dry weather it hides beneath leaf litter and other debris.

Bird & Tyler (in press) report an additional genus and species new to the State fauna recently found in the north east. It is a *Uperoleia* species: a small burrowing frog most certainly occurring in southwestern Queensland and only just penetrating the north east periphery of South Australia.

Chelidae

Although its presence in the north east has been known for many years and it is common in large water bodies, the specific identity of the tortoise *Emydura* is uncertain (Fig. 2).

Fig. 2. *Emydura sp*. from the Cooper Creek drainage (G. R. Johnston).

Turner (1976) observed breeding in August.

Gekkonidae

Popularly known as geckos, the members of this diverse group share a soft skin and large eyes covered by a transparent membrane (the spectacle). They are nocturnal and shelter beneath bark, fallen branches, or flat stones or live in burrows.

In terms of number of species the dominant genus is *Diplodactylus* which includes species that secrete a viscous fluid from spines and pores in the tail. This fluid is claimed to be a vesicant and presumably has a protective role (Rosenberg & Russell 1980).

Pygopodidae

These slender, legless creatures resemble snakes but are lizards most closely related to the Gekkonidae, and retain remnants of the hindlimbs in small flaps that are pressed against the body wall.

The Bronzeback, *Ophidiocephalus taeniatus*, was described in 1897 from a single specimen taken at Charlotte Waters, NT. It was rediscovered at Abminga, SA about 26 km south (Ehmann & Metcalfe 1978) and Coober Pedy (Ehmann 1980). This legless lizard lives beneath dense leaf litter, and geographically is likely to penetrate into the Lake Eyre Basin along suitable tree-lined water courses.

Agamidae

The dragon lizards are mostly elongate creatures with very long tails which they raise and use as a balancing organ when running.

Several of the dragons undergo elaborate social organisation and communicate by posturing.

HYLIDAE
Cyclorana platycephala
Cycorana Sp.
Litoria caerulea
L. latopalmata

Mitchell (1973) pioneered behavioural studies in Australian reptiles with his investigations of the Lake Eyre Dragon, Ctenophorus maculosus (Fig. 3). He demonstrated th~t it has a particularly high tolerance to temperature - surviving at up to 48.9°C but normally maintaining body temperature in summer at about 39°C. Working under extreme conditions Mitchell brought his equipment to the edge of the salt pans (Fig. 4), and found that the lizards retreated beneath the cracking salt crust during extreme conditions.

Varanidae

Commonly known as goannas the varanids are easily recognised by their long bodies, muscular limbs and long and deeply forked tongues. As indicated in Table 1, several species have been recorded and we consider that others have yet to be recorded.

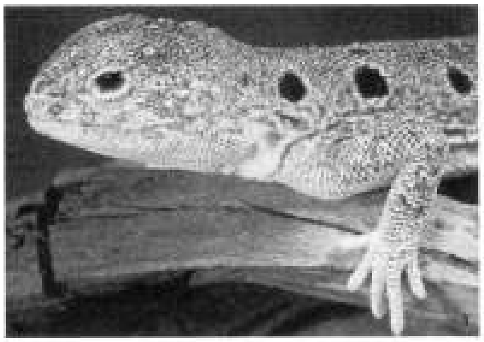

Fig. 3. The lake Eyre Dragon Ctenophorus maculosus (F. J. Mitchell).

The varanid fauna includes Australia's largest lizard: the Perentie, *Varanus giganteus*, which has a total length of up to 2.4 m. It inhabits rocky outcrops but forages widely in adjacent areas. The rarest of the S.A. goannas, the freckled pygmy goanna, V. tristis, is arboreal and most likely to be found in hollow limbs of trees in sparsely timbered country. The only SA localities at which it has been collected are: Innamincka, near Coongie Lakes, near Leigh Creek and at Maralinga.

Table 1. CHECKLIST OF AMPHIBIANS AND REPTILES.

Species marked with an asterisk have not been recorded from the north east but are considered likely to occur there.

FROGS

L. rubella

Fig. 4. F. J. Mitchell working at Lake Eyre. The recording apparatus was manufactured to his specifications in Adelaide by Both

Table 1 continued

LEPTODACTYLIDAE
Crinia deserticola
Limnodynastes spenceri
L. tasmaniensis
Neobatrachus centralis
Uperoleia sp.

TURTLES
CHELIDAE
Emydura sp

LIZARDS
GEKKONIDAE
Crenadactylus ocellatus
Diplodactylus byrnei
D. ciliaris
D. conspicillatus
D. elderi
D. galeatus
D. intermedius
D. stenodactylus
D. tessellatus
Gehyra pupurascens
G. variegata
Heteronotia binoei
Lucasium damaeum
Nephrurus levis
N. asper
Oedura marmorata
Rhynchoedura ornata
Underwoodisaurus milii

PYGOPODIDAE
Delma australis
D. nasuta
D. tincta
Lialis burtonis
Ophidiocephalus taeniatus
Pygopus nigriceps

AGAMIDAE
Ctenophorus decresii
C. fordi
C. gibba
C. isolepis gularis
C. maculosus
C. nuchalis
C. pictus
C. reticulatus
C. vadnappa
Diporiphora lalliae
D. winneckei
Gemmatophora gilberti
G. longirostris
Moloch horridus
Pogona vitticeps
Tympanocryptis cephalus
T. intima
T. lineata
T. tetraporophora

VARANIDAE
Varanus acanthurus
V brevicauda Veremius
V giganteus
V gilleni
V gouldii flavirufus
V tristis

SCINCIDAE
Cryptoblepharus carnabyi
C. plagiocephalus
Ctenotus ariadnae
C. brachyonyx
C. brooksi
C. helenae
C.leae
C. leonhardii
C. pantherinus
C. regius
C. robustus
C. saxatilis

C. schevilli
C. schomburgkii
C. strauchii
C. uber
Egernia inornata
E. slateri
E. stokesii
E. striolata
Eremiascincus fasciolatus
E. richardsonii
Lerista desertorum
L. labialis
L. muelleri
L. punctatovittata
L. xanthura
Menetia greyii
Morethia adelaidensis
M. boulengeri
Notoscincus ornatus
Tiliqua branchialis
T. multifasciata
T. occipitalis
Trachydosaurus rugosus

SNAKES
TYPHLOPIDAE
Ramphotyphlops australis
R. bituberculatus
R. endoterus
R. ligatus
R. unguirostris

BOIDAE
Aspidites ramsayi
Liasis stimsoni
Morelia spilota ? variegata

ELAPIDAE
Acanthophis pyrrhus
Demansia psammophis
D. torquata
Furina diadema
F. ornata
Oxyuranus microlepidotus
Pseudechis australis
Pseudonaja guttata
P. modesta
P. nuchalis
P. textilis
Simoselaps bertholdi
S. fasciolatus
Suta suta
Unechis monachus
Vermicella annulata

Scincidae

The diversity of form, habits and reproduction of these skinks reflects an evolutionary adaptability unrivalled by other Australian reptiles (Fig. 5). In their form they range from the common, large-scaled, *Trachydosauras rugosus* (the stump-tailed or shingle back lizard) to numerous snake-like creatures with reduced limbs andlor digits.

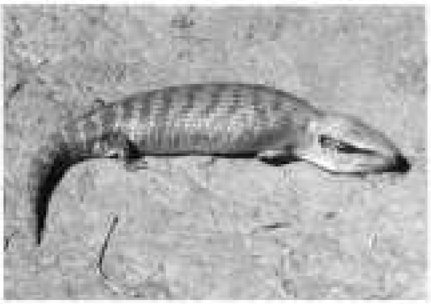

Fig. 5. The large skink Tiliqua multifasciata (G. R. Johnston)

Typhlopidae

Typhlopidae, the Blind Snakes, are small wormlike snakes with eyes reduced to small spots beneath the head scales. Nocturnal and nonvenomous, they feed on ants and termites and can be found in termite mounds or in loose earth under rocks and logs.

Ramphotyphlops australis, R. bituberculatus and R. endoterus have been collected and are widely distributed in the north east, while R. ligatus and R. unguirostris have not been found but they may exist in the region, the former on the eastern edge and the latter in the far southeast portion.

The bandy bandy, *Vermicella annulata*, a burrowing snake of the family Elapidae feeds exclusively upon Ramphotyphlops species (Shine 1980).

Boidae

The three species of python in South Australia occur in the area. Pythons are non-venomous snakes that kill their prey by constriction, asphyxiating rather than crushing them to death. The Woma Python, *Aspidites ramsayi,* is a terrestrial species usually found near sandhills and although it feeds on lizards and other snakes, rabbits have become an additional food source.

Liasis stimsoni, the Children's Python, is a small, light brown snake with dark, irregular blotches along the body (Fig. 6). It is found in rocky areas and along watercourses, feeding on birds, reptiles and small mammals. An isolated

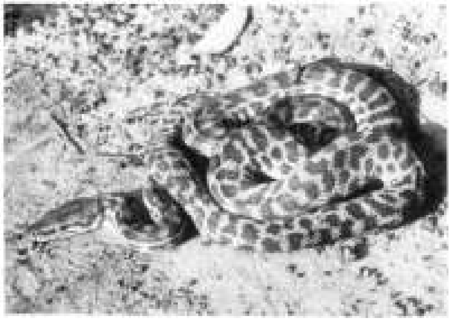

Fig. 6 The python *Liasis stemson* (G. R. Johnston)

population of the Carpet Snake, *Morelia spilota variegata*, exists around specimens can be found constructed by other animals.

Elapidae

The venomous, front-fanged snakes belonging to the family Elapidae are the most common terrestrial snakes in Australia. Although the bite of many species is potentially fatal, few bites occur and deaths are rare. The Desert Death Adder, Acanthophis pyrrhus, is represented in the SA Museum collection by two specimens, neither from the area. A specimen was reported to have been found at Moomba by Santos personnel but not retained by them (Reid & Gillen 1988). The Death Adder is a short, squat, banded snake with a large viper-like head and highly toxic venom. Little is known of the habits of A. pyrrhus but it would probably be found half-buried and camouflaged in loose soil, sand or litter, as it relies on ambushing prey which it attracts by twitching the worm-like tip of its tail.

In the extreme north east of the area is Australia's most highly venomous snake Oxyuranus microlepidotus known as the smallscaled snake or fierce snake. White (1981) provides an account of effects of envenomation, and in 1988 a further two cases (both in the north east) attracted considerable media attention through the severity of the effects and the major logistic problems involved in bringing the patients to medical facilities in Adelaide.

Oxyuranus microlepidotus feeds on small mammals and occurs on the flood plains of the Diamantina and Warburton Rivers, Goyder Lagoon and Cooper Creek (Turner 1976; Mirtschin & Reid 1982).

APPENDIX; Selected references on various aspects of amphibians and reptiles

FROGS

For identification of species two handbooks are available:

Tyler, M. J. (1977) 'Frogs of South Australia.' Revised edition. (South Australian Museum, Adelaide).

Tyler, M. J. (1978) 'Amphibians of South Australia.' (Handbooks Committee, Govt Printer, Adelaide.)

The biology of Australian frogs, including particular attention to arid adaptations, is the subject of:

Tyler, M. J. (1989) 'Australian Frogs.' (Viking O'Neil, Melbourne.)

REPTILES

Two recent reviews of reptiles are available. The former includes identification keys.

Cogger, H. G. (1986) 'Reptiles and Amphibians of Australia.' 4th Edtn. (Reed, Sydney.)

Houston, T. F. (1973) 'Reptiles of South Australia, a brief synopsis.' In South Australian Yearbook 1973. (Govt Printer, Adelaide.)

LIZARDS

A handbook on the Agamidae and Varanidae of South Australia has been published:

Houston, T. F. (1978) 'Dragon lizards and goannas of South Australia.' (South Australian Museum, Adelaide.)

There is also a technical account of the Pygopodidae:

Kluge, A. G. (1974) A taxonomic revision of the lizard family Pygopodidae. Misc. Publ. Mus. Zool. Univ. Michigan 147, 1-221.

A variety of aspects of the evolution, reproduction, physiology and ecology of lizards have been documented. The following are of particular relevance to the area:

Cogger, H. G. (1978) Reproductive cycles, fat body cycles and socio-sexual behaviour in the mallee dragon, *Amphibolurus fordi* (Lacertilia: Agamidae). Aust. J. Zool. 26, 653-672.

Moritz, C. (1983) Parthenogenesis in the endemic Australian lizard *Heteronotia binoei* (Gekkonidae). Science 220, 735-737.

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Greer, A. E. (1987) Limb reduction in the lizard genus *Lerista*. 1. Variation in the number of phalanges and presacral vertebrae. J. Herpetol. 21, 267-276.

SNAKES

Amongst a number of recent contributions, the following have particular relevance to South Australia:

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Shine, R. & Covacevich, J. (1983) Ecology of highly venomous snakes: the Australian genus *Oxyuranus* (Elapidae). J. Herpetol. 17, 60-69.

Schwaner, T. D. (1985) 'Snakes in South Australia: a species list and overview.' In South Australian Yearbook. (Govt Printer, Adelaide.)

Smith, L. A. (1985) A revision of the *Liasis childreni* species-group (Serpentes: Boidae). Rec. W Aust. Mus. 12(3), 257-276.

REFERENCE

Bird, P. & Tyler, M. J. (in press) First South Australian record of the fossorial leptodactylid frog genus *Uperoleia* Gray. *Trans. R. Soc. S. Aust.* **114**,

Ehmann, H. F. W. (1980) The natural history and conservation of the bronzeback (*Ophidiocephalus taeniatus* Lucas and Frost) (Lacertilia, Pygopodidae). In C. B. Banks & A. A. Martin (Eds) Proceedings of the Melbourne Herpetological Symposium, Royal Melbourne Zoological Gardens, Melbourne. (Royal Zool. Soc. Vict., Melbourne)

Ehmann, H. F. W. & Metcalfe, D. (1978) The rediscovery of *Ophidiocephalus taeniatus* Lucas and Frost (Pygopodidae, Lacertilia) the bronzeback. *Herpetofauna* **9**(2), 8-10.

Mirtschin, P. J. & Reid, R. B. (1982) Occurrence and distribution of the inland taipan *Oxyuranus microlepidotus* (Reptilia: Elapidae) in South Australia. *Trans. R. Soc. S. Aust.* **106**, 213-214.

Mitchell, F. J. (1973) Studies on the ecology of the agamid lizard *Amphibolurus maculosus* (Mitchell). *Trans. R. Soc. S. Aust.* **97**, 47-76.

Reid, J. R. W. & Gillen, J. (Eds) (1988) The Coongie Lakes Study. (Dept of Environment & Planning, Adelaide).

Rosenberg, H. I. & Russell, A. P. (1980) Structural and functional aspects of tail squirting: A unique defense mechanism of Diplodactylus (Reptilia: Gekkonidae). *Can. J. Zool.* **58**, 865-881.

Shine, R. (1980) Reproduction, feeding and growth in the Australian burrowing snake *Vermicella annulata*. *J. Herpetol* **14**, 71-77.

Turner, A. K. (1976) Herpetofauna of northeastern South Australia. In M. R. Foale (Ed.) The far north east of South Australia. A biological survey conducted by the Nature Conservation Society of SA (Inc.) 2nd-30th August 1975. (Nature Conservation Society of SA, Adelaide).

Tyler, M. J. (1990) Geographic distribution of the fossorial hylid frog Cyclorana platycephala (Gunther) and the taxonomic status of *C. slevini* Loveridge. Trans. R. Soc. S. Aust. **114**, 81-85.

White, J. (1981) Ophidian envenomation. A South Australian perspective. *Rec. Adel. Children's Hosp* **2**(3), 311-421.

16: Fishes

by C. J. M. GLOVER

INTRODUCTION

Despite its aridity the north east deserts features a diversity of aquatic habitats inhabited by an equally diverse and abundant fish fauna. The major types of aquatic habitats there have been described by Glover (1982) and Glover & Inglis (1971).

DIVERSITY OF FISHES

Twenty-three species of fish representing 11 families are presently recorded here (Table 1) and include most of the species known in the Lake Eyre drainage (Glover 1982). This fauna includes some predominantly tropical forms, others predominantly or exclusively temperate, and some more or less equally tropical/temperate forms. The best represented families are the Plotosidae (eel-tail catfishes), Atherinidae (hardyheads), Teraponidae (perches) and Eleotridae (gudgeons). Most remaining families are represented by only a single species.

The fishes include the widely occurring, usually common and abundant, bony bream *Nemat%sa erebi,* Lake Eyre hardyhead *Craterocephalus eyresii,* spangled perch *Leiopotherapon unicolor,* desert goby *Chlamydogobius eremius* and Eastern gambusia, *Gambusia holbrooki,* all of which range elsewhere (Fig. 1). Conversely, a few fishes endemic to the north east are highly restricted in occurrence, albeit locally abundant i.e. the Dalhousie catfish *Neosilurus* sp. novo 1, hardyhead *Craterocephalus dalhousiensis* and goby *Chlamydogobius* sp. nov., and the Flinders Ranges gudgeon *Mogurnda* sp. Novo.

The Eastern gambusia and the goldfish *Carassius auratus,* are exotics introduced into many parts of mainly temperate Australia. The record of exotic redfin perch *Perea fluviatilis* in the Cooper Creek drainage (Glover 1982) is erroneous.

Most of the fish fauna is well known taxonomically, apart from some of the eel-tail catfishes which are difficult to differentiate, and some species awaiting description. Following recent electrophoretic comparisons of body proteins, some taxa have been demonstrated to be distinct from morphologically similar forms, and a pilot study by Baverstock, Adams and Glover has suggested that more cryptic species await discovery in the north east and elsewhere in Australia's central drainages. The existence of evidently endemic taxa at Dalhousie Springs and at Elizabeth Springs in Queensland suggests long isolation of these populations (Glover 1989a).

Fishes remaining unrecorded in the temperate north east, but known elsewhere in the more northern parts of the Lake Eyre drainage system (Glover 1982), are predominantly tropical forms. Some of them may occur in the north east, but remain unrecorded because they occur only sparsely and/or sporadically.

Principal publications concerned with identification and description include those of Allen & Cross (1982), Lake (1978), McDowall (1980), Merrick & Schmida (1984), Nelson & Rothman (1973), Scott, Glover & Southcott (1974) and Vari (1978).

ECOLOGY

The ecology of most north east fishes has been studied, at least in part, though not always upon north east populations or stocks. Merrick & Schmida (1984) summarised most of what is known and provided a comprehensive bibliography of the widely scattered literature reporting individual studies. Other authors have provided some similar information for certain species e.g. Cadwallader & Backhouse (1983), Lake (1967a, 1978), Leggett & Merrick (1987), McDowall (1980). An historical review of central Australian ichthyology is provided by Glover & Sim (1978b). Ecological and biogeographical studies specifically upon arid Australia's fish fauna have been largely undertaken in the north east e.g. Glover (1971-1988b), Glover & Inglis (1971), Glover & Sim (1978a), Ivantsoff & Glover (1974), McKay (1985), Puckridge & Drewien (1988). Some of this work has been summarised by Davey (1983) and Robinson & Casperson (1986).

Topics that have been examined in some of the species (in the north east or elsewhere), include one or more of the following: tolerance to physicochemical factors [e.g. Beumer (1979Cj.), Bishop *et al.* (1980), Glover 1971-1989b, Glover & Sim

Table 1. A CHECKLIST OF THE FISHES OF SOUTH AUSTRALIA'S NORTH EAST DESERTS
Compiled principally from SA Museum collection and field records

Family and species	**Common Name**	**Comments on status in north-east deserts**
Clupeidae *Nematalosa erebi* (Gunther, 1868)	Bony bream	In all types of aquatic habitat, except artesian springs. Common and abundant. In Lake Eyre.
Retropinnidae *Retropinna semoni* (Weber, 1895)	Australian smelt	Only in river systems. In patches, usually in abundance. In Lake Eyre.
Plotosidae *Neosilurus argenteus* (Zietz, 1896)	Silver tandan (catfish)	Only in river systems. In patches, sometimes in abundance. Type locality: Finke River & Cooper Creek.
Neosilurus hyrtlii Steindachner, 1867	Hyrtl's tandan (catfish)	Only in river systems. Uncommon, occasionally abundant.
Neosilurus glencoensis (Rendahl, 1922)	Yellowfin tandan (catfish)	Only in river systems. Uncommon, in patches, occasionally abundant.
Neosilurus sp nov .1	Dalhousie catfish	Only at Dalhousie Springs, where it is common and abundant. Endemic to the north east. Proposed type locality: main spring (Ca 1).
Neosilurus sp nov .2	Barcoo catfish	Only in river systems. Uncommon. Possibly restricted to the Cooper Creek drainage. Proposed type locality: Cooper Creek.
Poeciliidae *Gambusia holbrooki* (Girard, 1859)	Eastern gambusia (Mosquito fish)	In all types of aquatic habitat. Fairly common, especially in bore drains. Usually abundant. Introduced exotic that has adversely affected some native fish populations and may well threaten others.
Melanotaeniidae *Melanotaenia splendida tatei* (Zeitz, 1896)	Desert rainbow fish	In all types of aquatic habitat, except artesian springs. Uncommon, in patches; sometimes abundant. Type locality: Finke River.
Atherinidae *Craterocephalus stercusmuscarum* (Gunther, 1867)	Fly-specked hardyhead	Questionably recorded at Dalhousie Springs, (see Glover 1989a). Unknown elsewhere in the north east.
Craterocephalus eyresii (Steindachner, 1884)	Lake Eyre hardyhead	In all types of aquatic habitat. Common, frequently abundant. In Lake Eyre. Designated type locality: Strangways Springs (south-east of William Creek township).
Craterocephalus dalhousiensis Ivantsoff & Glover, 1974	Dalhousie hardyhead	Confined to Dalhousie Springs, where it is fairly common and abundant. Endemic to the north east. Type locality: main spring (Ca 1).

Family and species	**Common Name**	**Comments on status in north-east deserts**
Percichthyidae *Macquaria ambigua* (Richardson, 1845)	Yellowbelly, callop, golden perch	In river systems. Relatively common, especially in deeper waters where it can be abundant. In Lake Eyre.
Teraponidae *Leiopotherapon unicolor* (Gunther, 1859)	Spengld perch	In all types of aquatic habitat. Extremely common, frequently abundant.
Amniataba percoides (Gunther, 1864)	Banded (or black-striped) grunther	In river systems. Not common; recorded only in the Neales River where sometimes it may be abundant..
Bidyanus welchi (McCulloch & Waite, 1917)	Welch's perch	In river systems. Neither common nor abundant. Type locality: Cooper Creek near Innamincka.
Scortum barcoo (McCulloch & Waite, 1917)	Barcoo perch	Only in the Cooper Creek system. Uncommon and evidently not abundant. Type locality: Cooper Creek.
Eleotridae *Mogurnda mogurnda* (Richardson, 1844)	Purple-spotted gudgeon	Only at Dalhousie Springs, where it is common though evidently not abundant.
Mogurnda sp nov	Flinders Ranges gudgeon	Confined to the eastern Flinders Ranges (Balcanoona Creek and a couple of springs); sometimes abundant. Endemic to the north east. Proposed type locality: Balcanoona Creek
Hypseleotris klunzingeri (Ogilby, 1898)	Western carp-gudgeon	Only in the Cooper Creek system; fairly common, usually abundant.
Gobiidae *Chlamydogobius eremius* (Zietz, 1896)	Desert Goby	In all types of aquatic habitat. Very common and usually abundant in artesian springs and bores, especially in the vicinity of the southern and western margins of Lake Eyre. Endemic to the Lake Eyre drainage division. Type locality: Coward Springs railway bore.
Chlamydogobius sp nov	Dalhousie goby	Evidently confined to Dalhousie Springs, where it is very common though variable in abundance. Endemic to the north east.
Cyprinidae *Carassius auratus* (Linnaeus, 1758)	Goldfish	Only in Coongie Lakes, but not abundant. An introduced exotic, which at present does not seem to pose a threat to native species here (see Puckridge & Drewien 1988).

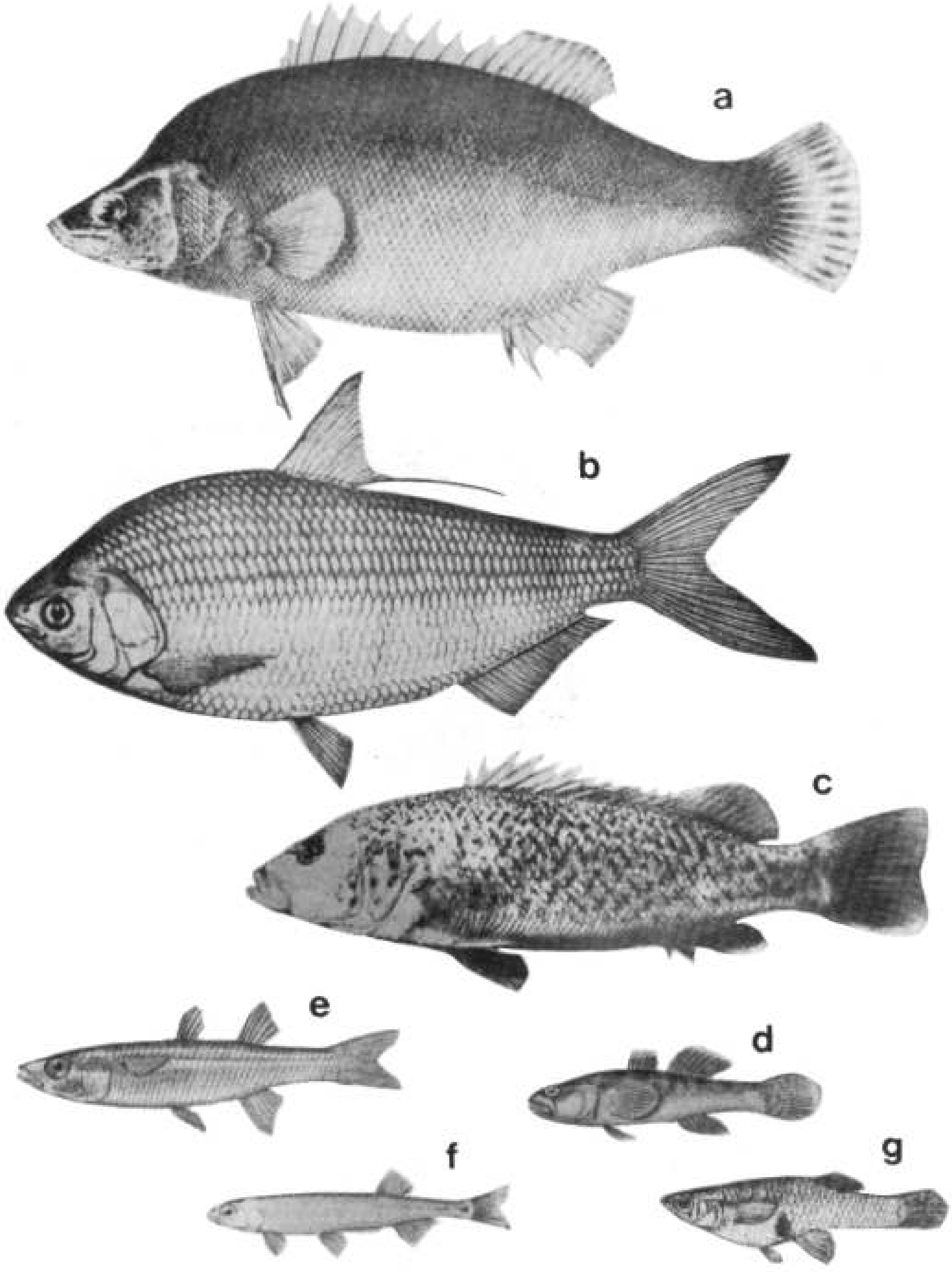

Fig. 1. Common Fishes of the north east deserts (with maximum lengths): (a) Yellowbelly *Macquaria ambigua* – 76 cm; (b) Bony bream *Nematolosa erebi* – 47 cm; (c) Spangled perch *Leiopotherapon unicolor* – 25 cm; (d) Desert goby *Chlamydogobius eremius* – 6 cm; (e) Lake Eyre hardyhead *Craterocephalus eyresii* – 10 cm; (f) Australian smelt *Retropinna semoni* – 10 cm; (g) Eastern gambusia (Mosquito fish) *Gambusia holbrooki* – 6 cm.

(1978a) Merrick (1980), Midgley (1983), Ruello (1976)], reproduction and growth [e.g. Anderson *et al.* (1971), Beumer (1979b), Glover (1971), Lake (1967a, 1967b, 1967c), Llewellyn (1971, 1973), McKay (1985), Milward (1966), Puckridge & Drewien (1988)], diet/feeding [e.g. Bishop *et al.* (1980), Cadwallader (1979), Glover (1971, 1973, 1988a), Lake (1967a), Merrick (1973), Pollard (1974)], parasitism/disease [e.g. Beumer *et al.* (1982), Mackiewicz & Blair (1980), McKay (1985), Puckridge & Drewien (1988)) and migration [e.g. Puckridge & Drewien (1988), Reynolds (1983)].

Glover's (1982) report on the ecology of central Australian fishes is based principally on species occurring in the north east. The north east's aquatic environment comprises four major habitat types: river systems, artesian springs and bores, and dams/reservoirs - whose chemico-physical parameters (particularly temperate, salinity and dissolved oxygen) are labile.

Most north east fishes are distinctly tolerant and adaptable to the extremes of chemico-physical and other parameters. The most successful species are those that are widely dispersed, usually common and frequently abundant, and which inhabit all or most types of habitat there i.e. bony bream, Eastern gambusia, Lake Eyre hardyhead, spangled perch and desert goby (Glover 1982; Glover & Sim 1978a).

Fish dispersal in central Australia has been discussed by Spencer (1896), Basedow (1914), Glover (1971, 1973, 1979, 1982, 1989a, 1989b), Glover & Inglis (1971) and Glover & Sim (1978a) who conclude that floodwaters are the major (if not exclusive) dispersal mechanism in this region. Conditions in Lake Eyre when it fills with floodwaters are presumably a critical factor in permitting movement of fish between major drainage basins in the Lake Eyre drainage division. Lake Eyre may be the essential transfer point for such movements (Glover 1982, 1989b).

Nevertheless, aerial dispersal (transportation of fish or their fertilised eggs via thermals or birds) of central Australian fish possibly occurs, if only very rarely. Convincing evidence in support of this mode of transfer occurring in central Australia is lacking: what evidence is available is scarce (perhaps due to the regions sparse human habitation) and invariably flimsy or unconfirmed. Effective aerial dispersal of fish in central Australia (resulting in establishment of new viable populations), requires a rare and fortuitous set of circumstances unlike in other regions of Australia where such events are evidently more common (Gudger 1929; Whitley 1972). Unproductive aerial dispersal, with fish being deposited anywhere but in another water body, seems a more likely event in central Australia.

Other ecological phenomena of north east fishes that have been addressed include the following:

a) Speculation that fish inhabiting artesian bore drains have arrived there as a result of them or their eggs being transported with artesian water through the aquifer to be ejected at the bore heads. This assertion has been rejected by Basedow (1914) and Glover & Inglis (1971). It has been demonstrated that fish were not ejected from bores at Oodnadatta and the former Beresford railway station by placing nets over their overflows (at the latter in December 1979 by the present author).
b) Conjecture that some fish, or their eggs, aestivate in bed mud of dry river courses or dams. This possibility has been examined by Spencer (1896), Glover (1971,1973), Glover & Inglis (1971), Lake (1978) and Beumer (1979a). The present evidence suggests that no true fish (unlike some crustacea) in central Australia can survive aestivation in completely dry mud, though the desert goby (and possibly some other fishes such as the spangled perch can survive at least for short periods buried in wet or moist mud (Glover 1971, 1973).
c) Speculation as to how fish (usually spangled perch) come to be in newly filled (previously totally dry) dams shortly after heavy rainfall. Despite views to the contrary it now seems most likely that such appearances are due to fish entering in flash floodwaters (even very shallow floods of short duration), though some may result from aerial dispersal. Although Lake (1967a) ascribed the sudden appearance of spangled perch in newly refilled dams to the reappearance of formerly aestivating fish, he subsequently reported (Lake 1978) that he believed spangled perch did not aestivate, and was convinced that because this fish is capable of moving swiftly in very shallow water, it could colonise otherwise isolated dams via heavy deluges briefly connecting them with permanent natural waterways.
d) Mass mortalities of fish in Lake Eyre. This phenomenon has been documented by Dulhunty & Merrick (1976a, 1976b), PeakeJones (1955), Ruello (1976), Stuart (1865) and others. Evidence provided by Dulhunty & Merrick (1976a, 1976b), Glover (1982, 1989b), Glover & Sim (1978a) and Ruello (1976) suggests that these deaths are caused by one or more of the following factors: high water salinity, water deoxygenation, low or rapid drop in water temperature, algal toxins andlor gill clogging by algae.

A comprehensive study of the biology of the desert goby, undertaken mostly in the north east

(Glover 1971, 1973, 1982) provides examples of other types of ecological adaptations and opportunism (apart from the goby's inherent tolerance to extremes of water salinity, temperature and oxygen tension) which have proved appropriate for survival in the regions commonly harsh and tenuous aquatic environments. These include behaviour such as the avoidance of lethally warm water by congregating in cooler side-shallows or lying embedded in cooler stream-bed silt, or by partly withdrawing from the water and seemingly effecting evaporative cooling (= thermal refuges) whilst performing aerial respiration. Also, by resorting to aerial respiration or by utilising highly oxygenated water provided in the vicinity of mats of photosynthesizing algae (= respiratory refuges) in otherwise oxygen depleted habitats; and by concealing from or avoiding the attention of predators through a strong preference for plant cover, a pronounced ability to change colour rapidly to conform cryptically with background and non-reliance on feeding in daylight (by being able to locate food nonvisually). Additionally, its broad spectrum diet comprising that flora and microfauna which is virtually ubiquitous in artesian surface waters in arid Australia and its rapid growth and ability to quickly establish large populations are also features which have undoubtedly facilitated the goby's successful occupancy of so many water bodies, including very small shallow ones.

More recent wide-ranging regional studies, at Dalhousie Springs (Glover 1989a) and Coongie Lakes (Puckridge & Drewien 1988), have provided much additional information on the ecology of the fish faunas of these biologically important localities.

FISHERIES

Eyre (1845) reports that fish was a major food item of central Australian aborigines and Burke & Wills *et al.* (1861) refer to fishes they obtained from aborigines (or that they caught) and provide aboriginal names for them (Glover & Sim 1978b). These latter fishes all seem to be forms present in the north east (inclUding bony bream, catfishes and perches {?}) where, it is inferred, the aborigines ate them. But Gason (1879), writing of the Dieri tribe of the lower Cooper Creek drainage, states 'fish and other freshwater inhabitants are few and unimportant' (as food), but listed the aboriginal names of three fishes (including what seem to have been bony bream and probably yellowbelly) (Glover & Sim 1978b). Kerwin & Breen (1986) have documented the net fishing techniques formerly employed by tribal aborigines in the Innamincka region to catch bony bream and yellowbelly. R. W. Ellis *(in litt.)* reports that when large fish (in river systems) and other animals were scarce in times of drought, aborigines in the Simpson Desert area (including Dalhousie Springs) and elsewhere in central Australia evidently collected large numbers of 'small fish' from artesian springs and prepared them for eating by pounding them into a paste. These 'small fish' presumably comprised any species inhabiting artesian springs, and by inference would have frequently been the desert goby, and to a lesser extent the Lake Eyre hardyhead.

Few of the north east's fishes attain a size suitable for present-day recreational and commercial fisheries. Nevertheless, both fisheries continue to operate in the north east on a significant scale. The present recreational fishery is a popular but highly fluctuating one, undertaken mainly by influxes of local and visiting fishermen, especially during non summer holiday periods. The main target species is yellowbelly. Bony bream and spangled perch are also sought, whilst other fishes are taken more or less incidentally. The recreational fishery is mainly concentrated on large waterholes in the Cooper Creek drainage between Innamincka and Coongie Lakes, and in the Diamantina River drainage south of Birdsville. Fishing is undertaken to a large extent with gill nets (an illegal technique in the north east!) and to a lesser extent with hook and line. In some dams, introduced spangled perch provide good line-fishing.

The present lucrative commercial fishery is also a highly fluctuating one, though essentially illegal by virtue of the netting technique employed. Well organised covert fishing operations apparently reap large and profitable catches of yellowbelly. These are despatched by freezer road-transport mostly to the Melbourne market. The commercial fishery's operations are mainly conducted in waterholes between Innamincka and Coongie Lakes.

CONSERVATION

The north east's fish fauna has for a long time been subject to natural threats posed by its frequently harsh environment, but is clearly well adapted to survive these. Furthermore, any human-related threats prior to European settlement were seemingly minimal or nonexistent, due to the relatively low density of the aboriginal populations and the nature of their culture. Until the 1960s it was believed that the remoteness of the north east region precluded any significant human-induced threat to its fish fauna, but this is no longer the case.

With the advent of European settlement in the north east came the stocking of cattle and the drilling of artesian bores, and later the introduction of rabbits and exotic fishes. All of these actions have had a detrimental effect on the native fish fauna.

It is now evident that the proliferation of uncontrolled bore flows and free-ranging domestic cattle have been mainly responsible for the severe degradation of many artesian springs to the detriment of their fish inhabitants. Until a programme of regulating or capping-off the uncontrolled flows of many old or disused pastoral and railway bores was initiated in 1978 by the South Australian Department of Mines, there is little doubt that the extra drain of water from the artesian basins had contributed to a significant reduction in flow from some springs, sometimes causing previously active springs to become no more than seepages or to cease flowing altogether. Paradoxically, although bores have seemingly contributed to the deterioration of certain springs in the north east, they have provided beneficial supplementary and alternative habitats (sometimes major) for fish and other aquatic life - as the occupation of many bore drains by fish demonstrates (Glover 1971; Glover & Sim 1978a). Some spring habitats have been severely damaged and polluted by cattle (Glover 1971) and elsewhere cattle and feral rabbits have contributed to the destruction of ecologically important aquatic vegetation (Puckridge & Drewien 1988). In recent years the South Australian Department of Environment and Planning has erected, or re-erected, protective fencing around certain springs to prevent or reduce damage from cattle and motor vehicles.

The introduction of the Eastern gambusia and goldfish threatens some of the native fish fauna by competition and possibly by the introduction of pathogens, if not by direct predation (Glover 1989a; Lloyd 1982; Lloyd *et al.* 1986; Puck ridge & Drewien 1988). The Eastern gambusia is certainly widespread and abundant in parts of the Lake Eyre drainage, including Cooper Creek and numerous bore drains. Glover (1989a) has reported Eastern gambusia causing partial displacement of native fishes in an artesian habitat in the Lake Frome basin, and Puckridge & Drewien (1988) have expressed concern at the extent to which the species has become established in the Coongie Lakes. McKay (1984) has provided data which suggest that the Eastern gambusia may eliminate smaller native species. The presence of these exotics, and the high risk of perhaps even more damaging exotics becoming established in the north east (e.g. European carp *Cyprinus carpio* which was reported in a dam at nearby Leigh Creek by Glover 1987) is a matter of grave concern.

With dramatically rising numbers of tourists visiting the north east in recent years, the aquatic habitats of some popular localities have been affected by damage and destruction of ecologically significant waterside vegetation and fish nesting sites, removal of ecologically important snags, erosion of banks, displacement of fish larvae from their habitats, excessive fishing pressure and pollution (Puckridge & Drewien 1988). The fencing-off of ecologically sensitive sites (particularly to vehicular traffic), the regulation and monitoring of human activities and the provision of camping and interpretive facilities, as at Dalhousie Springs, should reduce pressure on the environment from visitors.

The illegal use of nets by recreational and commercial fishermen, particularly in permanent waterholes, threatens the survival of the larger fishes in the north east. Even those of the entire Lake Eyre drainage may be at risk - especially as similar activities are conducted in the same drainage system in Queensland (Puck ridge & Drewien 1988).

Exploratory and other mining operations also raise matters of concern for the survival of some fish communities. The environmental aspects of some of these activities have been carefully considered, investigated and monitored (e.g. Kinhill Stearns 1983, 1984; Kinhill-Stearns Roger 1982) but some concerns relating to fish and their habitats remain unresolved or have only recently been noted or highlighted (Puckridge & Drewien 1988).

Some species seem secure because they are abundant and widely dispersed (e.g. Lake Eyre hardyhead, spangled perch). But endemic species with highly restricted ranges (Dalhousie catfish, hardyhead and goby, and Flinders Ranges gudgeon) are vulnerable to extinction by natural or other disasters (Glover 1987).

Components of the north east fish fauna are clearly threatened and to ensure their perpetuity there should be appropriate regulation of human activities in ecologically sensitive areas, and a monitoring programme capable of promptly detecting adverse changes in the environment.

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Figure 1 was prepared with illustrations reproduced from Scott *et al.* (1974) by permission of The Flora and Fauna of South Australia Handbooks Committee.

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17 Vertebrate Fossils

by N. S. PLEDGE & R. H. TEDFORD

INTRODUCTION

Until 1953, no pre-Pleistocene non-marine vertebrate fossil had been reported from South Australia, and indeed no Tertiary mammal fossils were recognised on the Australian mainland. But in that year, palaeontologists led by the late Professor R. A. Stirton of the University of California at Berkeley found the first of what was to be an important succession of mid and late Cainozoic mammal remains in ancient sediments of the Lake Eyre Basin (Tedford 1985). Thus began the renaissance of vertebrate palaeontology in this country.

In the north east deserts region, vertebrate fossils are found mainly in three time intervals and geological terrains: middle Cretaceous marine shales, middle Tertiary freshwater sediments, and Pliocene and Pleistocene stream and lake sediments. Their distribution is shown in Fig. 1.

CRETACEOUS

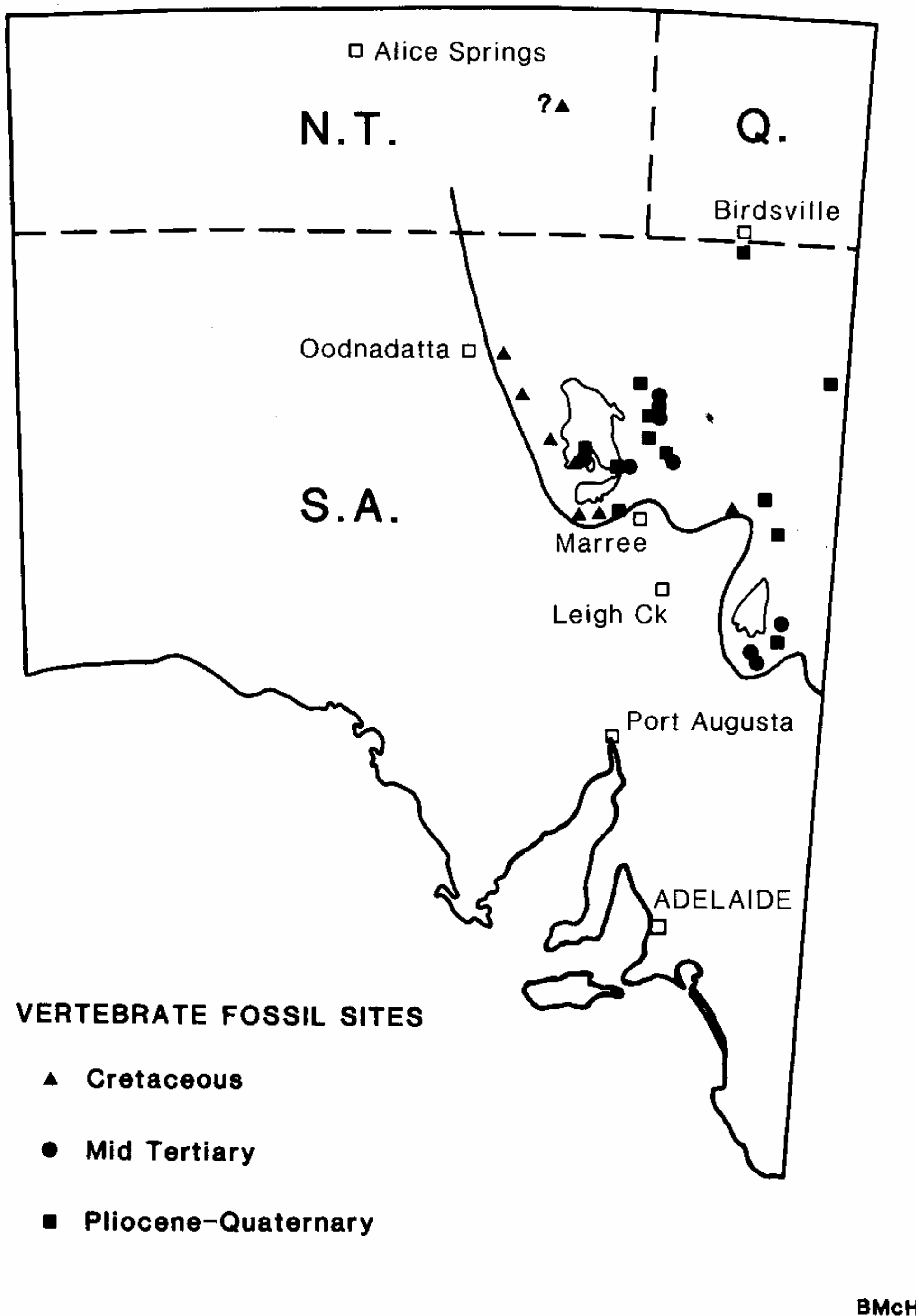
Most Cretaceous sediments are of marine origin (Marree Formation and equivalents), and there are few good vertebrate fossils known from this region. Shark teeth, probably *Hypotodus (Odontaspis)* or *Scapanorhynchus,* have been found near Murnpeowie, and a jaw of the elephant 'shark' *Edaphodon eyrensis* was collected near Lake Eyre South (Long 1985). Other specimens, possibly the Cretaceous shark *Cretolamna obliqua,* have been found in the northern Simpson Desert in the Northern Territory in rocks questionably mapped as Tertiary Etadunna Formation. Fish teeth and bone fragments have been found in micro-fossil samples from a number of localities (Ludbrook 1966). Fossils of marine reptiles, which are relatively common in the opal fields of Andamooka and Coober Pedy, west of this region, are rather rare, and most are of plesiosaurs (reptiles with a seal-like body and paddles and a long neck and tail). Sixteen neck vertebrae of a plesiosaur reported by Howchin (1928) from the Neales River were identified as *Woolungasaurus* by Persson (1960). An isolated vertebra was collected near Oodnadatta (Freytag 1964), and some poorly preserved fragments and a tooth (subsequently lost) were found near Murnpeowie (Pledge unpubl.). In 1983, a partial skeleton of a small plesiosaur was found at a small lake near Curdimurka (L. Barnes pers. comm.), and in 1970 a portion of the snout and some other bone fragments of the large ichthyosaur, *Platypterygius australis,* were found at Bopeechee, west of Marree (pledge unpubl.).

Although a few dinosaur bones have been found at the opal fields, nothing definable has yet been found in this area. However, a fragment of a large bone reported by Stirton *et al.* (1961) from Lake Howitt may be dinosaurian. The sediments there are the non-marine Winton Formation, which generally is poorly exposed. Good outcrops of Winton Formation on Babbage Peninsula in Lake Eyre, and on its western side have yielded two teeth of the lungfish *Ceratodus wollastoni* (T. H. Rich pers. comm.; A. Kemp pers. comm.).

MIDDLE TERTIARY

Non-marine sediments of this age are widespread, yet vertebrate fossils have been found only in two relatively small areas: east of Lake Eyre (Stirton *et al.* 1968), and south of Lake Frome (Fig. 1). They come from the Etadunna Formation of the Lake Eyre Basin and its time equivalent, the Namba Formation of the Tarkarooloo Basin, respectively. Correlations between the two basins are based mainly on faunal similarities (Fig. 2).

Woodburne *et al.* (unpubl.) have elaborated on earlier work on the Etadunna Formation (Stirton 1955; Stirton *et al.* 1961; Pledge 1984; Woodburne *et al.* 1986) so defining a succession of five faunal assemblages within the Ngapakaldi fauna of previous authors. The age of the Etadunna Formation, estimated by Stirton *et al.* (1961) as late Oligocene (on the basis of the perceived evolutionary stage of the marsupials), is commonly regarded as Mid Miocene as the result of regional correlation with pollen- and spore-bearing marine sequences. Woodburne *et al.* (unpubl.) sampled to determine the position of the Formation within the paleomagnetic time scale, but results are equivocal. Meanwhile, Lindsay (1987) has found



ig. 1. Locality map: Cretaceous and Cainozoic vertebrate sites.

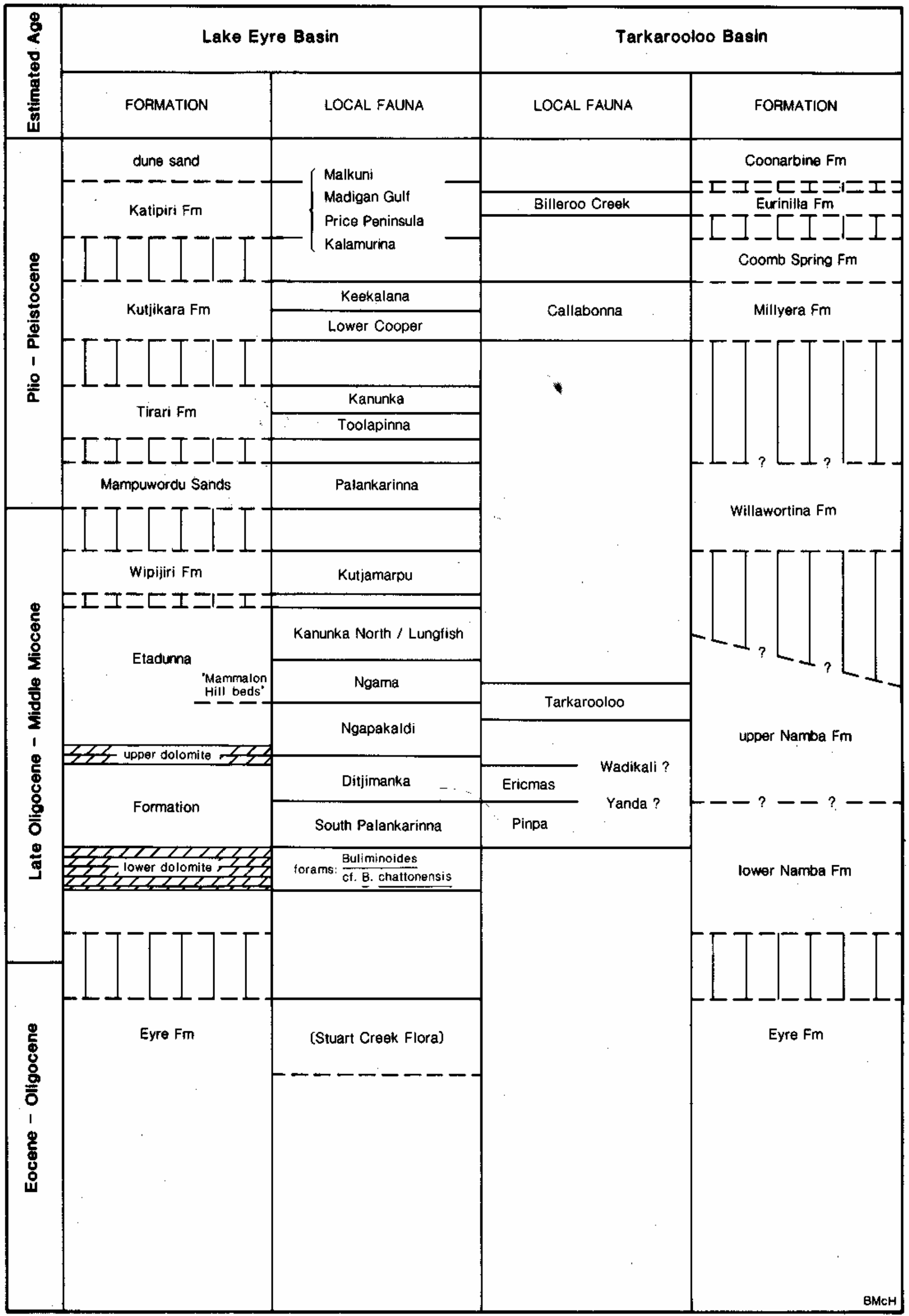


Fig. 2. Correlation chart, Cainozoic formations and faunas.

fossils of a viable monospecific population of foraminiferans *(Buliminoides* sp. cf. *B chattonensis)* which suggest a late Oligocene age, agreeing with a rubidium/strontium date of 25 million years, on illite from the Etadunna Formation (Norrish & Pickering 1983; Wells &..Callen 1986). The overlying Wipajiri Formation (Stirton *et al.* 1967) bears a younger assemblage, the Kutjamarpu Fauna, taxonomically distinct from the Ngapakaldi fauna but clearly related to it in composition (Table1)

Table 1. MIOCENE MAMMAL SPECIES FROM THE ETADUNNA (1), NAMBA (2), AND WIPAJIRI (3) FORMATIONS.

- Monotremata
    - *Obdurodon insignis* (1, 2)
- Dasyuridae
    - *Keeuna woodburnei* (1)
    - *Ankotarinja tirarensis* (1)
    - *Dasylurinja kokuminola* (2)
    - *Wakamatha tasselli* (2)
    - *Apoktesis cuspis* (1)
- Thylacinidae undet. (1)
- Perameloidea
    - peramelids undet. (1, 2, 3)
- Thylacoleonidae
    - *Prisciieo pitikantensis* (1)
    - *Wakaleo oldfieldi* (3)
- Vombatidae
    - *Rhizophascolonus crowcrofti* (3)
    - Vombatid indet. (2)
- ?Wynyardiidae
    - *Namilamadeta snideri* (2)
    - *Namilamadeta* sp. indet. (1)
    - *Muramura williamsi* (1)
    - *Muramura* sp. undet. (2)
- Ilariidae
    - *Ilaria lawsoni* (1)
    - *Ilaria illumidens* (2)
    - *Kuterintja ngama* (1)
- Phascolarctidae
    - *Perikoala palankarinnica* (1)
    - *P. robustus* (1)
    - *Madakoala devisi* (2)
    - *M. wellsi* (2)
    - *Litokoala kutjamarpensis* (3)
    - *L. kanunkaensis* (1)
- Phalangeridae undet. (1, 2)
- Miralinidae
    - *Miralina daylei* (1)
    - *M. minor* (1)
    - *M.* cf. *minor* (2)
- Ektopodontidae
    - *Chunia illuminata* (1)
    - *C.* cf. *illuminata* (2)
    - *C. omega* (2)
    - *Ektopodon stirtoni* (1)
    - *E.* cf. *stirtoni* (2)
    - *E. serratus* (3)
- Chiroptera
    - ?Rhinolophidae indet. (1)
- Cetacea
    - Rhabdosteidae indet. (2)
- Pilkipildridae
    - *Pilkipildra handi* (2)
    - *P. taylori* (1)
    - *Djilgaringa thompsoni* (2)
- Petauridae undet (1, 2)
- Pseudocheiridae
    - *Pildra antiquus* (2)
    - *P. secundus* (1, 2)
    - *P. tertius* (3)
    - *P. magnus* (1)
    - *Marlu praecursor* (2)
    - *M. kutjamarpense* (3)
    - *M.* cf. *kutjamarpense* (1)
    - *Paljara tirarensae* (3)
- Burramyidae
    - *Burramyswakefieldi* (1)
    - burramyid undet.
- Potoroidae
    - *Purtia mosaicus* (1)
    - *Purtia* sp. undet (1)
    - *Wakiewakie lawsoni* (3)
    - hypsiprynmodontines undet. (1, 2)
    - *Palaeopotorous priscus* (2)
    - *Gumardee* sp. indet. (2)
    - *Bulungamaya* sp. undet. (3)
- Macropodidae
    - *Nambaroo tarrinyeri* (2)
    - *N. saltavus* (2)
    - *N. novus* (2)
    - *Nambaroo* spp. undet. (1)
    - Balbaroo spp. undet. (3)
    - *Pinaroo* spp. undet. (1)
- Palorchestidae
    - *Ngapakaldia tedfordi* (1, 2)
    - *N. bonythoni* (1)
    - *Pitikantia dailyi* (1)
- Diprotodontidae
    - *Raemeotherium yatkolai* (1, 2)
    - *Neohelos tirarensis* (3)
    - *?Neohelos* sp. indet. (1)

Three faunal assemblages are recognised in the Namba Formation (Callen & Tedford 1976; Rich & Archer 1979), but no equivalent of the Wipajiri Formation has been found in the Tarkarooloo Basin.

Lower Vertebrates

Isolated fish bones are abundant, and seem to represent at least two species of bony fish representing the Ariidae (cat fish) and Percichthyidae (bass) (Estes 1984). Lungfish teeth also are common (Fig. 3) and represent several species: *Ceratodus wollastoni, Neoceratodus djella, N. eyrensis,* and *N. gregoryi* (Long *et al.* 1982). All are long-ranging and occur widely in fossil assemblages of the Lake Eyre and Tarkarooloo Basins, as well as in Queensland and the Northern Territory. Frog bones have been found there including the extinct *Australobatrachus ilius* and *Limnodynastes archeri* (Tyler 1976, 1982) as well as some living species.

Only two species of chelonians have been identified in the Tertiary of South Australia. The aquatic turtle *Emydura* sp. is abundant, and partial and complete shells have been collected (Gaffney 1979), whereas the terrestrial horned tortoise *Meiolania* sp. is known only from a few fragments (Gaffney 1981).

Fragmentary crocodilian remains are common, but articulated or associated bones are rare. Consequently, little is known of the crocodiles except that they belong to new species (P Willis pers. comm.). An undescribed one may be related to the ziphodont *Quinkana* (Molnar 1981)

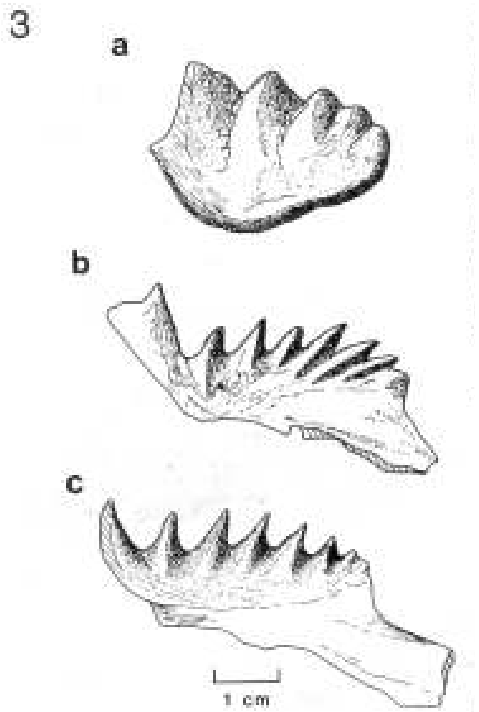


Fig. 3 Lungfish teeth: a) *Ceratodus wollastoni*, b) *Neoceratodus eyrensis*, c) *N. gregoryi*. (After Kemp & Molnar 1981).

Only a few fragments of squamatans have been found. These comprise some vertebrae of a large snake, a goanna *(Varanus)* (Estes 1984), and a few jaws assumed to represent the lizards *Egernia* and *Tiliqua* (Estes 1984; Pledge 1984).

Birds

Isolated fossil bones of birds are numerous and diverse, and mostly represent species associated with an aquatic environment: grebes, pelicans, cormorants, ducks, cranes, rails, stone curlews, and gulls. There are also hawks, pigeons and song birds. Most surprising is the presence of two species of flamingoes - *Phoenicopterus novaehollandiae* and *Phoeniconotius eyrensis* (Miller 1963b) - and representatives of the extinct flamingo-like family Paleolodidae, known also from Europe and North America at this time (Rich & van Tets 1982; Rich & Baird unpubl.). A pelican *(Pelecanus tirarensis* and an emu *(Dromaius gidju)* have been*)* described, but all the other taxa are still being studied. Eggshell fragments referred to the giant flightless dromornithids have been found at Lake Clayton, east of Muloorina Homestead.

Monotremes

Isolated teeth, from three localities, have been ascribed to a platypus, *Obdurodon insignis,* (Fig. 4; Woodburne & Tedford 1975). In modern platypus, only nestlings have teeth, which are replaced in the adult by horny structures. The juvenile platypus teeth are similar to these fossil teeth. Two bone fragments also have been described by Archer *et al. (1978).*

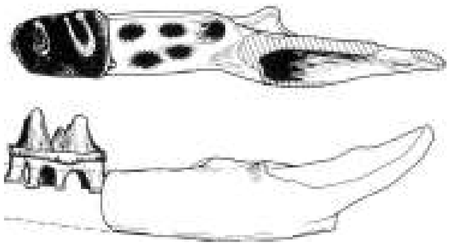


Fig. 4. Platypus *Obdurodon insignis,* tooth and jaw fragment (composite). (After Woodburne & Tedford 1975; Archer *et al.* 1978). Reinterpretation based on *Steropodon galmani*

Dasyurids

Fossils are mostly small jaws or teeth and are relatively rare. Five species have been described (Archer 1976, 1982; Archer & Rich 1979; Campbell 1976); others are being studied, including a possible thylacinid

Bandicoots

There are several primitive dasyurid-like forms being studied.

Possums

Ringtails are abundant, with eight species described (Table 2) from six successive levels (Woodburne *et al.* 1987; Pledge 1987b). Burramyids and petaurids are less common. Three extinct families of possum-like animals are now recognised: Ektopodontidae (Fig 5b) (originally thought to be a monotreme) (Stirton *et al.* 1967; Woodburne & Clemens 1986), Miralinidae and Pilkipildridae, which show affinities with the cuscuses (Phalangeridae) (Archer 1987)

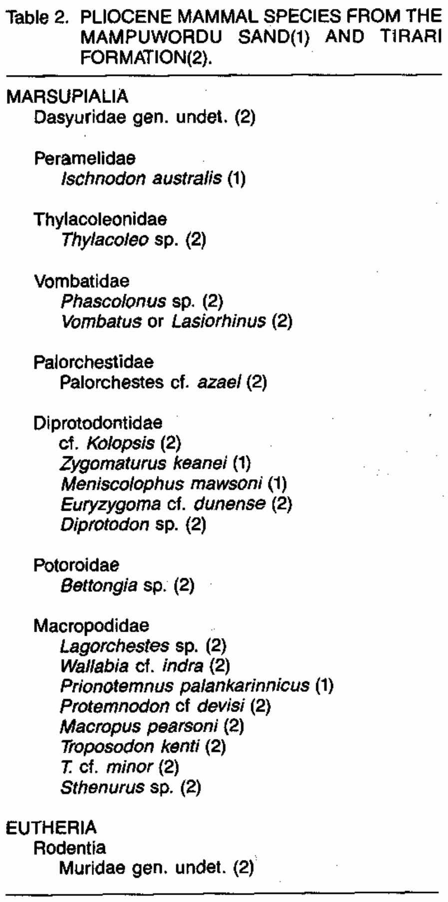


Table 2. PLIOCENE MAMMAL SPECIES FROM THE MAMPUWORDU SAND(1) AND TIRARI FORMATION(2).

- MARSUPIALIA
  - Dasyuridae gen. undet. (2)
  - Peramelidae
    - *Ischnodon australis* (1)
  - Thylacoleonidae
    - *Thylacoleo* sp. (2)
  - Vombatidae
    - *Phascolonus* sp. (2)
    - *Vombatus* or *Lasiorhinus* (2)
  - Palorchestidae
    - Palorchestes cf. *azael* (2)
  - Diprotodontidae
    - cf. *Kolopsis* (2)
    - *Zygomaturus keanei* (1)
    - *Meniscolophus mawsoni* (1)
    - *Euryzygoma* cf. *dunense* (2)
    - *Diprotodon* sp. (2)
  - Potoroidae
    - *Bettongia* sp. (2)
  - Macropodidae
    - *Lagorchestes* sp. (2)
    - *Wallabia* cf. *indra* (2)
    - *Prionotemnus palankarinnicus* (1)
    - *Protemnodon* cf *devisi* (2)
    - *Macropus pearsoni* (2)
    - *Troposodon kenti* (2)
    - *T.* cf. *minor* (2)
    - *Sthenurus* sp. (2)
- EUTHERIA
  - Rodentia
    - Muridae gen. undet. (2)

Koalas

Six species of koalas are known from six horizons within the Etadunna/Namba and Wipajiri Formations (Woodburne *et al.* 1987; Stirton *et al.* 1967). All represent extinct forms, only one of which *(Litokoala)* may be related to the extant koalas.

Wombats

Only the Wipajiri Formation has yielded certain wombat remains. They represent a primitive form *(Rhizophascolonus crowcrofti)* still having closed roots to its teeth, instead of rootless, persistently growing teeth of the modern species (Stirton *et al.* 1967). However, a damaged specimen from the Tarkarooloo local fauna of the Namba Formation may represent modern wombats (Rich & Archer 1979).

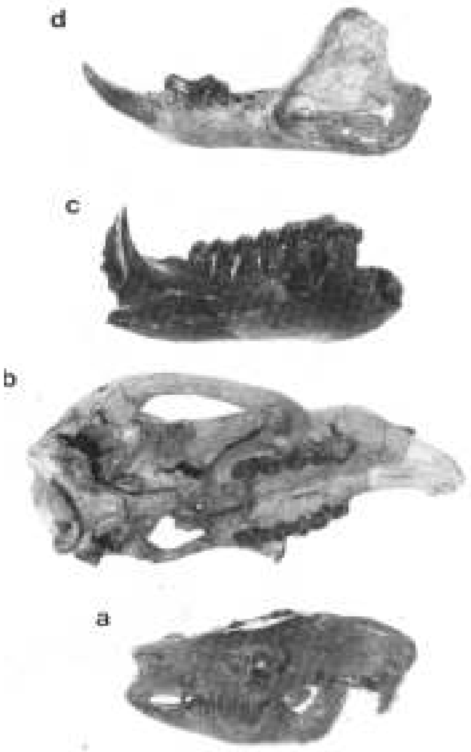


Fig 5 Mid Tertiary marsupials: a*) Muramura williamsi,* b*) Ngapakalda tedfordi,* c*) Ektopodon stirtoni,* d) *Wakaleo oldfieldi*

Wynyardiidae

Remains representing possibly three species are ascribed to this ancient family (Fig. 5a). Studies continue (Tedford *et al.* 1977; Rich & Archer 1979; Pledge 1987a, and in prep.) and suggest that they are related to both koalas and wombats.

Ilariidae

This is another extinct vombatiform family, of generally large (calf-sized) quadrupedal animals. Only a few specimens represent the species that occur in both the Lake Eyre and Tarkarooloo subbasins (Tedford & Woodburne 1987).

Thylacoleonidae

Ecological reasons may explain the rarity of the marsupial-lion family, relatively common in Pleistocene cave deposits. Two small primitive species have been described: *Priscileo pitikantensis* Rauscher, 1987 (Etadunna Formation) and *Wakaleo oldfieldi* Clemens & Plane, 1974 (Wipajiri Formation, Fig. 5d).

Palorchestidae and Diprotodontidae

These families include the largest marsupials in the Cainozoic faunas. Best known in the Tertiary of South Australia is the palorcheslid *Ngapakaldia tedfordi* (Slirton 1967), a browsing quadruped about the size of a sheep (Fig. 5c). Partial skeletons have been found in two localities at Lakes Pitikanta and Ngapakaldi in the Lake Eyre Basin, and jaws and teeth at Lake Tarkarooloo. Diprotodontids first appear with the primitive species *Raemeotherium yatkolai* Rich *et al.* (1978), from Lake Pinpa, Tarkarooloo Basin. The poorly-known *Neohelos tirarensis* from the Wipajiri Formation is related to *Raemeotherium.*

Macropodoids

Rat kangaroos (Potoroidae) and kangaroos (Macropodidae) occur in all but the oldest faunal unit, and represent many species, only a few of which have yet been described (Case 1984; Woodburne 1984; Flannery & Rich 1986). Few of these species have clear relationships to Quaternary or living species, and they represent aspects of an ancient diversification of the kangaroo family.

Placentals

The earliest non-marine placentals in Australia are represented by a single tooth of a microchiropteran bat, from the Etadunna Formation (Archer 1978). This specimen is identified tentatively as a rhinolophid. Cetaceans are an unexpected component of the faunas of the Namba Formation. A number of vertebrae, teeth, and periotic and other bones have been found in three localities, and represent an extinct group of freshwater dolphins, the Rhabdosteidae (Fordyce 1983).

Overall, these faunas suggest that the environment was one of permanent lakes and streams (Callen 1977), bounded by diverse riparian forest, with more open country beyond, but little grassland. The climate may have been mild with regular rainfall.

PLIOCENE AND PLEISTOCENE

Deposits of these ages blanket all older rocks and crop-out extensively in the Lake Eyre and Tarkarooloo basins. Fluviatile, lacustrine and aeolian environments of deposition are abundantly represented and contain fossil vertebrate remains. The Pliocene is represented only by fluviatile deposits, the Mampuwordu Sand and overlying Tirari Formation, of the Lake Eyre Basin. Pleistocene deposits are more widespread: fluviatile deposits of penultimate and last glacial age, the Kujitara and Katipiri formations respectively, of the Lake Eyre Basin

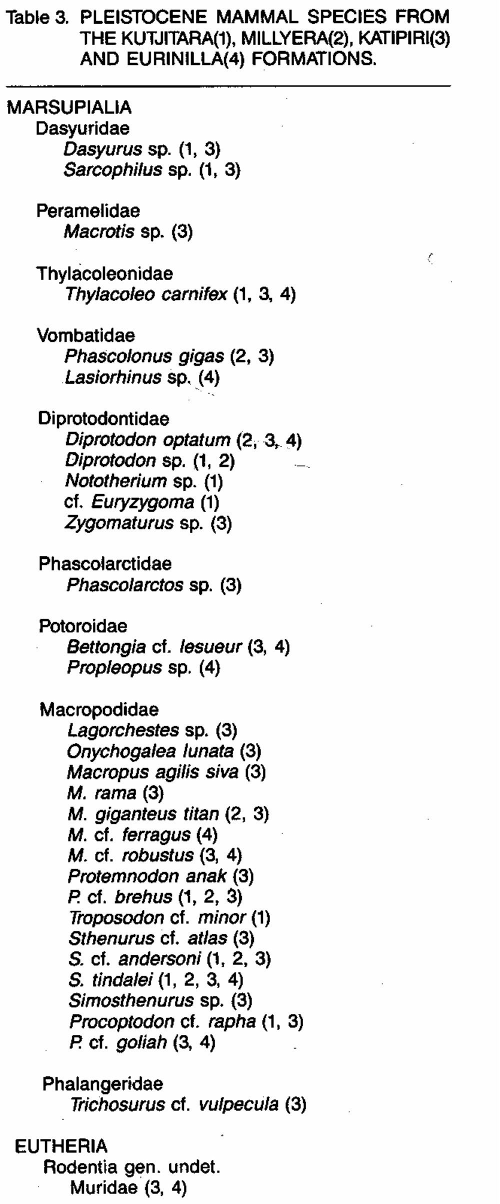


Table 3. **PLEISTOCENE MAMMAL SPECIES FROM THE KUTJITARA(1), MILLYERA(2), KATIPIRI(3) AND EURINILLA(4) FORMATIONS.**

MARSUPIALIA
- Dasyuridae
  - *Dasyurus* sp. (1, 3)
  - *Sarcophilus* sp. (1, 3)
- Peramelidae
  - *Macrotis* sp. (3)
- Thylacoleonidae
  - *Thylacoleo carnifex* (1, 3, 4)
- Vombatidae
  - *Phascolonus gigas* (2, 3)
  - *Lasiorhinus* sp. (4)
- Diprotodontidae
  - *Diprotodon optatum* (2, 3, 4)
  - *Diprotodon* sp. (1, 2)
  - *Nototherium* sp. (1)
  - cf. *Euryzygoma* (1)
  - *Zygomaturus* sp. (3)
- Phascolarctidae
  - *Phascolarctos* sp. (3)
- Potoroidae
  - *Bettongia* cf. *lesueur* (3, 4)
  - *Propleopus* sp. (4)
- Macropodidae
  - *Lagorchestes* sp. (3)
  - *Onychogalea lunata* (3)
  - *Macropus agilis siva* (3)
  - *M. rama* (3)
  - *M. giganteus titan* (2, 3)
  - *M.* cf. *ferragus* (4)
  - *M.* cf. *robustus* (3, 4)
  - *Protemnodon anak* (3)
  - *P.* cf. *brehus* (1, 2, 3)
  - *Troposodon* cf. *minor* (1)
  - *Sthenurus* cf. *atlas* (3)
  - *S.* cf. *andersoni* (1, 2, 3)
  - *S. tindalei* (1, 2, 3, 4)
  - *Simosthenurus* sp. (3)
  - *Procoptodon* cf. *rapha* (1, 3)
  - *P.* cf. *goliah* (3, 4)
- Phalangeridae
  - *Trichosurus* cf. *vulpecula* (3)

EUTHERIA
- Rodentia gen. undet.
  - Muridae (3, 4)

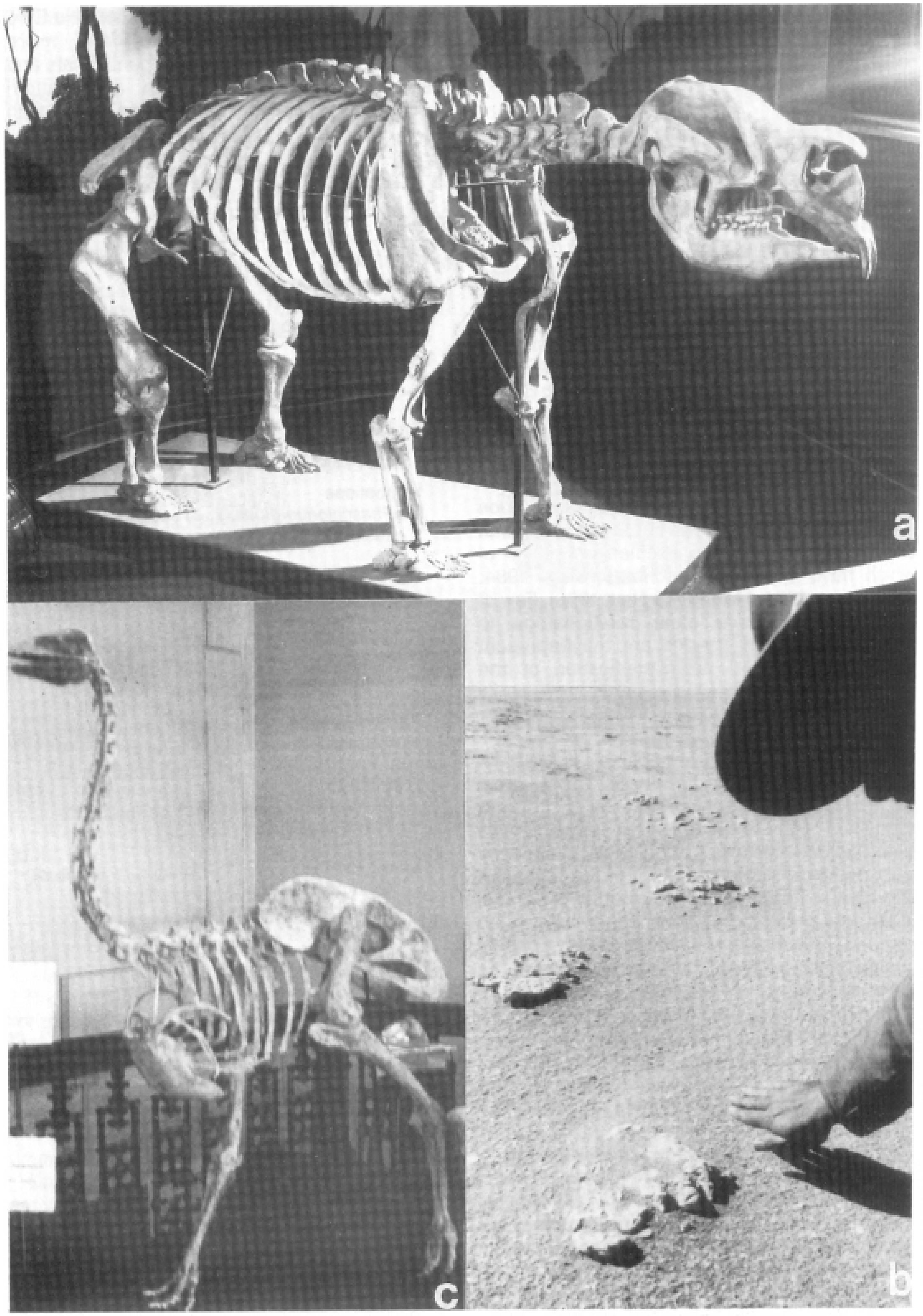


Fig. 6. Lake Callabonna fossils (Pleistocene): a) *Diprotodon optatum*, b) *Diprotodon* (?) trackway, c) *Genyornis newtoni*.

(Tedford *et al.* 1986), and the Katipiri-equivalent Eurinilla Formation (Williams 1980) of the Tarkarooloo Basin have all yielded diverse fossil vertebrates. The penultimate glacial Millyera Formation at Lake Callabonna is the only significant fossil site in a lacustrine environment.

Recent investigations have enabled Tedford *et al.* (1986) to recognise nine faunas within the fluviatile deposits of the Lake Eyre Basin, compared with the three described by Stirton *et al.* (1961). Many of these faunas are dominated by fish, lungfish, the turtle *(Chelodina* sp.) and crocodile *(Crocodylus?* sp.) bones, and the rare giant goanna *Megalania prisea.* Marsupials are abundant, most noticeably the diprotodontids and large kangaroos (Tables 2 and 3). Bird bones are common and the diverse fauna includes emus, pelicans, cormorants, ducks and flamingoes (De Vis 1905; Miller 1963 a, b, 1966; Rich & Van Tets 1981; Rich *et al. 1987).*

The taxonomic richness of the northern fluviatile deposits is in contrast to the fauna of the playa lake mire of Lake Callabonna which includes only a few species of large animals, represented by almost complete and articulated skeletons. The fauna of the Callabonna Fossil Reserve is dominated by *Oiprotodon* (Fig. 6a; Stirling 1900; Stirling & Zeitz 1899), possibly two sympatric species (D. L. G. Williams pers. comm.). Other marsupials include the giant wombat *Phaseolonus gigas* reported by Stirling (1913b) and the extinct kangaroos *Protemnodon* cf. *brehus, Maeropus* cf. *titan,* and three species of *Sthenurus* (Tedford & Wells unpubl.). There are also emus and the dromornithid *Genyornis newtoni* (Fig. 6c; Stirling & Zietz 1900, 1905; Stirling 1913a). These animals appear to have become mired in lake bed clay surrounding spring-fed waterholes. It is remarkable that there are no remains of any predator or scavenger that might have been attracted to the feast. At Callabonna, limy surface mud which often caked around the feet and in the hair or feathers of the victims, preserved footbones perfectly articulated, and left impressions of granulated foot pads, hairs and feathers in the lime. Trackways of *Diprotodon* also have been found where the animals' feet had compressed this limy crust (Fig. 6b). Similar situations occurred on Lake Eyre: remnants of a few *Diprotodon* and *Genyornis* skeletons were found near Babbage Peninsula (Pledge unpubl.).

CONCLUSIONS

The species lists for the Pliocene (Table 2) and Pleistocene (Table 3) when compared with that for the Miocene (Table 1) emphasize the faunal change which took place between Miocene and Pliocene time. The Miocene faunas contain many taxa of extinct families, no genus of which survived into Pliocene time. Pliocene and Pleistocene faunas on the other hand are similar in composition; the same families and most genera are present in both, but different species may be represented. Compared with the living fauna of Australia, Pleistocene faunas contain three extinct marsupial families (Thylacoleonidae, Palorchestidae and Diprotodontidae), many extinct kangaroo genera (all species of *Propleopus, Protemnodon, Troposodon, Sthenurus, Simosthenurus* and *Proeoptodon)* and some large forms clearly related to living taxa (e.g. *Maeropus agilis siva,* and M. *giganteus titan).* Most of the smaller marsupials and rodents continue into the Holocene, but many have become extinct in central Australia and now have more peripheral distributions (e.g. *Phaseolaretos, Maeropus agilis, Sareophilus).*

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18: Butterflies

by R. H. FISHER

INTRODUCTION

A significant number of butterfly species has adapted to the rather harsh environment provided by the central arid areas of the Australian continent. Each of the five major families Hesperiidae, Papilionidae, Pieridae, Nymphalidae and Lycaenidae - is represented. But in arid areas population densities, especially of insects, may fluctuate enormously. In years of good rainfall, high humidity and an abundance of host plants, there may be many generations of a butterfly species, while in less favourable conditions a species may virtually disappear from a particular habitat, to become evident again when more suitable conditions prevail.

In the arid north east of South Australia little, if any, serious collecting of butterflies has been undertaken, as the area has been comparatively inaccessible until recent years. There are a few specimens in the South Australian Museum, collected randomly by interested people, but any attempt to describe the butterfly fauna of this region must be based on our much broader knowledge of habitats, and our considerable knowledge of the butterflies and host plants which occur in adjacent areas.

It is possible then to predict with some confidence that about 25 species will be recorded for this area when systematic field work has been undertaken. Such research, to be of value, must cover as wide a range of seasonal fluctuations as possible.

Meanwhile, a list of species from adjacent areas is presented here with relevant comments. Subspecific names have not been used unless of particular significance. These and details of life histories and distribution are reported by Fisher (1978). It should be noted that the arid north east includes part of the Lake Eyre Basin, Flinders Ranges and Eastern regions, terms adopted by the State Herbarium, Adelaide for botanical distributions. These regions are sometimes quoted here when giving the distribution of host plants.

THE BUTTERFLY FAUNA

Hesperiidae

Two species of this family, *Croitana aestiva* and C. *arenaria* have been described from the Alice Springs area and C. *arenaria* has been recorded recently from northern Eyre Peninsula (Moore 1988). It seems highly probable that either or both these species will be recorded elsewhere in the arid areas of Australia, especially as the host plant, *Enteropogon acicularis* (windmill or curley grass), has a wide distribution that includes the north east of South Australia.

Papilionidae

One species, *Papilio demoleus* (chequered swallowtail, Fig. 1), is common at times in the north of the State. Its host plants *(Psoralea* spp.) are widespread, with five species occurring in the Lake Eyre and Eastern regions.

Pieridae

Seven species of this family should occur in the north east. *Anaphaeis java* (caper white) and *Elodina padusa* (narrow-winged pearl white, Fig. 2) have larvae which feed on *Capparis mitchellii* (native orange) and are often common near these trees in the Flinders Ranges. The habitat of C. *mitchellii* extends well into the Lake Eyre and Eastern regions. *Eurema smilax* (small grass yellow), *Catopsilia pomona* (lemon migrant) and C. *pyranthe* (common migrant, Fig. 3) are recorded from many areas in the north of the State. All three appear in migratory flights (usually in a southern direction) in other parts of Australia, but only *E. smilax* is considered common in South Australia. Various *Cassia* spp., with distributions that include the Lake Eyre and Eastern regions, provide food for the larvae. *Delias aganippe* (wood white), with wings coloured brightly red and yellow beneath, has been recorded from much of the State including Lake Eyre. Its appearance in most areas, however, is somewhat spasmodic. Its larvae feed on a number of widespread plants including *Santalum* spp. (quandong etc.) and *Amyema* spp. (mistletoes). The ubiquitous *Pieris rapae* (cabbage white) has been recorded from the Flinders Ranges and other localities near the centre of the continent and no doubt will occur in the north east. As well as domestic cruciferous plants its larvae feed on many species from several families

Fig. 1. *Papilio demoleus.* Chequered swallowtail.

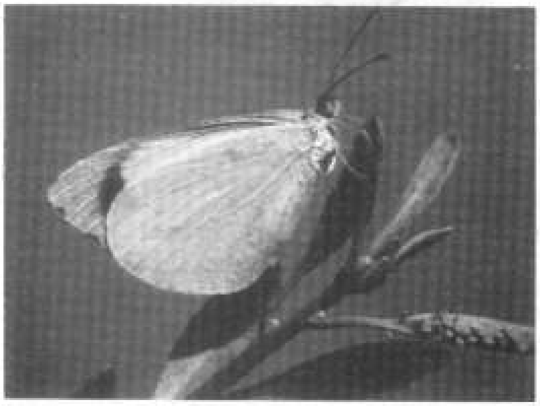

Fig. 2. *Elodina padusa.* Narrow-winged pearl white.

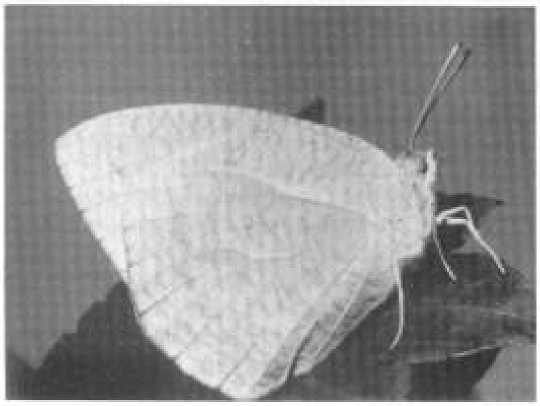

Fig. 3. *Catopsilia pyranthe.* Common migrant.

Fig. 4. *Vanessa kershawi.* Painted Lady.

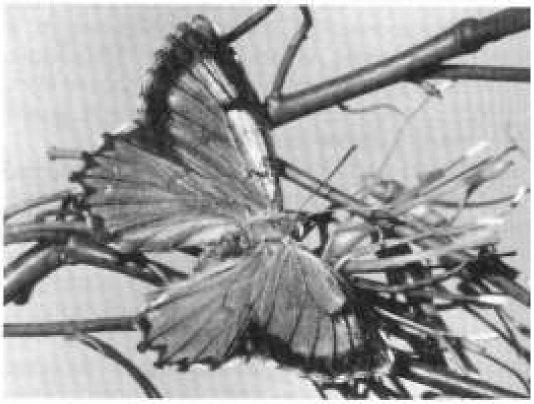

Fig. 5. *Ogyris amaryllis.* Amaryllis azure.

Fig. 6. *Jalmenus icilius.* Icilius blue.

Nymphalidae.

At least five species of this family should occur in the north east. *Danaus chrysippus* (lesser wanderer) has been recorded in immense flights on several occasions near Moomba. Under suitable conditions it is a common butterfly in many of the arid northern parts of the State, where its host plant is *Cynanchum floribundum* and probably several other asclepiads. The introduced *Danaus plexippus* (wanderer) occurs less commonly. *Vanessa itea* (Australian admiral) occurs in the northern Flinders Ranges and probably further north. Its larvae feed commonly on the introduced European nettle, *Urtica urens,* whose distribution now includes the Lake Eyre and Eastern regions. Two other nymphal ids, *Vanessa kershawi* (painted lady, Fig. 4) and *Junonia villida* (meadow argus) occur throughout coastal and inland Australia. Larvae of V. *kershawi* feed on the Compositae, especially *Helichrysum* spp. (everlastings); those of J. *villida* feed on a number of native plants from several families (Plantaginaceae, Verbenaceae etc.). A sixth species from this family, *Hypolimnas bolina* (common eggfly), has been collected in the Flinders Ranges on rare occasions. More common in the north and east of the continent, this species, under suitable conditions, apparently extends its range towards the arid centre. One of its host plants, *Alternanthera denticulata,* occurs in the north east.

Lycaenidae

This family is well represented in the arid areas and at least ten species should occur in the north east. The type locality for the subspecies *Ogyris genoveva splendida* (genoveva azure) is Mt Painter, and its range no doubt extends at least some distance north and east of this point. Both *0. oroetes* (silky azure) and *0. amaryllis* (amaryllis azure, Fig. 5) occur in arid areas, and the latter has been recorded near Lake Frome. These three species have larvae which feed on mistletoe *(Amyema* spp.). *Jalmenus icilius* (icilius blue, Fig. 6) and *J. lithochroa* (lithochroa blue) have been recorded from the Flinders Ranges and areas east of them, and one of their host plants, *Acacia victoriae,* is abundant and widespread in the north of the State. *Theclinesthes miskini* and *Nacaduba biocel/ata* (double-spotted lineblue) also have larvae which feed on A. *victoriae,* and are commonly seen flying over these trees. *Theclinesthes serpentata* (chequered blue) is very common inland, and its host plants include various saltbushes (Atriplex spp.). The larvae of *Lampides boeticus* (pea blue) and *Zizina labradus* (common grass-blue) feed on the flowers and leaves of a variety of leguminous plants, and both species occur throughout the continent.

VAGRANT SPECIES

Far to the north and east of the broad flood plains of the Cooper lie the tropical and subtropical regions of Australia where there is an abundance of butterfly species. It is well within the capabilities of many of these species to cross the intermediate areas aided perhaps by suitable winds when temperature and humidity are favourable. This movement of species beyond their usual range has been observed by Fisher (1978), will occur again, and may give rise to vagrants in the arid north east.

ACKNOWLEDGEMENTS

I acknowledge the invaluable contributions of Jessop (1984) who provided help in establishing the distribution of butterfly host plants in arid areas of South Australia.

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19: National Parks

by C. W BONYTHON

INTRODUCTION

The places in this region having statutory protection under the National Parks & Wildlife Act include those designated National Park (three), Conservation Park (two) and Regional Reserve (two). It might be supposed that conservation protection would be minimal in this remote corner of the State, but the opposite is the case. Total park area here is 71,000. km^2, which is 29% of the total area of the north east deserts and 70% of the total parks area of the State. The former percentage compares more than favourably with the 11% average for the whole of South Australia. Even if the Regional Reserves are excluded, because they offer a lesser degree of environmental protection, the ratio for the north east deserts becomes 11% - still considerably higher than the 7% State average without the Regional Reserves.

Recognition of the importance of conserving South Australia's unique ecological places, and the more ready availability of largely unmodified land, resulted in the creation of six parks in the north east deserts with part of a seventh also included. Five of the parks are large, making this by far the preponderant group of large parks in South Australia.

The five large parks are Lake Eyre National Park, Witjira National Park, Simpson Desert Conservation Park, Simpson Desert Regional Reserve and Innamincka Regional Reserve. The others are the Elliot Price Conservation Park and an extension of the Gammon Ranges National Park into the north east deserts region (Fig. 1).

These parks have primarily been created to conserve typical desert terrains but, paradoxically, it is the presence, or occasional large incursions, of water into the region that are responsible for producing so much interest and variety. The water of the 'mound springs' of the Great Artesian Basin, specifically conserved in Witjira National Park, is the best example of permanent water presence. The episodic regular river flows into South Australia from the north east, as the result of seasonal rainfall over monsoonal Australia, produce an oasis ecology in the Coongie Lakes of the middle Cooper Creek area (conserved in the Innamincka Regional Reserve). Finally, the huge floods resulting from rare, mighty, cyclonic downpours far away in the north and east, and carried into South Australia as floods in rivers like the Cooper, Diamantina, Georgina and Finke, produce dramatic hydrological and ecological results in Lake Eyre, one of the largest *salinas* in the world.

LAKE EYRE NATIONAL PARK
(Area – 12,280 sq km)

This huge park comprises the bed of Lake Eyre North and part of the Tirari Desert. It nearly surrounds Elliot Price Conservation Park. Unfortunately it does not include Lake Eyre South, which later may be added, nor the string of significant 'mound springs' to the southwest. Only one of the four important Tertiary fossil lakes east of Lake Eyre lies within the park. It will be considered here in its two quite different partsthe lake and the sandridge desert.

The Lake Eyre National Park deserves conservation status mainly because of the lake's great size and its geographical setting as a terminal lake at the focus of an inland drainage basin that occupies one-sixth of the total area of Australia, but also because it includes the lowest area on the surface of the continent, 15 m below sea level.

The lake as we now see it is the result of the large-scale natural processes active in such arid terminal lake systems. Over periods of years to decades, and changing in irregular cycles, hydrophysico-chemical processes run their course as Lake Eyre changes from a dry *salina* to a flooded lake and then back to a dry *salina.* At the same time there are wide-ranging fluctuations in wildlife populations. The inorganic stages of each cycle include flooding of the lake, salt crust dissolution, evaporation, re-deposition of the salt and even a subtle ageing of the dry salt crust over one or more decades (Bonython & Fraser 1989).

The wildlife of Lake Eyre the *salina* is of the scantiest, but that most interesting reptile

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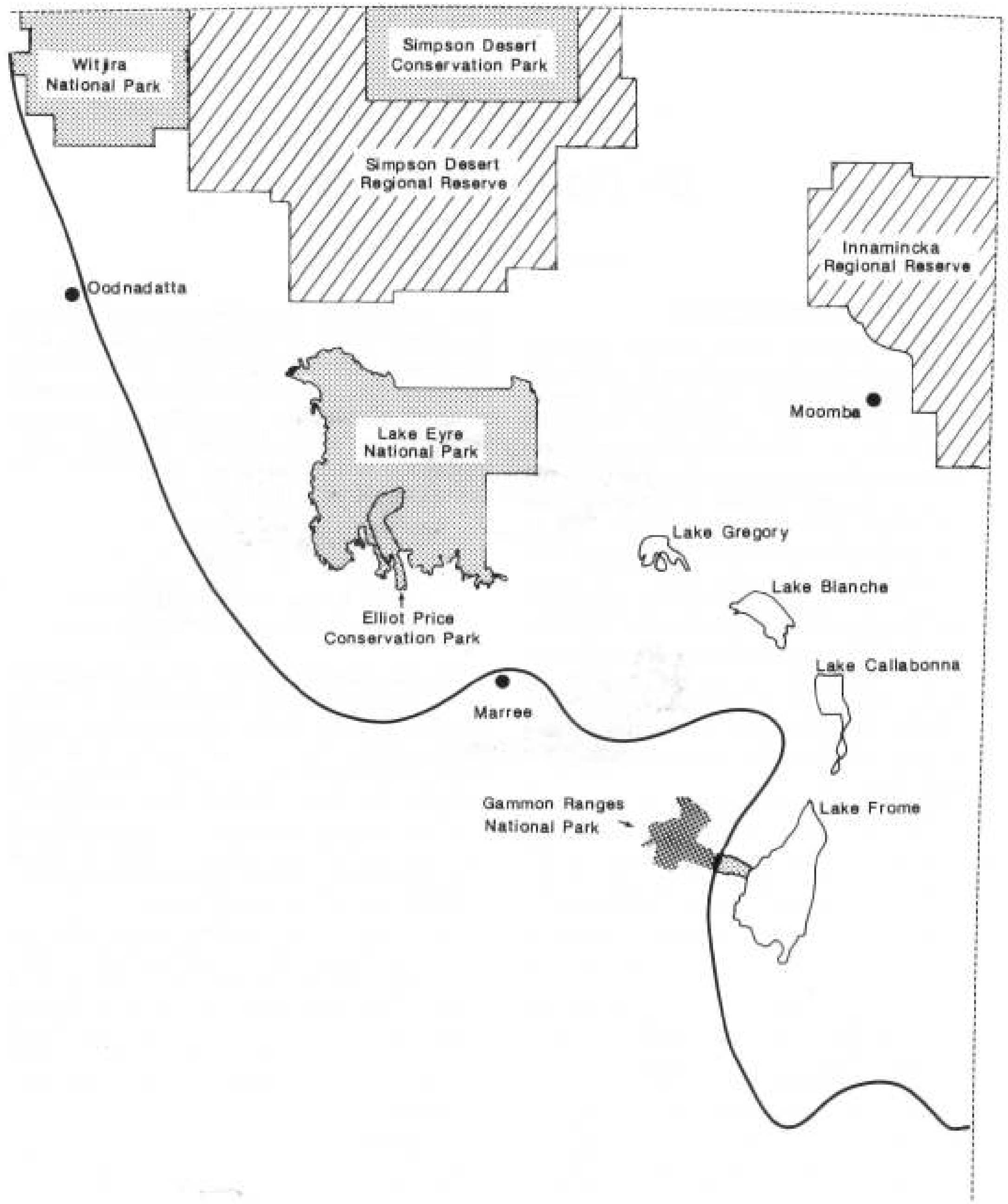

Fig 1. National parks, regional reserves and conservation parks in the north east deserts region

Ctenophorus maculosus, the Lake Eyre Dragon, inhabits the dry salt crust, feeding on ants. Apart from land birds flying over it, the *salina* surface may be traversed by shore-based feral animals like the camel.

In paradoxical contrast is the explosion of wildlife occurring in the truly lacustrine stages of Lake Eyre when fishlife rapidly develops, and flocks of coastal birds migrate inland to feed on the fish and remain to breed. Common fish are bony bream *(Nematolosa erebi)* and Lake Eyre hardyhead *(Craterocephalus eyresii),* while birds include pelicans *(Pelecanus conspicillatus),* black cormorants *(Phalacrocorax carbo)* and whiskered

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terns *(Chlidonias hybrida).* When the lake level falls and salinity increases the fish die in catastrophic numbers and subsequently the birds depart or die

The minute and microscopic life of Lake Eyre as a lake are the brine shrimp *(Parartemia* sp.) and algal, protozoal and bacterial organisms, including salt flagellates.

The shores of Lake Eyre support a limited flora, including hummocks of nitre-bush *(Nitraria billardieri),* samphire *(Halosarcia halocnemoides)* and scattered shrubs like needlebush *(Hakea leucoptera)* and native willow *(Pittosporum phylliraeoides).*

The sandy desert component of the Lake Eyre National Park is approximately one-third of the 12,000 sq. km Tirari Desert. It is really a southward extension of the Simpson Desert, and it exhibits the typical parallel sand ridges with the same sorts of sand and interdune vegetation and a similar -fauna. Lake Ng~pakaldi is the only significant Tertiary fossil lake included in the park (Stirton *et al. 1961).*

No Draft Management Plan has been prepared for the Lake Eyre National Park. In due course plans must be made for handling visitors - limiting the vehicular access tracks, defining camping areas and providing for rubbish removal. Travel on the dry lake bed, albeit in specialized vehicles, should be controlled. Boat-sailing on the filled lake presents less of a conservation problem.

Lake Eyre can offer breath-taking sights, such as a vast expanse of wind-whipped 'inland sea' and an equally vast, but still and silent, dry *salina.* Such are the essence of any great national park.

WITJIRA NATIONAL PARK

(Area - 7,769 sq. km; created 1985)

The Mount Dare pastoral lease was acquired primarily to conserve the Dalhousie Springs complex - the largest and strongest-flowing group of 'mound springs', fed by water leaking from the aquifer of the Great Artesian Basin. It was dedicated as Witjira National Park.

Other natural features of considerable conservation value are also protected there. Stony tablelands and gibber downs, the dissected remains of a silcrete land surface, are the first to be protected in a South Australian reserve. The protection of the terminal floodplain of a major arid zone river system - in this case the Finke River floodplain, occupying about 10 per cent of the park - is another 'first'. The eastern 30 per cent of the park includes part of the southeastern corner of the parallel sandridge system of the Simpson Desert (Cohen 1989; Rowberry 1986).

A number of Aboriginal archaeological and mythological sites exist in the park, for this is tribal land of the southern Aranda people. Relics of early European settlement are present in the form of the old Dalhousie ruins and the remains of the Blood's Creek telegraph station.

The Dalhousie Springs are the most significant group in Australia consisting of 60 active springs distributed over 60 sq. km. One has a flow of 14.3 megalitres per day. It is not surprising that they support a flourishing wildlife oasis. Discovered as late as 1870, they were soon taken as the base for a pastoral enterprise. This use degraded their natural values, but, as now conserved, they will largely recover.

The vegetation round the springs includes paperbark tea tree *(Melaleuca glomerata),* and a dense understorey of small shrubs and semiaquatic plants - sedges, reeds and rushes. Among the latter are bamboo reed *(Phragmites australis),* cutting grass *(Gahnia trifida),* bulrush *(Typha)* and bare twig rush *(Machaerina juncea).* While these occur in many of the other mound springs of the area, there are some restricted solely to Dalhousie, like *Eleocharis geniculata* and *Fimbristylis ferruginea* (Harris 1981; Symon 1985).

Many birds of the Great Artesian Basin frequent the springs, including the black-tailed native hen *(Gallinula ventralis),* the letter-winged kite *(Elanus scriptus)* and the grass owl *(Tyto capensis).* They are also notable for the native fish inhabiting them. Of particular note is the Dalhousie hardyhead *(Craterocephalus dalhousiensis),* a creature well adapted to high temperature and salinity.

The stony tablelands are mainly bare, but occasional plants of saltbush *(Atriplex nummularia)* and bluebush *(Maireana aphylla)* may be found. Birds include the gibber bird *(Ashbyia lovensis)* and the cinnamon quail-thrush *(Cinclosoma cinnamomeum).*

Other flora and fauna include many also found in the Simpson Desert Conservation Park and Regional Reserve.

The park is both vast and remote, so essentially it has a wilderness character which future management strategies must attempt to conserve. No Draft Management Plan has been issued, but the collection of basic information has begun. It needs to take into account visitor access and movement by four-wheel drive vehicles along designated tracks, and camping at designated sites. However, vehicles must be substantially excluded from the springs area where movement should be restricted as far as possible to foot traffic only.

Licences for mining exploration pre-dated the park's creation, but it can continue under controls gazetted when the park was proclaimed. A 'control zone' round the springs complex has been delineated where any mining exploration must be conducted sensitively and under tight control.

The National Parks and Wildlife Service will collaborate with the southern Aranda people for their best enjoyment of the spiritual aspects of their cultural landscape.

SIMPSON DESERT CONSERVATION PARK

(Area - 6,927 sq. km; created 1967)

SIMPSON DESERT REGIONAL RESERVE

(Area - 29,642 sq. km; created 1988)

These two parks - the second partly enveloping the first - are together roughly semi-circular in shape, with the diameter lying along the northern border of South Australia. They cover all the Crown Lands in this part of the State not occupied for pastoral or other purposes, and they join westwards with the recently created Witjira National Park, forming a single contiguous agglomeration of reserves some 44,338 sq. km in extent. It is logical to consider the two Simpson Desert parks together (NPWS 1983; Batistich 1988). The term 'southern Simpson Desert' conveniently equates with them.

Vast though they are, and conserving as they do most of the Simpson Desert in South Australia, these two parks represent only 23% of the 170,000 sq. km of the whole Simpson Desert (Bonython 1980) most of which is in the Northern Territory. Queensland has its own Simpson Desert National Park of 5,050 sq. km, adjoining South Australia's. The Northern Territory has yet to declare a national park in its sector.

The most striking feature of the Simpson Desert is its great grid of parallel sand ridges aligned approximately southsoutheast - northnorthwest. Some individual ridges continue for 150 km in length - occasionally reaching 300 km. They are separated by 200 to 1,000 m, and they are from 10 to 30 m high. While in the north, the sand is a deep red colour, in South Australia it is much paler.

The sandridge grid is not completely uniform, however. Three variants are recognized in the southern Simpson Desert (Fatchen & Barker 1979) - the western, central and eastern dune systems.

The ridge crests are likely to be wind-blown and bare, but the side slopes and the inter-ridge valleys (swales) are sparsely vegetated. Because the ridges have been formed by winds blowing from more than one direction they are frequently asymmetrical, the east side commonly being the steeper.

In the sand forms there is little variation from the repetitive, monotonous grid of sand ridges. However, one strikingly different formation is the Approdinna Attora Knolls southwest of Poeppel's Corner - two low limestone outcrops.

Apart from the Kallakoopah Creek anabranch there are no stream channels in the southern Simpson Desert, in contrast with the northern part. However, the southern desert has another distinction in being dotted and interlineated with a considerable number of mostly interdune, and hence elongate, claypans and *salinas* whose only catchment is their own inter-dune valley. They hold water - and then briefly - only after heavy local rain in exceptional years.

Mean annual rainfall in the southern Simpson Desert is about 100 mm, but it is highly variable; more is likely to fall in summer than in winter. Temperatures are likewise extreme, ranging from frosty mornings in winter to maxima approaching 50°C in summer. It is Australia's harshest desert; but while it cannot compare in this respect with the Sahara, for instance, it has been likened to the Kalahari (NPWS 1983).

Graetz *et al.,* (1982), using LANDSAT imagery, have defined a number of ecological associations, including four in the southern Simpson Desert. However, and speaking generally, the following dominant plant associations paint a fair picture of the area of interest (Crocker 1946; Lewis 1975):

1. *Zygochloa paradoxa-Acacia* low shrubland:
   This is characteristic of the desert sand ridges the tops and upper slopes of which include sandhill cane-grass *(Zygochloa paradoxa),* parrot bush *(Crotalaria cunninghamii),* sandhill wattle *(Acacia ligulata),* elegant wattle *(Acacia victoria e)* and native senna *(Cassia pleurocarpa),* while the lower slopes have scattered needlebush *(Hakea leucoptera).* After the rain the sand will support ephemeral species including buck bush *(Salsola kali),* Stuart's daisy *(Myriocephalus stuartii)* and fan flower *(Scaevola collaris).*
2. *Triodia basedowii* hummock grassland:
   The lower slopes and inter-dune swales are dominated by spinifex/porcupine grass (Triodia basedowii).
3. Ephemeral herbland:
   The playas and claypans in the swales contain small plants including saltbush (Atriplex spongiosa), bindy-eye (Sclerolaena limbata and S. intracata) and samphire (Halosarcia halocnemoides).

More than 150 species of birds inhabit the southern Simpson Desert. Those in considerable number are wedge-tailed eagle *(Aquila audax),* black kite *(Milvus migrans),* flock pigeon

(Phaps histrionica) and zebra finch *(Poephila guttata)*. The Eyrean grasswren *(Amytornis goyderi)* occurs widely through the Simpson Desert but is quite rare elsewhere. The Australian bustard *(Ardeotis australis)* ranges widely but sparsely through the area; it is an endangered species.

Mammals are few, but include the red kangaroo *(Macropus rufus),* the long-haired rat *(Rattus villosissimus)* and the greater bilby *(Macrotis lagotis).* Feral animals are more common - the dingo *(Canis familiaris dingo),* the camel and the rabbit. Reptiles include geckoes, dragon lizards, skinks and snakes.

Up to and including much of the nineteenth century, Aborigines occupied parts of the southern Simpson Desert, their existence based on a series of native wells. The major tribes were (Tindale 1974) the Wangkangurru, the Karangura and the Jeljendi. Today no Aborigines remain - only their former wells, disused and sanded up.

Exploration for oil and gas was going on in the southern Simpson Desert before any park dedication - and continued after it, because exploration rights were incorporated in the park proclamation. Most of the area has now been covered by seismic survey grids, and a few bores have been drilled. The legacy from this is a number of tracks now used by the four-wheel drive vehicles of park visitors - particularly two main tracks which are now the principal vehicle routes through the desert.

A Draft Management Plan for the Simpson Desert Conservation Park (NPWS 1983) has been issued. Besides giving much background information it sets out management objectives and proposals.

The objectives cover boundaries, zoning, native flora and fauna, Aboriginal and historic relics, petroleum exploration, visitor use, pest control and fire. It is interesting that the proposed enlargement of the park has been markedly surpassed by the recently created Regional Reserve. Zoning proposes that most of the park be zoned 'natural area' with corridors for 'visitor access'. Petroleum exploration has to be accepted, but there is accent on environmental controls on the explorers and insistence on rehabilitation measures, particularly concerning redundant access tracks. The effects will be monitored. Consideration is also given to the safety of visitors, park sign posting and interpretive programmes.

A leaflet by Friends of the Simpson Desert Conservation Park (1988) gives summarised description, history and safety precautions for desert travellers.

ELLIOT PRICE CONSERVATION PARK

(Area - 646 sq. km; created 1967)

Hunt Peninsula, which juts northwards into Lake Eyre, has been reserved as a sample of land in the driest part of Australia - annual rainfall about 100 mm - land that has never been grazed (Bonython 1967). One-third of it is the 'dry' land of the peninsula and Brooks Island, while twothirds is the strip of lake bed surrounding them. Elliot Price was a great local pioneer, and the park was made possible when he voluntarily agreed to surrender 180 sq. km of pastoral lease.

The terrain is largely limestone (dolomitic mudstone) partly carpeted in the south with thin siliceous sand, thus differing from the general lands bordering Lake Eyre. For instance, the limestone forms a prominent line of low coastal cliffs. There are also areas of gypseous loam, and occasional saltpans and depressions. Wave-built terraces of limestone rubble denote higher lake levels during past centuries (Dulhunty 1975). 'The. Spit' is an interesting wave-formed shoreline feature in the northwest (See Chapter 8).

Aboriginal artifacts are found - hammerstones, scraping knives and spearheads.

The vegetation is like that round the rest of Lake Eyre, but the limestone and shoreline gullies host some different communities. Galahs and whitebacked swallows nest in burrows in gypseous cliffs. Mammals are scarce, but include kangaroos and feral camels.

The park is separated from grazing lands south of it by a 14 km-long fence erected for its protection across the full width of Hunt Peninsula. Management problems include the prevention of the proliferation of vehicle tracks and the safety of visitors in this lonely location.

INNAMINCKA REGIONAL RESERVE

(Area - 13,818 sq. km; created 1988)

A new category of national park was created by South Australia in 1988 - the Regional Reserve, in which the conservation of the environment with its wildlife is married with the exploitation of natural resources, as in pastoralism and petroleum extraction. Its viability relies on agreement, co-operation and goodwill between the government agencies and the exploiters. Its justification is that, while the environmental protection can be only selective and limited under this arrangement, there would be no protection at all without the multiple use agreement, seeing that exploitation rights already exist and cannot be terminated without enormous compensation cost and without injuring the national interest.

Both Innamincka and Simpson Desert Regional Reserves were proclaimed on 22 December 1988 (Batistich 1988). They are the first such multiple use parks in Australia.

The Innamincka Regional Reserve has a wide range of terrains - six 'land systems' qre defined (NPWS 1988) - including dunefields, sandy plains, gibber deserts, dissected tablelands and the dominating Cooper Creek frontage and its associated Coongie Lakes wetland system.

There are 2,500 sq. km of Cooper Creek wetlands - channels, swamps, floodouts and terminal lakes. The Coongie Lakes component is particularly interesting; in 1987 an intensive environmental study, sponsored by Dick Smith's Australian Geographic, determined in fact and figure just how significant and important it is (Reid & Gillen 1988). It proves to be one of the ecologically richest wetland areas in Australia.

Over 200 species of birds have been identified, one-third being waterbirds. In addition to resident species and nomadic breeders, large numbers of waders and shorebirds use this wetland as a migratory stop-over. The density of breeding raptors is one of the highest in the world. It is on the list of Wetlands of International Importance ratified by the Ramsar Convention. Over 600 plants, 20 mammals, 50 reptiles, eight frogs and 17 fishes have been identified in the Coongie Lakes.

The Draft Management Plan (NPWS 1988) was released jointly with the park proclamation. The main objects are to conserve the natural, scenic and cultural values and to make them available to the public; to co-operate with the commercial exploiters to achieve the protection and maintenance of the long-term conservation values; to handle the increasing number of visitors - estimated at already 30,000 per annum; to carry out the monitoring and research; and to disseminate information to the public for their enjoyment and safety.

Five 'management zones' have been defined:

The Coongie Zone of some 600 sq. km is the most important for conservation, and in it greater emphasis will be given to limit exploitation activities and minimise their impact on the natural environment. The Cooper Zone covers the main middle Cooper channels and wetlands. The Innamincka Zone follows upper Cooper Creek with its historic sites, the Township Zone is round Innamincka itself, while the balance is called the Greater Reserve Area.

Public access to parts of the regional reserve will be restricted or available only by permit. A newall-parks pass is also announced - a 12-month Desert Parks Pass for access and camping in all of the six full parks of the north east deserts.

GAMMON RANGES NATIONAL PARK

(Area - 1,282 sq. km; created 1970)

(Portion within deserts region - c.200 sq. km)

Where the boundary of the north east deserts region skirts the foot of the Flinders Ranges west of Lake Frome it intersects a tongue of this park that extends out to the lake shore. The part thus defined has an area of c. 200 sq. km.

This 'plains' section had been added to the mainly mountainous park as part of the large Balcanoona Station acquisition during 1979-83 (Bonython 1984). It is as different as chalk is from cheese compared with the rest of the Gammon Ranges National Park, and it fittingly takes its place in the deserts environment.

As Mitchell grass *(Astrebla pectinata)* grassland near its southern distributional limit, it is an ecologically important area, and until it acquired its protected status this unit had scarcely been conserved at all in South Australia.

Its inclusion also created a continuous ecological transect from the summit of the Flinders Ranges to the shore of dry Lake Frome - equivalent to a 'mountain top to the sea' transect - and has greatly enhanced the value of the park.

The plain is also of legendary significance to the Adnjamathanha Aborigines. No management plan for the park has yet been released.

THE FUTURE OF CONSERVATION MANAGEMENT

The generous national parks coverage in the region must be partly discounted because of the inherent permission for mining exploration and mining, in all the parks except the Elliot Price Conservation Park. While these activities are subject to some conservation-orientated 'control', environmental protection cannot be regarded as being as full as in national parks without mining provisions.

In the Regional Reserves the protection must be even further discounted because of the wider licence for resource exploitation. They are an innovative experiment, watched with interest - and also with some initial misgivings - by most conservationists. Still, the concept allows for some statutory conservation where none would have been possible under the former arrangements. These shortcomings throw a heavier onus on skilful and effective parks management. New strategies need to be developed to cope with the more intractable problems.

A fundamental long-term problem presents itself concerning the hydrology of the Innamincka and Lake Eyre parks. Damming the still-natural, far-flung rivers could drastically alter the ecology of the Cooper Creek and Coongie Lakes wetlands which are dependent on regular, natural, seasonal flooding. The unique Lake Eyre phenomenon is similarly threatened, but the rare, huge river floods that go on to fill Lake Eyre are more likely to over-ride man-made works like dams, and so it is more likely to persist.

APPENDIX

Definitions of certain categories of national park created under the National Parks and Wildlife Act 1972, as amended.

National Park: A protected area containing multiple natural values including scenic beauty, wildlife, geological and geomorphological features, Aboriginal sites, history and pre-history which are of outstanding significance and offer inspiration to visitors.

Conservation Park: An area protected principally for the conservation of native flora and fauna representative of the State's natural heritage, and which may, to a lesser degree, contain all or any of the features conserved in a National Park.

Regional Reserve: An area where the natural environment and its wildlife are as far as possible protected while the exploitation of the natural resources of the area goes on simultaneously under a joint, cooperative arrangement between the government agencies and the exploiters.

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20: Biogeography

by M. J. TYLER

INTRODUCTION

At its most fundamental level biogeography is concerned with the documentation and interpretation of the distribution of the flora and fauna. Accuracy of analysis of issues such as origins and dispersal routes of organisms largely hinges upon the degree of resolution of the distribution data.

A study of the biogeography of the north east deserts is inhibited by the relative paucity of observations. The extent of the observations is largely determined by the accessibility of the sites. In practical terms this means that less than 1% of the total land surface has been visited by biologists.

For almost any landmass, attempting a biogeographic analysis with such a constraint would seem of dubious value. However the reality is that the nature of the north east deserts is unique in several ways and that meaningful analysis is possible. For the most part the area is homogeneous in terms of its extreme aridity. Exceptions are the mound springs on the western boundary, the semi-permanent Coongie Lakes in the north east, and the waterholes along the ephemeral flood routes such as Cooper Creek that link the Coongie Lakes to Lake Eyre. These geographically 'atypical' features have attracted disproportionate attention. They are the areas of greatest biological diversity and are reasonably well documented.

BIOGEOGRAPHIC STATUS

When Spencer (1896) proposed the division of Australia into a series of biogeographic provinces, the state of knowledge was extremely poor by modern standards. It would be anticipated that the elaboration of understanding of the nature and distribution of the flora and fauna over the last century would modify his scheme substantially. It is a source of surprise that time and improved knowledge have not had much impact: the boundaries remain largely unaltered.

The concept of a biogeographic Province as a meaningful unit hinges upon several criteria, including the existence of a significant number of species confined to the Province, and of endemics with a common geographic distribution that coincides with that of the Province (Moore 1961).

In the case of the huge Eyrean Province that embraces central Australia including the southeast deserts it is unlikely that these criteria can be met. It is in fact a largely artificial conglomeration of those species that would not fit within the Bassian or Torresian Provinces (Fig. 1). Thus although there are species with distributions that are wholly within the Eyrean Province, it is likely that future studies will cause this Province to be split into more meaningful components.

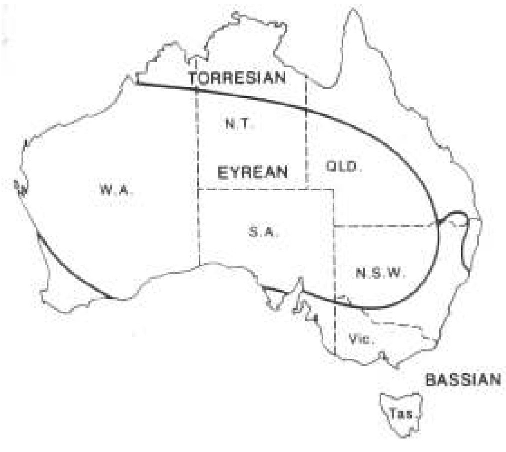

Fig. 1. Biogeographic provinces of Australia (after Tyler 1978).

Within the Eyrean Province the north east deserts is not a distinctive and natural biogeographic unit, because it lacks effective barriers to dispersal. The boundaries for this study are the mound springs to the west, Lake Eyre to the south, and the State boundary at the north and east. It therefore is a convenient segment of South Australia that can be defined and documented, but cannot be expected to have a biogeographic cohesiveness.

Laut *et al.* (1977) used the term province in an entirely different way. In fact they divided South Australia into eight 'environmental provinces'. The north east deserts form a portion of their 'northern arid province' (Fig. 2). Within the northern arid province they recognised sub-units that they termed 'environmental associations', of which most of those occurring in the north east were associated together in a larger unit that they termed the 'Lake Eyre Environmental Region'.

There is no conflict between the interpretation of Spencer (1896) and Laut *et al.* (1977) because their criteria were quite different. Spencer's physical areas were defined principally by phytogeographic and zoogeographic data, whereas Laut *et al.* (1977) sought patterns of association from plant communities and physiographic features. Those patterns provided definable units and a system for recognition that hopefully is utilitarian.

Fig. 2. Delimitation of the 'northern arid province' (after Laut *et al.* 1977) with the north east deserts region recognised here superimposed upon it.

ACCUMULATION OF KNOWLEDGE

Even today travel in the north east deserts is considered a hazardous occupation that is not to be undertaken lightly. Accordingly the problems faced by the early European scientific explorers were horrendous by modern standards.

By the turn of the century the greatest activity had focussed upon Lake Calabonna where fossil remains of the large marsupial *Diprotodon australis* and the large bird *Genyornis newtoni* had been reported to F. B. Ragless by a local aboriginal in 1892. Ironically when a party arrived in the following year to excavate the remains it rained. Stirling (1900) graphically describes the party's camels sinking up to their bellies in the glue-like mud.

He writes of gales, temperatures in tents rising to 120°F and the torture of the innumerable flies.

In fact it is only in recent years that any real progress has been made towards documenting the flora and fauna. The establishment of Moomba and the local support provided there by Santos employees has been a major step, enabling numerous collectors to reach and study areas further north. Edmonds (1986) has summarised the contributions of their predecessors working in less fortunate circumstances.

The north east has received intense attention over the past 15 years with areas such as the Dalhousie Springs being the subject of a specific study (Zeidler & Ponder 1989) and Lake Eyre the topic of a monograph (Bonython & Fraser 1989).

SIGNIFICANT ENVIRONMENTAL ASSOCIATIONS

The north east deserts can be defined as a physical unit largely because of atypical peripheral characteristics: the mound springs on the western boundary, Lake Eyre at the south and the floodplains of Cooper and Strzelecki Creeks at the east.

The greater part of the area has what Lange & Fatchen (Chapter 11) described as 'very meagre vegetation', with relief being provided only in localised areas such as along floodways and at mound springs. Thus survival of organisms is for the most part determined by the capacity to withstand periods of drought, whilst to flourish requires the ability to capitalise upon a nonseasonal and highly unreliable rainfall.

The peripheral aquatic components are totally different. The mound springs include a number of animal species that are unique to them. Whether they are the relicts of formerly more widespread forms, or whether they evolved in isolation, or are the consequence of a combination of these origins is uncertain.

In contrast the waters of the eastern boundary are ephemeral with, at the extremes, massive flooding interspersed with periods of aridity. To survive, an organism must be hardy, adapted to drought conditions and capable of responding rapidly to favourable times.

SURVIVAL AND DISPERSAL

One of the most fascinating aspects of the biogeography of the north east is the temporal fragility of a significant proportion of the fauna, affecting most significantly the flood plain areas, the faunal composition and density must be perceived as undergoing distinct cyclic trends.

During sustained droughts the freshwater fauna will become restricted to remnants of water that

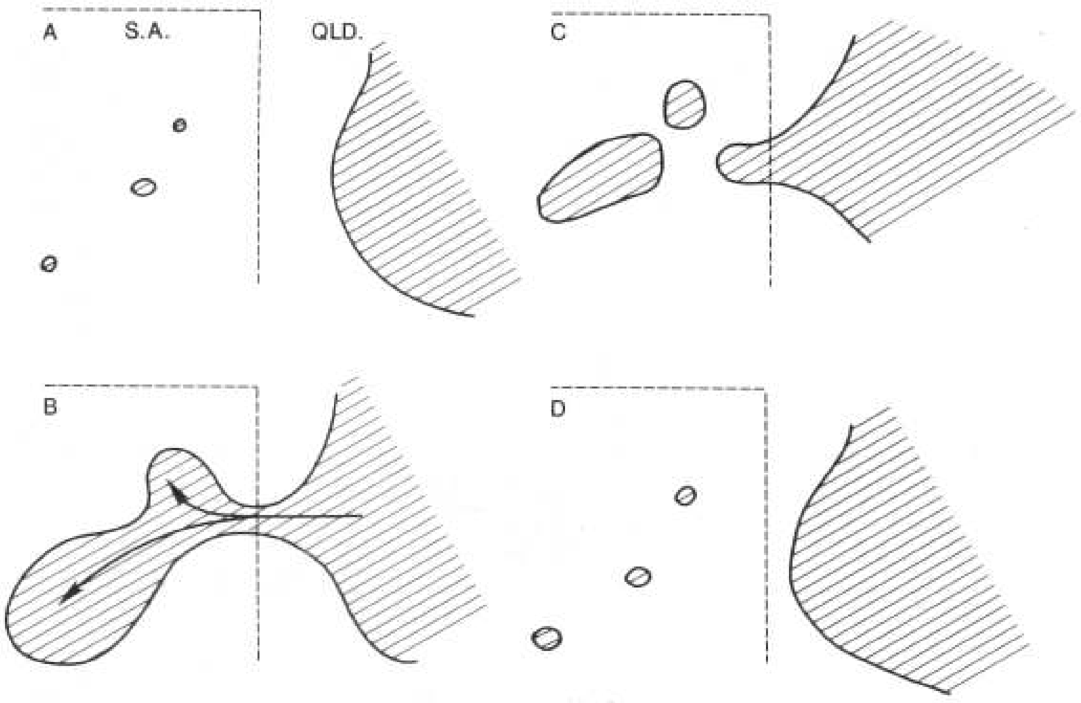

Fig. 3. Diagrammatic representation of the sequence of occupation, dispersal and colonisation events in the eastern portion of the north east deserts. A. Distribution of an aquatic taxon during a period of aridity. B. Dispersal during flooding when water enters from the east. C. Fragmentation following early phases of aridity. D. Further contraction of populations during sustained aridity.

remain, hence becoming locally extinct in areas of former abundance.

The overall southwestern direction of flow of temporary rivers and creeks determines that entry into the eastern and southern portions of the area will be from the north east. Thus the origin of the flood-transported fauna will be predominantly from southwest Queensland.

Thus although the periphery of creek beds, and particularly the margins of the billabongs, will sustain the most moist dependent life, the overall pattern in the area is of extinction, followed by recolonisation and proliferation, and finally repeated extinction as aridity sets in. This pattern of events is represented in a diagrammatic fashion in Fig. 3.

To the west of the area the age and origins of the flora and fauna of the mound springs has been the subject of considerable interest. This interest stems in part from the present lack of flood links with adjacent ephemeral water sources, and thus uncertainty about the dispersal and origins of the organisms that inhabit the mound springs. Kotwicki (1989) has addressed this issue in relation to the lack of impact of the Finke River upon the most northern of the mound springs: Dalhousie Springs.

The high degree of endemicity of the Dalhousie Springs fish fauna (Glover 1989) has required an adequate span of time for speciation to occur. Curiously the frog fauna is extremely depauperate throughout the mound springs. The marsh frog *Limnodynastes tasmaniensis* was collected at Dalhousie Springs in 1985 and reported by Smith (1989) as the first record for the area and the first record for central Australia. It was, however, collected at Dalhousie Springs in '1976 and reported there by Tyler (1978). It has also been known to occur further east in the north east deserts for many years. Tyler (1978) expressed surprise at the vast numbers of *L. tasmaniensis* at Dalhousie Springs when it was first found there, noting that it had not been found previously by any of the numerous herpetologists who had visited the area. This phenomenon may be an example of the vast cyclic swings in numbers that seem to be characteristic of many Australian frog species, and are particularly conspicuous in arid areas.

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