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DESERT LANDFORM EVOLUTION: WITH SPECIAL REFERENCE TO THE AUSTRALIAN EXPERIENCE

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1. Introduction

When geomorphologists refer to deserts, they refer implicitly to the mid latitude rather than to the polar deserts. Such arid zones occupy about 20% of the continental areas (including about 4% hyperarid), and semiarid lands another 15%. Topographic barriers (rain shadow effects), continentality and ocean currents affect the aridity of the continents, and human activities have intensified and marginally extended the deserts, but basically the arid zones of the world are a function of the planetary insolational and pressure patterns, and of the present position of the continental masses with respect to those pressure patterns.

Thus, Australia has, since its separation from Antarctica in the Eocene, been drifting northwards. The present rate of migration is of the order of 6 cm per annum. The equatorwards motion has carried the continent astride the mid latitude high pressure zone with the result that Australia is, apart from Antarctica, the driest of the continents. Roughly one third of the Australian land mass is, from a climatic point of view, statistically arid, including a small area of hyperaridity around Lake Eyre. Another third is semiarid. Yet Australia lacks the landforms most typical of such desert regions as the Arabian Peninsula and the Sahara, namely extensive fields of active, mobile sand dunes. There are huge fields of linear sand ridges (Fig.1) but most are stabilised by vegetation. Moreover only sand ridges, longitudinal or linear dunes are widely developed, transverse dunes, barchans, dome and star dunes being absent or poorly represented.

2. The australian arid zone: the structural factor

Ptolemy realised that desert landscapes vary, for he subdivided the Arabian Peninsula into Arabia Petraea, the rocky or mountainous desert (the Hejaz); Arabia Felix, the fertile or coastal regions (the Hadramaut, Hasa, Oman and Yemen); and Arabia Deserta (the Nejd), the sandy desert. The Australian arid zone is thus typical in that several types of desert are represented. Mountains and ranges are developed on structural blocks that appear to have been persistently uplifted through time. Plains on the other hand are coincident either with basinal structures which have suffered repeated subsidence, or on the Western Craton, and especially the shield or crystalline sections, which have been subjected to long periods of weathering and erosion.

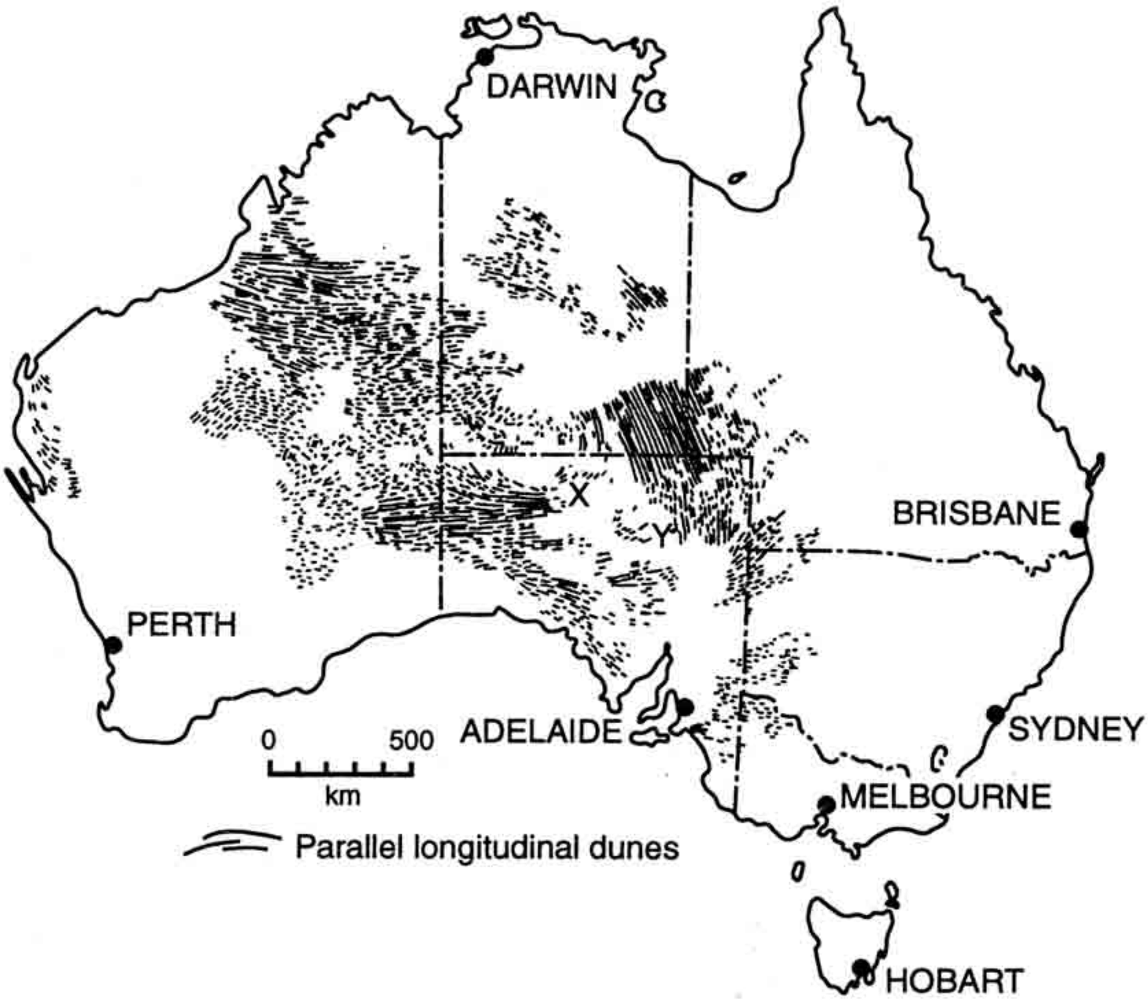


Fig. 1. Australian dune fields, active and stabilised. (After Jennings, 1968).

At the continental scale, lineament patterns (see e.g. Hills, 1961; O'Driscoll, 1992) determine the shape of many basins and uplands, as well as the alignment of such rivers as the Darling and Flinders. At the local scale, minor neotectonic forms are widely developed. Fault scarps are commonplace, even within cratonic areas, as a result of earthquakes associated with the joggling of blocks within the northward migrating continent. Thus the escarpment bordering Lake Eyre on its western side is a fault scarp of Holocene age. Though dissected in detail, the feature is regionally linear; the gypsite horizon exposed on the adjacent plains has been displaced and is now found below the halite crust of the bed of the salina; mound springs are formed on the bed of the salina as well as on other fault lines to the west; and earthquake epicentres are recorded from the vicinity (Wopfner and Twidale, 1967; Twidale, 1972a). The Mt Margaret and Levi fault scarps which delimit the eastern flank of the Peake and Davenport Ranges disrupt a Late Pleistocene gypsite surface (Wopfner, 1968). Dirt scarps were formed as a result of earthquakes east of Tennant Creek in the Northern Territory in 1988 (Bowman, 1992). Moreover, many granite exposures display fault scarps a few millimetres or centimetres high, but forming patterns of horsts and graben. A-tents or pop ups (Coates, 1964; Twidale and Sved, 1978), associated with the

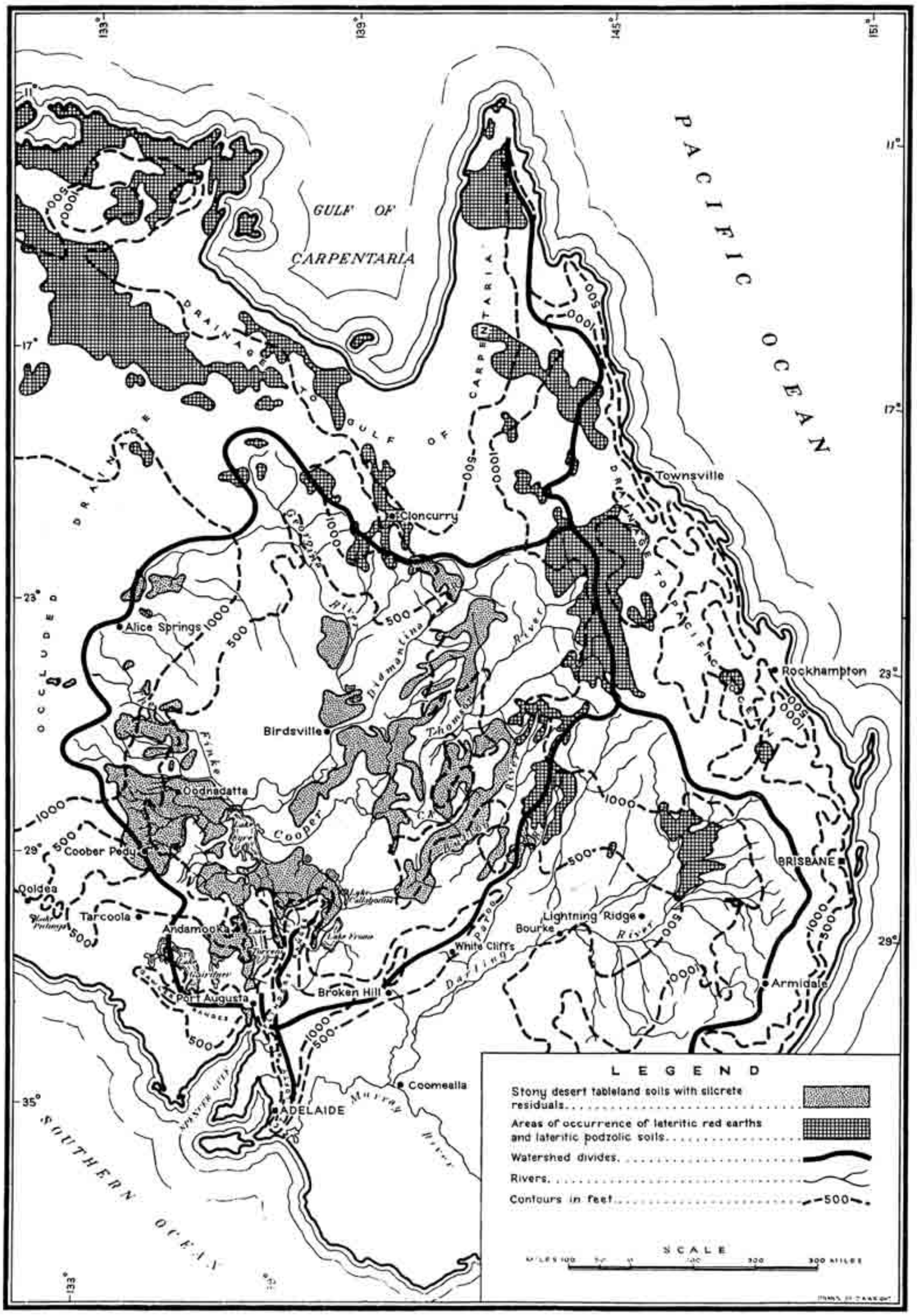


Fig. 2a. Map of lateritic and silcrete duricrusts in eastern Australia (CSIRO).

release of compressive stress, are also widely developed, as for instance in the Kulgera Hills and on granite and gneiss bornhardts in the interior of Western Australia (Twidale et al.,1993).

The morphology of the desert uplands varies according to structure and in this respect they are no different from their structural counterparts exposed in other climatic regions. Thus, though displaying particular variations in detail, the Flinders, George Gill, James, Krichauff and McDonnell ranges are typical fold mountain belts of Appalachian type, the Arcoona Plateau is characteristic of dissected flat lying sedimentary sequences. The Everard, Musgrave, Gawler and Reynolds ranges display the landforms typical of crystalline massifs. Gosses Bluff and the Wolf Creek Crater are typical meteorite impact forms. In addition, dissected remnants of Cainozoic duricrusted surfaces, most of them siliceous but including some that are ferruginous, are prominent throughout central Australia (Fig. 2a). Most are flat lying and give rise to plateaux (Fig. 2b), but there are some that have been folded and form cuestas and hogbacks, as for example in southwest Queensland (see Wopfner 1960; Sprigg, 1963) and in the northeastern piedmont of the Flinders Ranges (see Campana et al., 1963).

Fig. 2b. Silcrete capped mesa, Rumbalara, northwestern margin of Simpson desert (CSIRO).

Thus the uplands of the desert regions display structural and tectonic forms similar to those of other climatic regions. Admittedly, karst development is retarded or even degraded in such areas as the Nullarbor Plain, but by and large, structurally controlled forms are similar to their counterparts in other climatic contexts. Their characteristics are however more readily observed, and are longer preserved, in aridity. Summit bevels of unusually great antiquity are preserved on these arid zone uplands, whether sedimentary or crystalline (see Twidale, 1994; Twidale and Vidal Romani, 1994). Also, as pointed out by several workers, for example by Hills (1955), in the deserts, mountains and hills rise abruptly from the adjacent plains and valleys (Fig.3), probably as a result of scarp foot weathering and erosion (Twidale, 1967; 1978), so that most of inland Australia can be regarded as one vast inselberg landscape, albeit at scales ranging from the regional to the local.

In addition, and also because of scarp foot weathering and erosion, scarp recession is prominent in arid lands (Twidale and Milnes 1983; Twidale 1983). Both of these landscape characteristics arise, rather paradoxically, from the enhanced significance of what moisture there is in arid lands. Also, processes such as gully gravure (Bryan, 1940; Beaty 1959; Twidale and Campbell, 1986) are prominent, resulting in the formation of ribs and ridges running across the contour on the flanks of plateaux (Fig. 4).

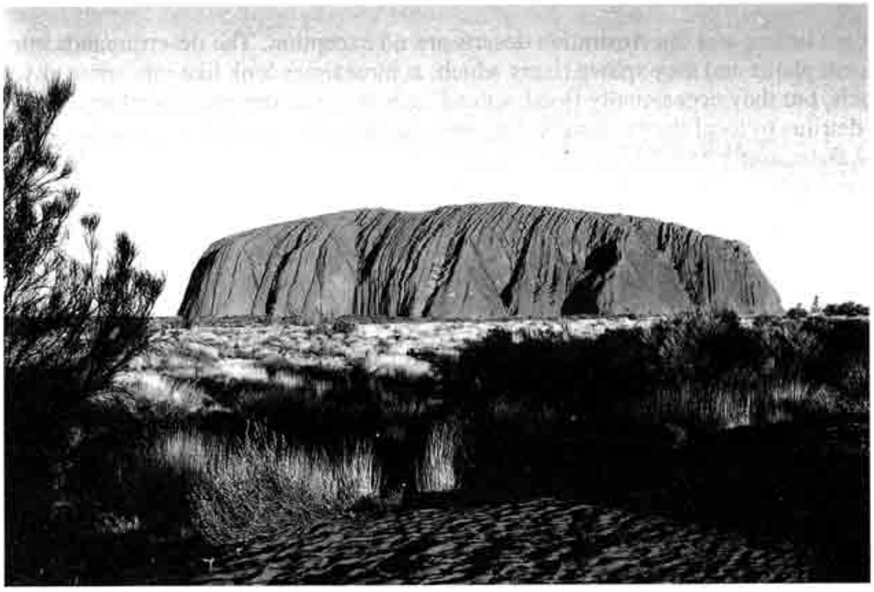


Fig. 3. Piedmont angle at base of Ayers Rock, central Australia.

Fig. 4. Inselberg landscape, Ooraminna Ranges, central Australia. Note rib, resulting from gully gravure, on slope in right foreground.

3. The work of running water

No desert is rainless and the Australian deserts are no exception. The desert upands attract more rain than the adjacent plains and they spawn rivers which, at most times look like innocuous dry sandy or rock strewn channels, but they occasionally flood, spreading huge distances over the plains, and carrying large quantities of detritus to local depressions. Oddly enough, however, in central Australia it is rivers like the Georgina and Diamantina which rise not in uplands, but on the monsoonal plains of northern Australia, which contribute the greatest quantities of water and sediment. In times of high flood most of the well named Channel Country of southwest Queensland and of the adjacent areas of South Australia and New South Wales is under water. River erosion, transport and deposition are clearly critical to dune development in the Simpson and other Australian deserts, and a similar conclusion is indicated by the field evidence from such arid areas as the Kalahari and parts of the Sahara, where dunes appear to be generated in association with depocentres.

Fig. 5. Anabranching channels in flood plain.

Rivers have also deposited extensive tracts of sediments to form plains of extraordinary flatness. Many display intricate patterns of anabranching channels (Fig. 5) as do the floors of overflow basins or lagoons such as Goyders Lagoon. But transport and deposition implies erosion, and rivers and streams are responsible for most erosional work in the uplands and bedrock plains within desert, as well as for the gullying in unconsolidated sediments such as those accumulated in lunettes and in the alluvium of valley floors. They have sculpted uplands such as Ayers Rock, where flights of potholes are scalloped in the steep bounding slopes of the residual (Twidale, 1978), cut into the scarps of ridges in the MacDonnell and other fold mountain ranges, and of duricrusted plateaux, and eroded rolling plains either in inherently weak rocks or in regolithic materials: most erosional work in deserts is due to rivers (cf. Peel, 1941).

Intense rainstorms are certainly experienced in desert regions but they are no more frequent or intense than those experienced in other climatic conditions. On the other hand the physical characteristics of desert surfaces frequently render them vulnerable to water erosion. They lack vegetational protection (root binding, umbrella effect). The stony carapaces of the gibber deserts protect the underlying surface against raindrop impact but other types of surface are exposed and vulnerable. Clay surfaces become baked and impermeable, so that run off is increased.

Two other fluvial forms, pediments and alluvial fans, are characteristically well developed in arid regions, though they are not restricted to them. Pediments are smooth erosional surfaces located in the

Fig. 6a. Covered pediments at Brachina, western piedmont of Flinders Ranges, seen from the air.

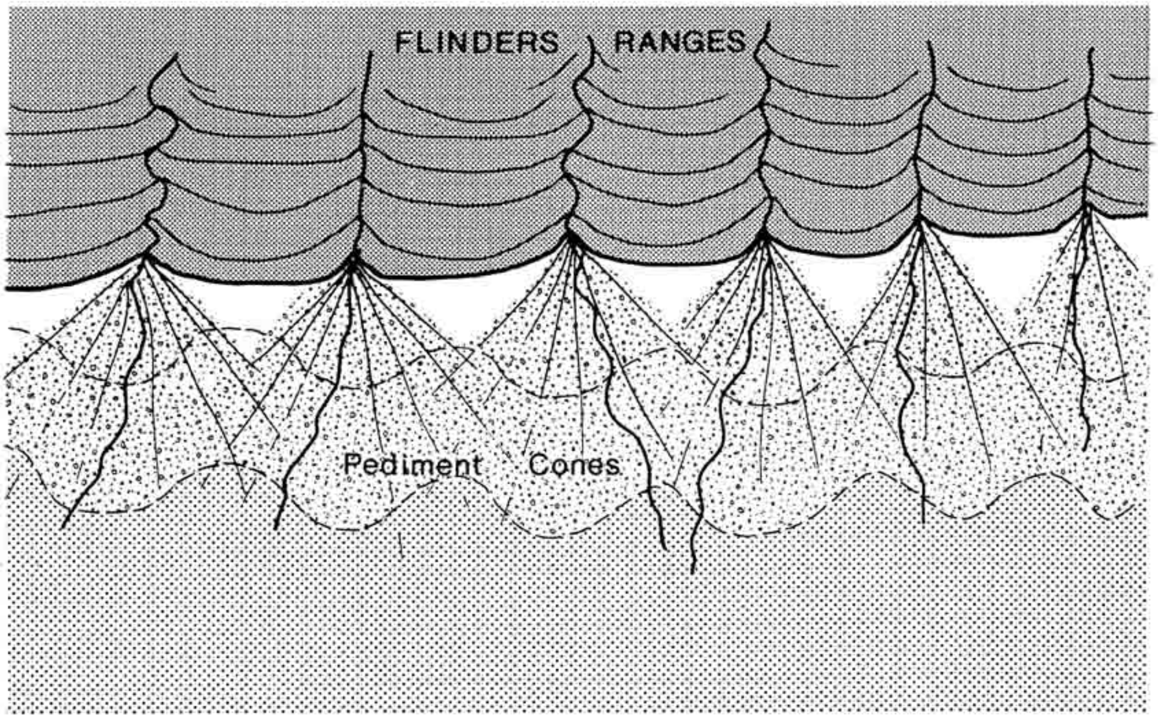


Fig. 6b. Suggested mode of development of covered pediments.

piedmont zone and meeting the backing scarp in a sharp break of slope, the piedmont angle or nick (Twidale, 1967). Pediments are well and widely developed in arid and semiarid lands but are also found in such humid areas as Korea and Japan, and in cold regions such as the Pyrenees and Alaska. They vary in character and origin (Twidale, 1981b).Covered pediments are typical of sedimentary terrains, are fan shaped, carry a protective veneer of transported materials, and are due to divaricating or distributary streams which , on debouching from their confined upland valleys, and simultaneously erode the bedrock and lay down point bar deposits as they migrate from side to side (Fig. 6a and b ; Twidale, 1981a).

Fig. 6c. Rock pediments in granite at Corrobinnie Hill, northern Eyre Peninsula, central Australia.

Mantled pediments (or platforms) are smooth gently sloping surfaces cut in bedrock but with a veneer of weathered bedrock. They are typical of granitic terrains. Rock pediments result from the stripping of the regolithic veneer from mantled pediments and are thus of etch origin.They are well represented in granitic rocks but are occasionally found in otjer rock types (Fig. 6c). Rock pediments formed in sediments reflect uniformity of outcrop in the catchment, and in particular a lack of any resistant material that would disintegrate to produce a protective veneer.

Alluvial fans consist of thick wedges of alluvium deposited in the piedmont zone (Fig. 7). In many areas they merge laterally to form aprons that extend long distances and through varied climatic zones. For example, the alluvial apron fronting the arid southwestern Flinders Ranges can be traced virtually unbroken for some 400 km, to south of Adelaide in a mediterranean semiarid regime (annual average precipitation circa 560 mm). They are found not only in arid and semiarid lands but also in cool mountainous regions such as the Canadian Rockies, Scotland, New Zealand and the Zagros Mountains of northern Iraq and Iran.

The distribution of pediments and fans varies in space and in time, yet both reflect deposition of debris by episodically or intermittently active streams emerging from confined mountain valleys onto plains, where they break their banks in flood and lose hydraulic efficiency as they develop large numbers of channels. The stream regime necessary for the development of fans and pediments may be due to occasional desert rainstorms, or to monsoons, or to spring melt of snow and ice. Whether erosional pediments or depositional fans develop appears to reflect the character of the *thalweg* or stream profile (Bourne, 1995). When and where, after long periods of stability, upland rivers emerge on to the plains concordantly, without any major break of gradient, pediments develop as the now unconfined and distributary (or divaricating) streams debouche essentially concordantly on to the plains or valleys, eroding the bedrock at the same time as they deposit a veneer of alluvium to produce covered pediments. Where, however, and for whatever reason, there has been a lowering of baselevel, the plains streams have rapidly incised their channels and the intervening plains as well. The upland rivers become discordant or perched and debouche discordantly on to the plains depositing thick wedges of alluvium. In the Flinders Ranges, this suggestion finds support first in the location of fans in broad depressions eroded into pediment aprons. Second, in the deposition of the fans following a late Cainozoic tectonic uplift of the Ranges. Third, in the development of a virtually continuous apron of alluvial fans from Port Augusta southwards, fronting a north-south upland which lacks fringing pediments and extends through precipitation zones that vary between 250mm in the north to 500mm in the south; the rivers are all exoreic and were thus adjusted to the glacioeustatic sealevel fluctuations of the Late Quaternary (see e.g. Twidale and Bourne, 1994; Bourne 1995).

Fig. 7. Alluvial fan at Parachilna, western Flinders Ranges.

4. Desert plains

Dune fields dominate the plains of central Australia (Fig. 8). In the eastern Simpson Desert, there are large linear sand ridges that are devoid of vegetation and which are clearly active, but over most of this, the most active of the Australian dune fields, only the dune crests are in motion, and then only intermittently or spasmodically. Moreover, there are in southeastern Australia, huge areas of relic dunes, that is, linear or longitudinal dunes apparently similar to those of the hyperarid and arid zones but now located in semiarid climates and stabilised by vegetation. These stabilised dunes merge imperceptibly with adjacent areas of dunefields which are at least spasmodically active. The northern relic dunefields may have been stabilised as a result of their migrating, as a result of plate motion, into the zone of monsoonal rainfall, but the more extensive areas of relic dunes located in southern South Australia, western Victoria and western New South Wales represent genuine climatic changes superimposed on effects due to continental drift. In these terms the northern relic forms ought to be older than their counterparts in southeastern Australia, but this remains to be investigated.

The fields of relic and active sand ridges together form what has rather simplistically been described and interpreted as an anticyclonic swirl around the centre of the continent (Fig.1), though such a concept implies that all the dunefields are of similar age, and that all are or were active simultaneously; and this is not so. The pattern itself poses several problems. For example, what is the reason for the abrupt change

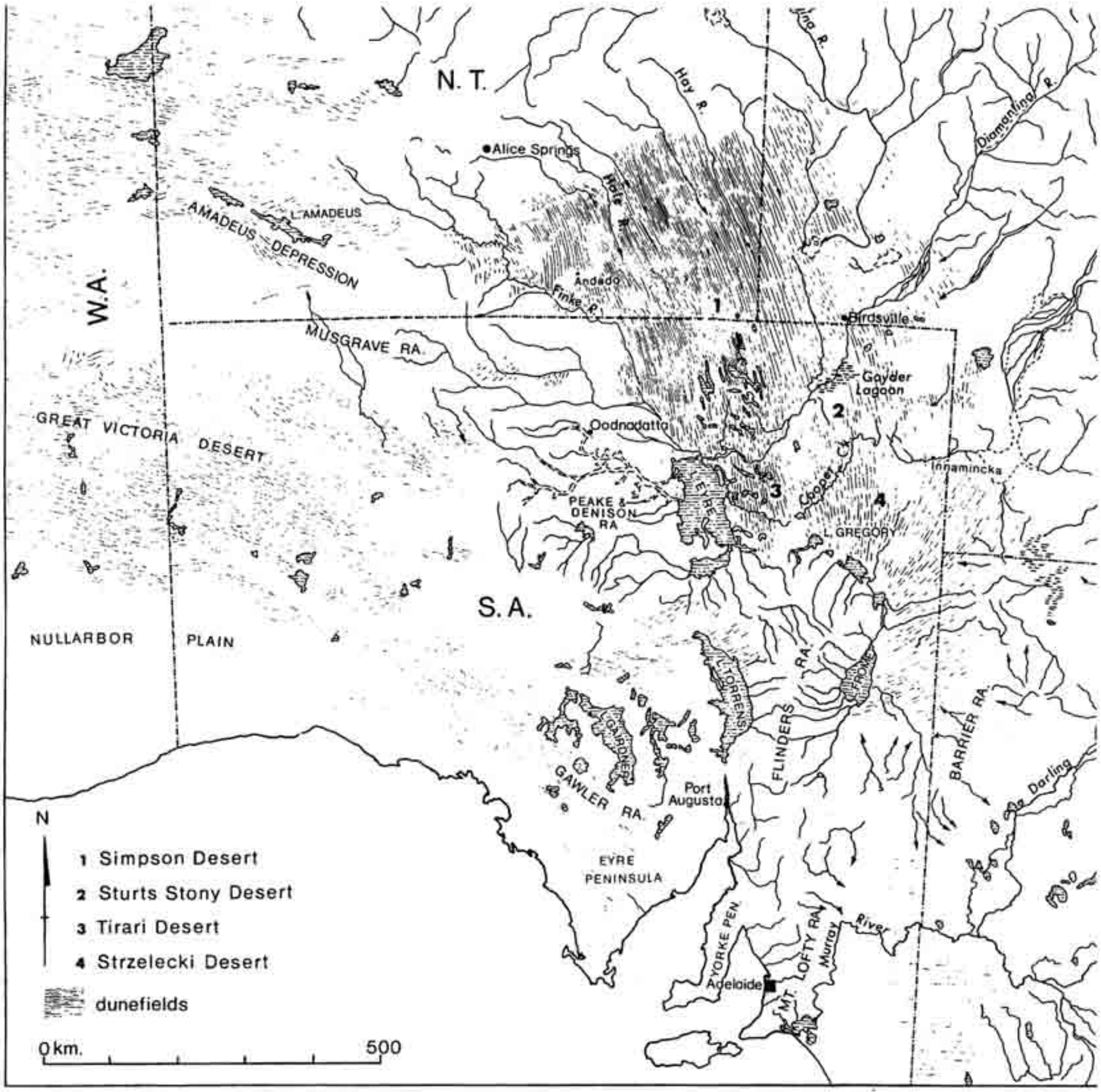


Fig. 8. Map of Simpson Desert.

in direction in dune trend (through about 120 degrees) where the west-east trending dunes of the Great Victoria Desert meet the SSE-NNW dunes of the Simpson Desert west of Lake Eyre (Fig 1 at X). And similarly that from an southwesterly to a northerly trend, achieved within a few tens of kilometres, in the vicinity of Lake Arthur, between Lake Gregory and the northern piedmont of the Flinders Ranges (Fig.1 at Y).

There are, as Jennings (1968) pointed out, regional departures from the simple pattern shown in Fig.1. In the Amadeus Basin, for example, the dunes describe a bewildering array of incomplete rectangular and circular patterns with numerous aberrant arms and spurs, star dunes and dome dunes and even domes with hollow crests. In the broad valley between the Sir George Gill and James ranges, southwest of Alice Springs, the sand ridges trend northeast-southwest.

In addition to fields of dunes, and as a result of the sorting action of the wind, as well as structural and topographic factors, several other types of desert plain are represented. Large areas are occupied by stony desert (reg, hamada, or, in Australia, gibber plains), of which Sturts Stony desert (see Sturt, 1849, for a fascinating account of this strange landscape) covered by a carpet of angular silcrete fragments, derived from the cappings of dissected silcrete capped plateaux, is the best known. Here, purple and black silcrete gibber occur side by side; whether the colour difference reflects a contrast in age (cf. Blackwelder, 1954), or whether it is due to original compositional variations, or to differences in shallow hydrological conditions, is not known.

The gibber plains vary in character according to the local bedrock and its weathering characteristics. Thus though the stony deserts of central Australia are dominated by siliceous rocks, and especially by blocks and fragments of silcrete, quartzite is a common component. Also, limestone gibber is prominent adjacent to outcrops of that kind, as for instance adjacent to parts of the northern Flinders Ranges, and ironstone on the stony plains of the Gibson Desert. The stony desert owes its origin partly to the evacuation of detritus of sand size and fines by wind and wash, partly to the vertical churning and sorting action associated with the wetting and drying of hydrophilic, and especially sodic, clays (gilgai action - see Hallsworth et al., 1955; Springer, 1963; Hallsworth, 1968).

Sorting and churning causes a gradual concentration of stones so that fines are protected against deflation, but until that occurs, the gibber plains contribute to duststorms, though bare flood plains of major rivers like that of the lower Diamantina, are the main source of fines in the Australian arid zone. Unfortunately, however, cleared and ploughed agricultural areas are the major contributors. Some of the dust deflated by the wind and carried in suspension high in the atmosphere is carried across the Tasman Sea to New Zealand, just as Saharan dust (and fauna, such as locusts) occasionally reach northwestern Europe on the wind.

Playas abound. There are many claypans small and large (like the Bilpa Morea Claypan of southwestern Queensland), but most of the depressions are salinas, many of them quite small, but including some that occupy a few thousands of km^2. Most carry a crust of halite though some, like lakes Gregory and Torrens are predominantly gypseous; and gypsum occurs beneath the halite crust of Lake Eyre. The playas vary in origin. Lakes Eyre and Torrens for example occupy downfaulted areas. Lake Amadeus and many of the lakes of the Yilgarn Block (e.g. lakes Lefroy, Carnegie, Wells) represent remnants of palaeodrainage systems dismembered by the onset of aridity, and in the case of Lake Amadeus, probably also by warping. Lake Gairdner occupies the site of a blocked upland drainage system, while Lake Woods may in part be a polje and due to dissolution and collapse of the underlying limestone. But many of the lagoons and claypans of the Channel Country of southwest Queensland and the northeast of South Australia are shallow depressions due to scouring and deposition by rivers in flood. Their outlines later become smooth and rounded as a result of wave action while water remains. Whatever their origin, such playas act as centres of deposition (or depocentres - see Wopfner and Twidale, 1967, 1988), as sources of sand, and as topographic obstacles, both of which are critical in the generation of dunes.

5. The dunefields

5.1 General remarks

More than any other desert, the Australian dunefields are dominated by linear or longitudinal dunes, sand ridges which are aligned roughly parallel to the vector or resultant of the main sand moving winds, which blow at 20km/hour or more. In the western Simpson Desert such winds blow from the SE and

SW, though in the east and southeast, the wind regimes are different for the resultants trend meridionally and SSW-NNE (Fig.8). Rectangular pattern of dunes composed of a combination of linear and transverse elements are found adjacent to the Finke, near Erldunda, at the northwestern edge of the dunefield. Barchanoid forms and barchan dunes are developed on the crests of some sand ridges in Sturts Stony Desert , the Strzelecki Desert (Wopfner and Twidale, 1967), transverse and climbing and falling forms in the Gawler Ranges (Campbell et al., 1995) and in the Ooraminna and Krichauff Ranges, and parabolic dunes in the Gawler Ranges and in the Corrobinnie Depression (Bourne et al., 1974; Campbell et al., 1995). Overwhelmingly, however, the dunefields consist of longitudinal sand ridges.

5.2 Regional structure and drainage

The dunes of the Simpson Desert *sensu lato* (i.e. including not only the Simpson *sensu stricto*, but also the Tirari and Strzelecki dunefields and Sturts Stony Desert- see Fig. 8), are the most active of all the Australian desert dunes. They may be taken as typical of the Australian dunefields (and of some others - see below) though their evolution and dynamics are unusual in some respects. The Desert extends over several structural regions but is largely developed over the Eromanga Basin, containing Mesozoic sequences. Not only does the basin structure provide artesian waters, and induce shallow surbsurface flows, but the Lake Eyre region is downfaulted, so that parts of the bed of Lake Eyre stand some 15 m below sealevel. Rivers focussed on Lake Eyre have extended well beyond the confines of the Eromanga Basin, and of the arid zone. It is for good reason that a major part of the Simpson Desert is located north and northeast of Lake Eyre, for the latter, and the riverine plains to the east and southeast, are the foci and termini of a drainage system which occupies some 1.3 million km^2 of central and northeastern Australia (Fig. 8). Some of the major rivers of this system, rise in monsoonal northern Australia and run every year. Given two or more consecutive years of heavy rains and run off they deliver water to Lake Eyre. Consequently, Lake Eyre is flooded several times each century (Kotwicki, 1986).

Vast quantities of water and sediment are carried toward, and the detritus deposited in, the lower parts of the Lake Eyre depocentres. The granitic and sandstone uplands that border the Eromanga Basin, and the duricrusted plateaux within and around the desert, are the sources of sediment from which the sand dunes are constructed. Some of the quartz sand may be derived directly from the weathering of granitic or other local bedrock (Folk, 1971) and may not have been transported long distances by the wind (Folk, 1971; Wasson, 1983).

But evidence from other areas (e.g. the Gawler Ranges, see Campbell et al., 1995) and the prolific generation of dunes in association with playas and flood plains in the Simpson Desert argues against this interpretation. Most of the sand has in an immediate sense at least, been transported by rivers to the lower parts of the Lake Eyre depocentres (Wopfner and Twidale, 1988) though most grains have been through several cycles of weathering, transport and deposition (marine, lacustrine, even glacial).Thus, zircon ages suggest that the sands of the northern Simpson Desert ,in particular, but also some now located in more southerly dunefields , originated in the Arunta Block, to the north of the Desert (Anonymous, 1994). But the stratigraphic evidence suggests that the sands have probably been through several cycles of weathering, erosion, transportation and deposition, though in an immediate sense they are derived from alluvial and lacustrine sediments and have been driven in a NNW direction by winds from the southerly quarter.

But whatever its history, the sand is carried by rivers to the lower reaches of the Lake Eyre basin. Following heavy rains the rivers run high and overtop their banks so that adjacent interdune corridors are flooded for many kilometres distant from the river. The channels, associated floodouts or "lagoons" and the flood plains of such major rivers (or creeks) as the Georgina and Diamantina, the Warburton and the Cooper are the major sources of sand from which dunes have been and continue to be constructed by the wind. Rivers also return sand to the desert system for rivers like the Todd, Hale, Hay, Gnallan-a-Gea and Mulligan carry southwards and deposit sand earlier carried northward on the wind.

Not only sand moved by rivers of the present regime is involved in dune formation for there is incontrovertible evidence that in Late Pleistocene times the lower part of the Lake Eyre basin was a vast complex of lacustrine and riverine sedimentary plains. Thus, river transport and deposition are crucial to dune genesis. Given the present dominance of sand moving winds (c.20-27 km/hour) from the southeast and southwest, the sands laid down in the depocentres of the lower parts of the Lake Eyre topographic basin, have been drifted northwards to give the sandy Simpson Desert, though other drainage basins, and particularly those centred on lakes Frome, Callabonna, Blanche and Gregory, are sources of sand for the Strzelecki and associated dune fields.

Such past and present surface waters, supplemented by subsurface flows in the river channels and in the strata associated with the artesian basin that underlies much of the region, have done much to counteract the climatic aridity of the region. This is why vegetation of the Simpson Desert is so relatively and surprisingly abundant. This in turn accounts for the widespread stabilisation of the dune corridors and lower flanks of the dunes, and for the only intermittent movement of the dunes. On the other hand the deleterious impacts of human interference such as pastoral overgrazing and the introduction of the rabbit and the goat are also explained, for given a reduction in the vegetation cover, climatic factors again come into play. Also, frequent flooding of parts of the eastern and southern Simpson Desert, and the resultant salinity of soils and shallow groundwaters inhibit plant growth, so that dunes and corridors are bare or only sparsely vegetated; and here dune generation and migration are obviously active.

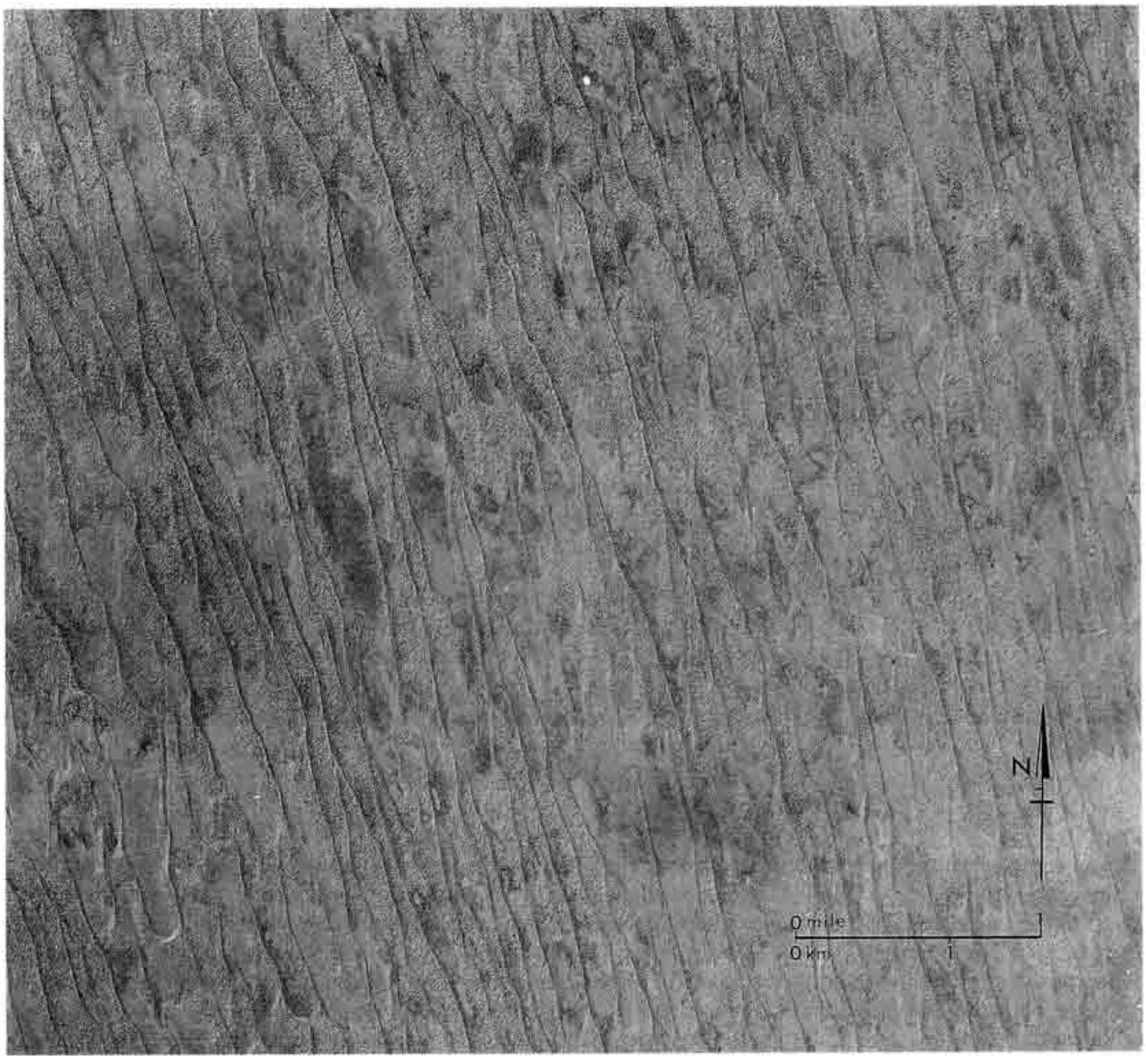


Fig. 9a. Longitudinal dunes: Vertical air photograph.

Fig. 9b. Longitudinal dunes: Low oblique, (C.T.Madigan).

5.3 Dune morphology and structure

The dunes of the Simpson Desert trend SSE-NNW, and several individual dunes extend unbroken for hundreds of kilometres (Fig. 9a). Tuning fork or Y-junctions (Fig. 9a and b) are common, most of them open to the south but some displaying the reverse orientation. Many of the tuning forks appear to be due to dune convergence, possibly as a result of the decrease in pressure consequent on the dunes becoming close and causing increased wind velocity in the interdune area (Tseo 1990,1993; also Tuck and Newman, 1974). Others, however, may be due to cross winds from the northwest, the efficacy of which is indicated by the scars of fires; yet others are of a lighter colour and may represent a new generation of sand ridges (see below). Crests vary from rounded to knife edges. In places the sharp crests are disposed *en echelon*, and barchanoid forms are commonplace. The dune sand is nowhere more than 38 m thick. In places sand covers also the interdune corridors, but quite commonly the dunes stand on a substrate of alluvial or lacustrine clays and silts. The dunes vary in height between 10 and 38 m. They are typically asymmetrical in cross section (Fig. 9c and d), the western slope most often being the more gentle with an inclination of 10-20 degrees, compared with 34-38 degrees for the eastern, or slip face; but the asymmetry is reversed after strong southeasterly winds. Sections cut across the dunes reveal planar foreset bedding alternating east and west and with dips of 10-30 degrees. In the corridors, however, the laminae of sand are horizontal.

Fig. 9c. Longitudinal dunes: Low oblique view of dunes in southwestern Sturts Stony Desert (H.Wopfner).

Some of the dunes, particularly those developed on the eastern side of the desert, are devoid of vegetation, but elsewhere the lower flanks of the dunes, what are termed 'plinths', carry a sparse cover of spinifex *(Triodia basedowii),* canegrass *(Zygochloa paradoxa)* and stunted shrubs. The crests are mostly devoid of vegetation.

5.4 Dune density

Dune density i.e. spacing per unit distance in a direction normal to dune trend (Twidale, 1981a; Twidale and Wopfner, 1990) varies regionally within the desert (Fig.10 a and b), and there is a consistent reciprocal relationship beween height and density. There are circa 15 low dunes (10-15m high) per kilometre, whereas there are only one or two of the high ridges (35-38m high) per kilometre. Wilson (1971,1972) related dune form and density to grain size, Ash and Wasson (1983) to sediment thickness and wind regime, and Tseo (1993) to formation by helical flow and bidirectional winds, but an evolutionary or time factor appears to be important in determining dune density. As is described below, many dunes appear to be generated in the lee of mounds of sediment accumulated on the leeside margins of playas , which, in the Simpson, is the northern shore. In addition, dunes are generated in the lee of river channels or remnants of flood plain channels. Initially, numerous small ribbons of sand are formed (Fig. 11a and b) but downwind these coalesce and are replaced by fewer but larger forms. As Sykes (1918) and Bagnold (1941) pointed out, sand tends to collect sand because of friction on the dune surface. The concurrent increase in dune height and width and decrease in dune density downwind from the source area suggests that dune density is a function of age. In that case the low, closely spaced dunes that dominate the western part of the Simpson Desert (Fig. 10 a and c) ought to be younger than the widely spaced high ridges typical of say the Birdsville area. There are complications for it is in the eastern desert that contemporary dune generation is most active (see below), but it can be argued that the recent dunes are, as it were, superimposed on a long established regional dune pattern.

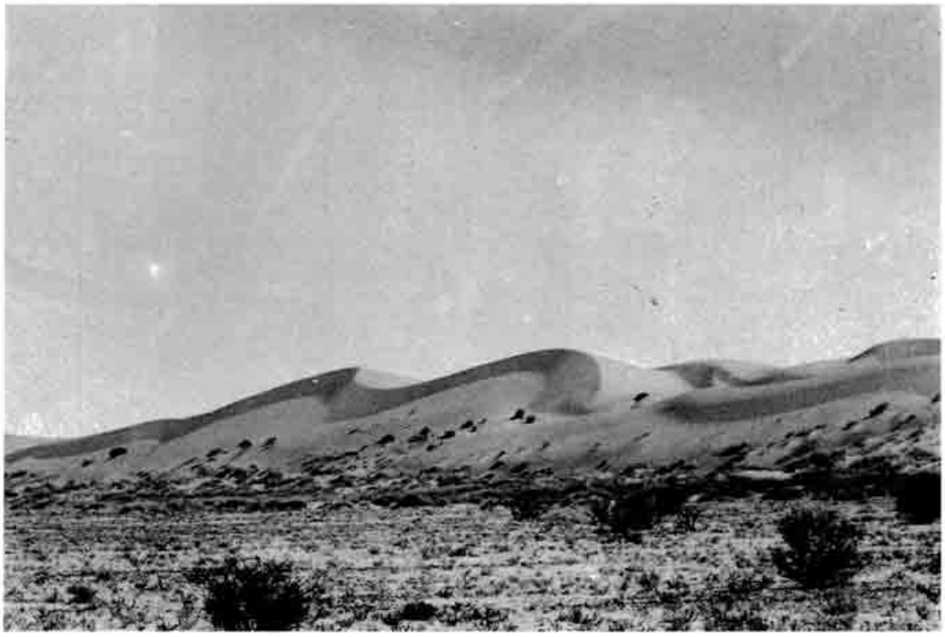


Fig. 9d. Longitudinal dunes: On the ground. (H. Wopfner).

5.5 Sand characteristics and colour

The sand is overwhelmingly (circa 98%) quartzitic, with only 0.5-1.5% heavy minerals such as maghemite, goethite, magnetite etc. Nodules of calcrete have formed beneath the floors of interdune corridors, and some even in the crestal zones of some dunes, partricularly in the northern Simpson Desert. The quartz grains are rounded to subangular, and ranging in diameter between 0.05mm and a coarse 1.2 mm. The median size of the grains is 0.5 mm on the crests and only 0.26-0.3 mm in the intervening dune corridors. The sand of the crests is well sorted. Clays are mixed in with the sand and attain concentrations of up to 5% by volume in the cores of the dunes, presumably as a result of illuviation.

Though the sand of the source areas is clean, and the dunes are a white, dirty white or pale yellowish grey colour, most of the dunes are red due to the presence on each of the sand grains of a patina of hematite and goethite derived from the alteration of clays trapped betwen the quartz grains. A change in colour from white or greyish white to light brown to salmon pink to bright red takes place downwind, i.e. with time, from the source areas. Thus colour provides a sound general guide to the relative age of dunes in a given area.

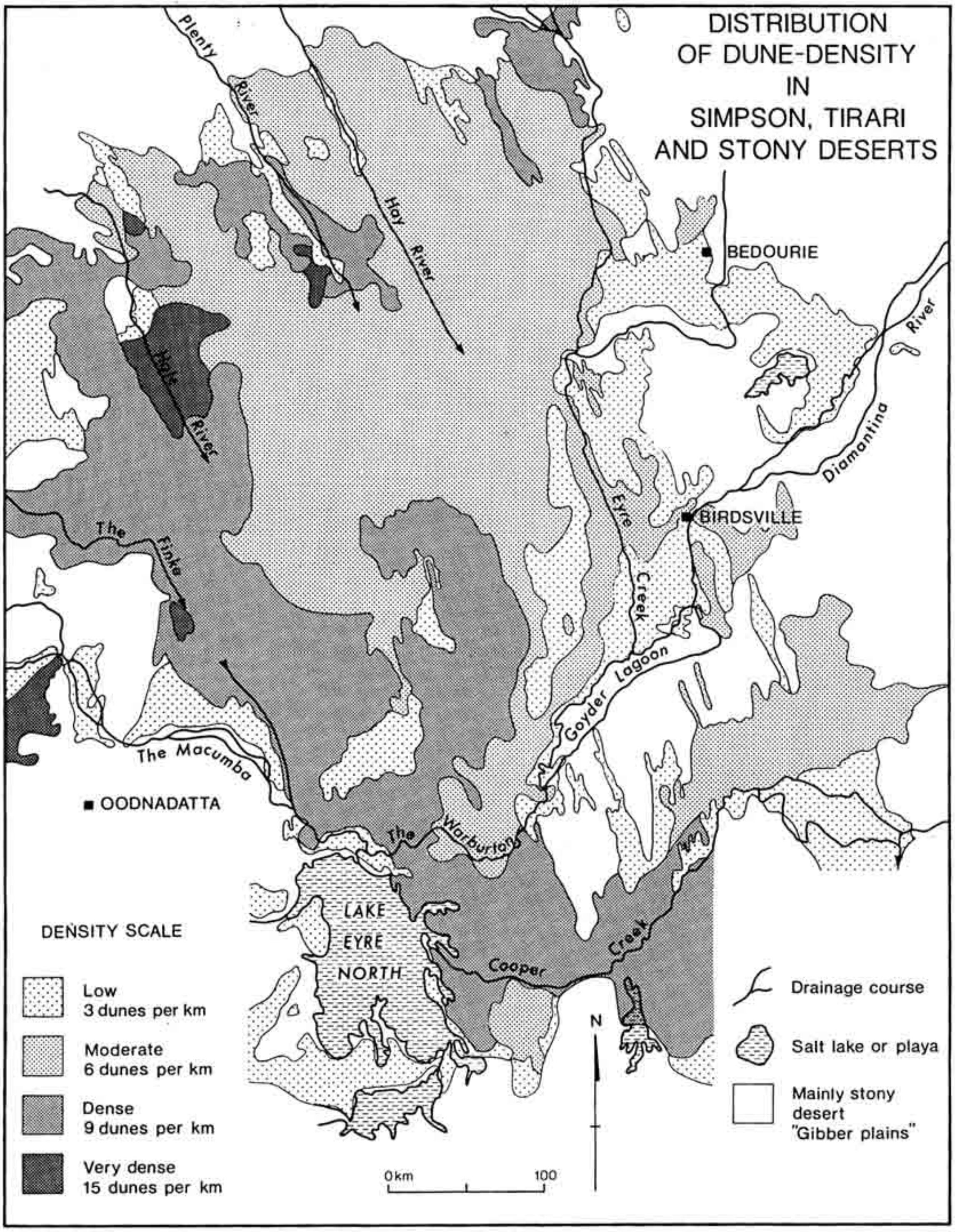
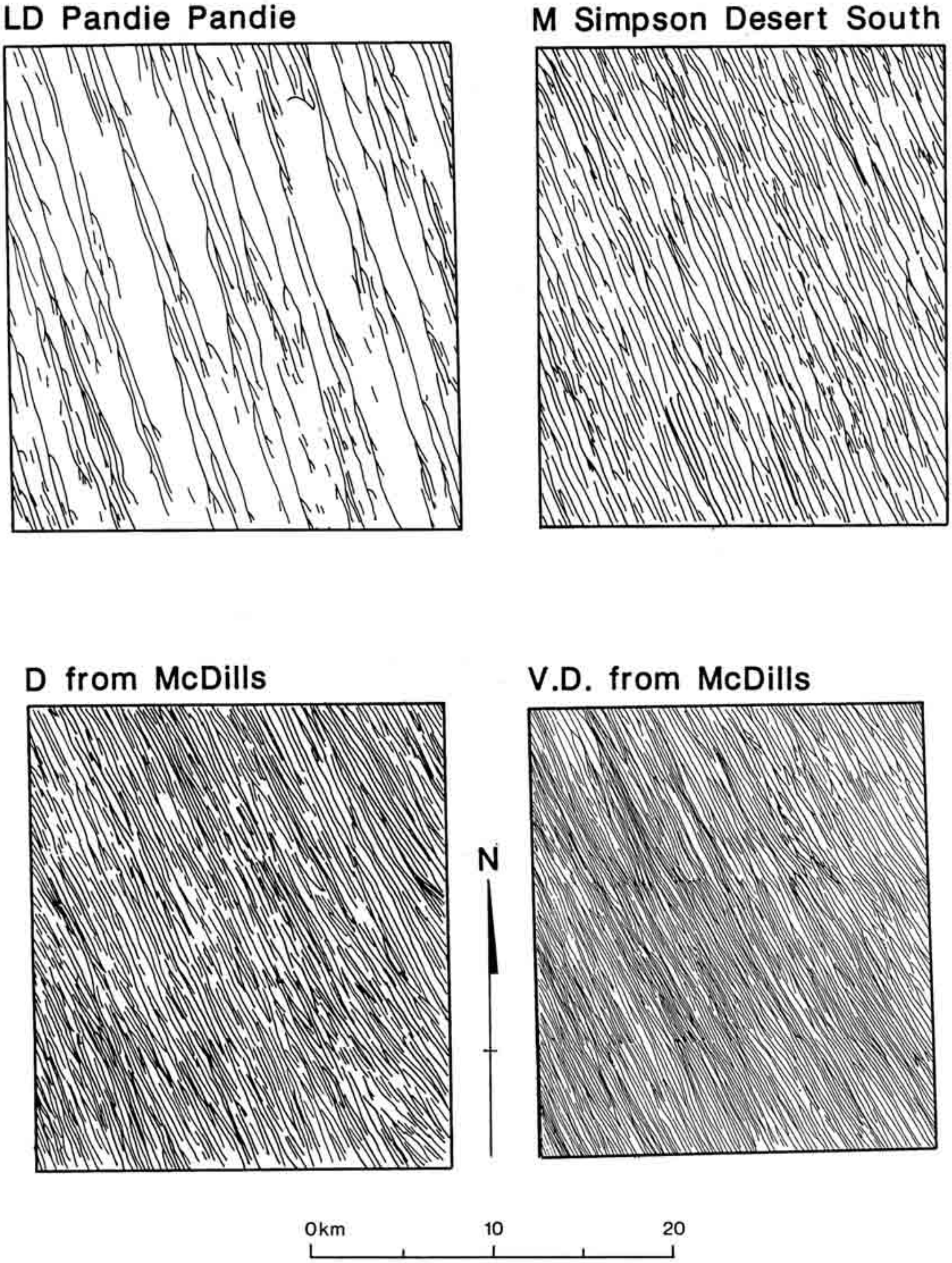


Fig. 10a. Dune density. Regional map.



LD Pandie Pandie

M Simpson Desert South

D from McDills

V.D. from McDills

Fig. 10b. Examples of dune density classes.

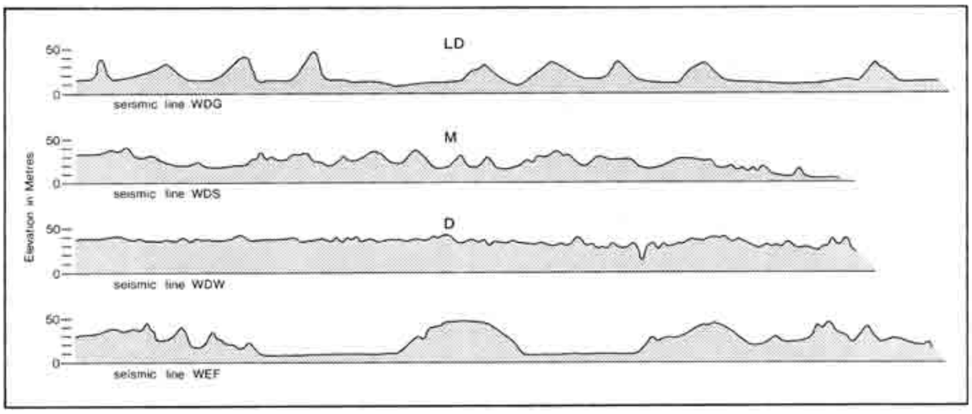


Fig. 10c. Section showing variation of dune height with spacing.

Fig. 11a. Tails of sand in lee of source bordering dune.

5.6 Sand movement and age of dunes

The sand grains are moved by saltation. Repeat photography, both from the air and on the ground, as well as local evidence, shows that the dunes are advancing to the NNW. The noses of dunes are presently advancing, albeit spasmodically, at an average rate of just under one metre per annum (Wopfner and Twidale, 1988), though in particularly auspicious circumstances (prolonged drought, rabbit plague) such as were experienced throughout central Australia in the nineteen twenties and 'thirties, some dunes in southwest Queensland moved 90 m in a decade (Ratcliffe, 1936,1937).

Fig. 11b. Part of the Simpson desert east of Lake Eyre, showing dismembered river system, source bordering dune and numerous small dunes in lee of mound (RAAF photograph).

12. Diamantina Flood plain southwest of Birdsville showing dunes advancing over Late Pleistocene and Early Holocene sediments.

Stratigraphic evidence shows that many of the dunes are of Holocene age, for they rest on fossiliferous alluvial or lacustrine materials of Late Pleistocene or even Early Holocene age (e.g. Wopfner and Twidale, 1967, 1988; Mabbutt and Sullivan, 1968: see Fig. 12). Remnants of an older dune field, in which the constituent sand ridges are oriented slightly askew from those of the contemporary field, have been noted (Wopfner and Twidale, 1967). Thermoluminescence dating, on the other hand, gives a much greater age for the dunes of the modern field, with ages of several tens of thousands, and even one or two hundreds of thousands of years suggested (Callen and Nanson, 1992; Nanson et al., 1992). It may be that the TL dates are of quartz grains which have retained a residual thermoluminescence from earlier periods of burial, or the dunes may be composite, with older plinths and younger crests (Spooner et al., 1988; Wopfner and Twidale, 1992).

The stratigraphic evidence is, however, difficult to repudiate. Also, an ancestral Lake Eyre dating from the period 40 000-20 000 years BP was at least 17 m deep (King, 1956) and occupied an area at least three times that of the present salina. In addition, the older Lake Dieri was even more extensive (Löffler and Sullivan 1977; D'Addario,1979). At the northern edge of the arid zone, Lake Woods, near Newcastle Waters, Northern Territory, was in Late Pleistocene times much deeper and areally extensive (Hills, 1955; Hutton et al., 1983).

Nanson and his co-workers also claim that the apparently younger, Holocene, dunes of the Birdsville area are constructed of reworked older sands, and that they are in reality simply modified older dunes This argument is difficult to sustain in light of the evident Early Holocene or latest Pleistocene age of the materials on which the dunes rest. Also, it is clear that dunes are still forming on the Diamantina River flood plain, and on other alluvial areas, where linear tongues of white or pale creamy white sand extend downwind from source bordering dunes (lunettes) or from channels and channel remnants (Fig. 13). Many of the channels and especially the channel remnants are ephemeral features and are likely to be destroyed in subsequent floods. They are unlikely to have persisted through the periods advocated by Nanson et al. (1992).

These youthful forms occur in areas where the largest local dunes are red and partly vegetated. In the same area, other dune ridges, with minor forms of distinct morphology (aretes, barchanoid features) developed on crests, are devoid of vegetation and of a pale brown colour. Similarly, short ridges and bars of a lighter coloured sand located in the northern Simpson Desert are interpreted as younger than most of the local dune population.

5.7 Origin of the dunes

The genesis of the dune forms can be considered to have occurred in two stages: initiation and maintenance. The longitudinal dunes of the Simpson Desert are depositional forms, not erosional (as suggested by King, 1956, 1960), nor are they derived from barchans (Bagnold, 1941; Lancaster, 1989). The internal structure of the ridges, their known changes in asymmetry according to wind direction, and wind strength and direction data (e.g. Brookfield, 1970) all suggest that once formed, the ridges are maintained not by horizontal vortices, as suggested by Bagnold, Folk and others, but by a bidirectional regime. Early observations by Madigan (1936,1939), later confirmed by Tsoar (1979, 1983), suggest that wind approaching a sand ridge obliquely is diverted parallel to the ridge once it has passed over the crest. In this way sand is driven to the NNW by both southeasterly and southwesterly winds.

Turning to the initiation of the dunes, work in the wind tunnel (e.g. Twidale, 1972b) shows that winds approaching normal to the trend of topographic obstacles are deflected as they pass over them. The obstacles may be positive (e.g. mounds) or negative (e.g. depressions): their effect on airflow is the same. Also, short lived but intense turbulent eddies are induced in the lee of the obstacle. Sand is deposited in the low velocity areas between eddies. Small, isolated obstacles initially induce twin vortices (Karman trails) between which sand is deposited, though parallel ridges are formed later. These tongues of sand are incipient sand ridges.

Field evidence amply confirms the conclusions derived from laboratory work. Examples from many parts of the Simpson Desert show that the first stage in initiation of longitudinal dunes is represented by the formation of topographic obstacles. Most commonly these take the form of lunettes or source bordering dunes, located on the northern or lee shores of salinas and playas, or on the edges of latitudinally trending river valleys. They trend roughly east-west, and are thus aligned approximately normal to winds from the southerly quarter that carry the sand to the NNW. The present lunette (the most recent of several) deposited at the northern margin of Lake Eyre North is some 50 m high (Dulhunty, 1975). River channels and isolated depressions that are remnants of channels also constitute obstacles which disturb the airflow (Twidale, 1972b).

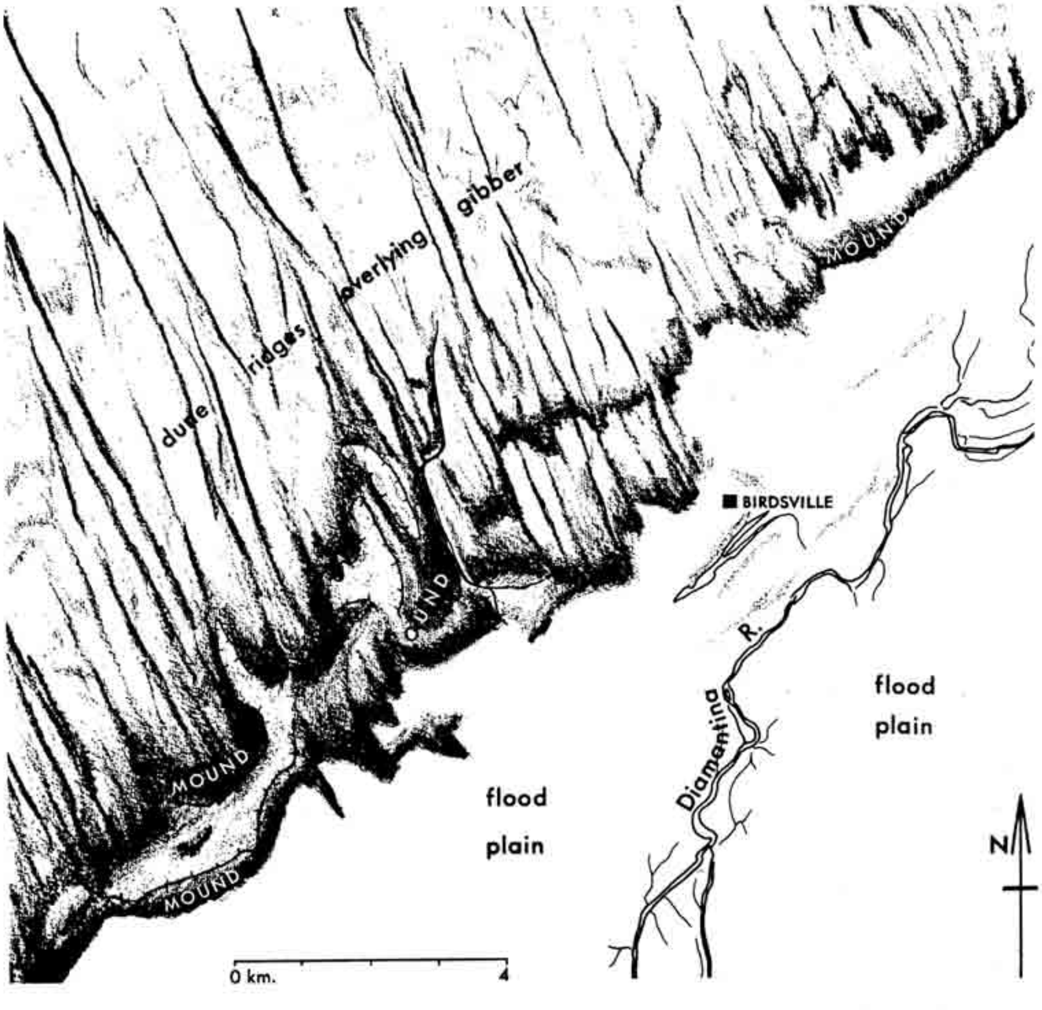


Fig. 13. Dunes in lee of source bordering dune, at northern margin of Diamantina flood plain south of Birdsville.

Numerous small linear dunes are initiated in the lee of source bordering dunes and of channels and isolated channel depressions (Figs. 11 a and b and 13). They form especially in the lee of the inside of meander loops, presumably because the exposed point bar deposited are a source of sand. Evidence of deflection of the wind on passing over transverse obstacles, whether positive or negative, is provided by the offsetting of sand ridges on the windward and lee sides of mounds, channels and playas (Fig. 14).

On flood plains such as that of the Diamantina, south of Birdsville, and within Sturts Stony Desert, horseshoe shaped dunes, manifestly of recent date, commonly occur around the upwind shores of such depressions (Fig.15). It is suggested they form there because sand blown to the moist shore area is trapped while dune movement continues on either side of the depression to produce horseshoe dunes.

Similar evidence has been observed in deserts in other parts of the world, such as the Kalahari where depocentres are sources of sand, and the Moenkopi dunefield of Arizona, where canyons disturb airflow, induce turbulence and allow the shaping of regolithic sand into dunes of various forms (see Hack, 1941).

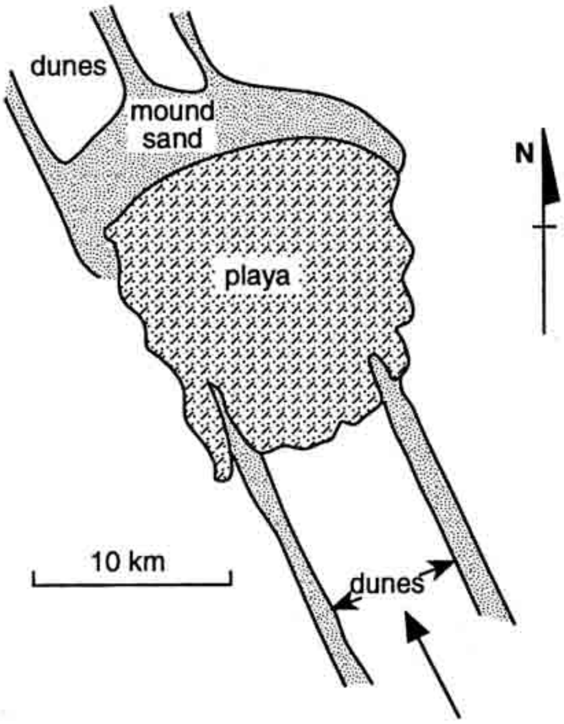


Fig. 14. Offset dunes west of Bedourie

5.8 Concluding comments

Investigations of a detail similar to that recorded from the Simpson Desert have still to be carried out in other parts of the Australian dune fields. The dunes carry more vegetation and so may be even less active than the sand ridges of the most arid part of the continent; but there is no reason to think that they differ in their genesis from those of the Simpson Desert. The age relations of the various fields of dunes remain problematic however, and it is not possible to state with certainty whether the Australian arid zone was once expanded overall or whether the arid zone has maintained a more or less constant area and migrated northwards during the later Pleistocene leaving the relic fields of southeastern Australia as testimony to climatic change. The situation is complicated by plate motions but there is some suggestion - and it is no more - that pluvial conditions as evidenced by lacustrine phases in playas, preceded the most recent period of dune formation both at the northern edge of the arid zone (Hutton et al., 1983) and at Lake Eyre (King, 1958).

6. Erosion by the wind

Despite aridity and the absence or scarcity of vegetation cover, erosion by the wind is less than that accomplished by running water, though it is difficult to estimate quantitatively from the morphological evidence. In consolidated rocks such as granite and gneiss, fluting and polishing take place in special conditions in which wind and sand are funnelled (e.g. Russell, 1932). More commonly, weakly consolidated rocks are fluted at various scales to form yardangs. Minor examples (at the scale of centimetres) are fairly common, but a few of modest size have been reported from the vicinity of Lake Eyre (King, 1956), but they do not compare in number, size, and perfection with those described from the American Southwest (e.g. Blackwelder, 1934), North Africa (e.g. Whitney, 1983, 1985; Breed et al., 1989) and, and especially, from the Lut of northern Iran (Bobek, 1969).

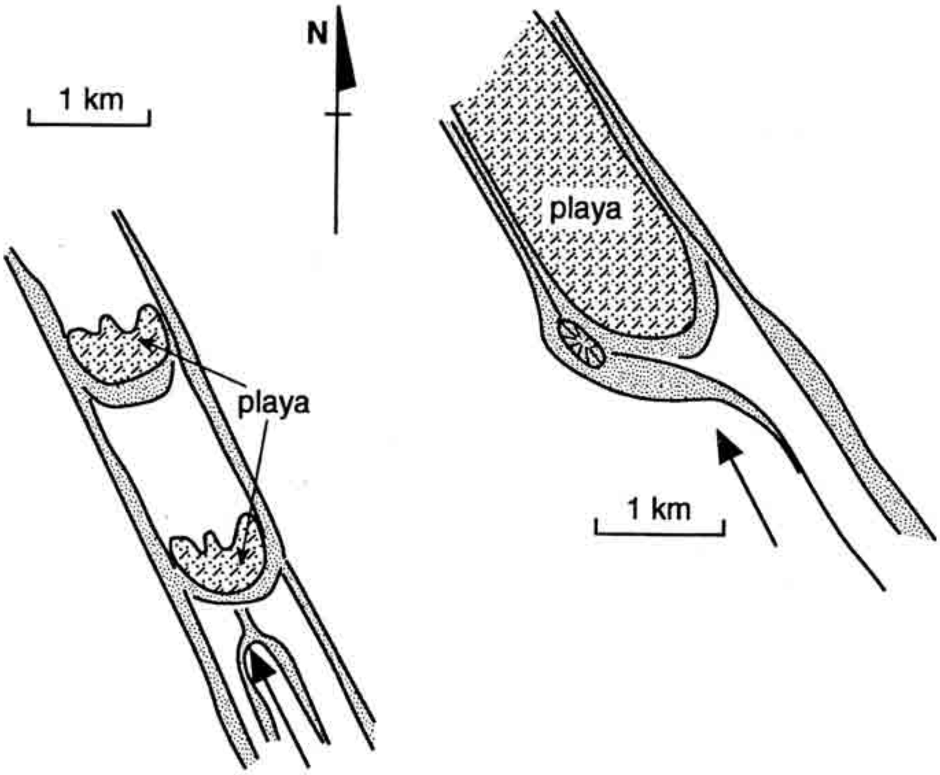


Fig. 15. Horseshoe dunes in Warburton flood plain.

Yet wind erosion must be more widespread than is usually conceded. Regional planation by the wind (e.g. Passarge,1904a and b, 1924; Keyes, 1913; Jutson, 1914) is now generally rejected as a model of landscape development in desert regions. Even in aridity, riverine erosion is preeminent, but literally millions of tonnes of dust are evacuated from arid lands in dust storms. Dust devils, similarly, transport large quantities of fine debris, and overall such deflation must lower the land surface, and Breed et al.(1989) have produced compelling evidence that wind abrasion and deflation are more widespread than has been generally accepted.

7. Inheritance in deserts

Because of the relatively low rates of weathering and erosion in deserts, earlier developed landforms are well and widely preserved. Much of the present regolith may be inherited from former humid periods though groundwaters are ubiquitous so that alteration may well continue.

In Australia, the most prominent examples of inherited regolithic features are the ferruginous and siliceous duricrusted plateaux that are so prominent throughout the Australian arid zone but especially in the centre, within and around the margins of the Great Artesian Basin. The stratigraphic evidence suggests that both of these duricrusts formed in humid conditions during earlier Cainozoic and Mesozoic times. As mentioned previously, there is evidence in the form of old shorelines, of lakes much more extensive than the present salinas (e.g. Löffler and Sullivan, 1977; D'Addario, 1979; Hutton et al.,1983), though some may be associated with short term rather than secular fillings of lake basins (e.g. Dulhunty, 1986). In addition, relics of palaeodrainages are widely in evidence. Van der Graaf et al. (1977) have described a system now disrupted as a result of the onset of aridity, but of Eocene age, and extending over most of the eastern half of the Yilgarn Block or Craton of Western Australia. In addition palaeodrainage channels identifiable either by their morphology (e.g. a disconnected series of salinas in linear or sinuous relationship, as in the Thurlga Channel, or abandoned channels, as at the northern edge of the Nullarbor Plain), or by their deposits as in the Tallaringa channel (e.g. Barnes and Pitt, 1976) and the Corrobinnie Depression and associated drainages (Bourne et al.,1974; Binks and Hooper, 1984). The ancient course of the lower Finke River can be distinguished beneath the desert sands, and many other examples have been revealed on Landsat imagery, both in North Africa (e.g. McCauley et al., 1982) and in Australia (e.g. Tapley, 1988).

Etch forms initiated in preQuaternary times, and hence older than the deserts in which they now occur, are widely preserved in the Australian arid zone. The high plains of the Yilgarn of Western Australia are of this type (Jutson, 1914; Mabbutt, 1961; Finkl and Churchward, 1973). The weathering essential to their formation predates the Tertiary. The Nullarbor Plain owes its remarkable flatness to etching by soil moisture of the limestone surface, possibly in latest Tertiary times but certainly prior to the later Pleistocene (Twidale, 1990). Two "ranges" located at the northeastern edge of the plain, the Ooldea and Barton ranges, are in reality coastal foredunes of putative Miocene age, preserved by a calcrete capping, and dating from when the Eucla Basin, on which the Nullarbor Plain is developed, was an embayment of the ocean (Benbow, 1990).

Similarly many inselberg massifs and individual hills, as well as rock pediments are etch forms, and exhumed plains and uplands, of various ages are commonplace in the arid zone, as elsewhere (e.g. Twidale and Campbell, 1989; Twidale, 1994). So far however, no old desert forms like the barchans of the Parana basin, preserved beneath basalt flows (Almeida, 1953), have been found in the Australian deserts.

8. Conclusions

Desert landscapes take many forms. The various desert uplands are azonal in the sense that they closely reflect the structure (active and passive) of the exposed crust, and that they are therefore similar to their structural counterparts elsewhere. Desert plains also vary in character, reflecting topography and the sorting action of water and wind, but dunefields are dominant.The form of the dunes varies with wind regime, and sand supply, though where dunes penetrate uplands, topography is a significant factor in determining dune morphology. Several generations of dunes are distinguishable but the vast majority are of Holocene age and many are actively forming at present.

Though transported and shaped by the wind, river action is critical to the formation of many dunefields for it is rivers that transport detritus to topographic lows or depocentres. Some of the sand of which the dunes are contructed may be locally derived from regolithic mantles but most appears to originate, in an immediate sense, in alluvial veneers associated either with present or recent river regimes.

Wind is mainly responsible for the transport and erosion of debris though sand blasting and deflation account for much minor fluting and polishing, and for some major yardangs and basins But even in deserts, rivers are responsible for most erosion for the sculpture of the uplands and forthe excavation of river valleys; though some fluvial forms may be inherited from past, more humid, conditions.

The Australian deserts differ from their counterparts in other parts of the world, in several respects. The prevalence of a markedly bidirectional wind regime has resulted in the development of fields of longitudinal dunes to the virtual exclusion of other types. Also the dunefields are comparatively well watered and vegetated so that sand movement is inhibited. The vegetation cover reflects a level of surface and subsurface moisture that is inconsistent with the precipitation regime. This is due in part to tectonism resulting in the formation of a structural basin the focus of which is the downfaulted and subsiding bed of Lake Eyre. The salina has become the focus of a huge catchment which drains not only arid lands, but also parts of the monsoonal north. In addition, the deserts being underlain by a structural basin and occupying part of a topographic depression, shallow underflows as well as artesian supplies are available even in the hyperarid region. Thus, though climatically the most arid part of Australia, at times the Lake Eyre basin belies the statistics, for the desert is frequently green. At these times sand movement is inhibited, though the same rivers that signal water in the catchment also bring to the desert the sands from which dunes will be shaped in the next drought.

In addition to the tectonic and topographic factors favouring river activity and vegetion growth, both midlatitude and tropical depressions frequently invade the interior, bringing rain to these usually parched areas: it is notable that all of the Simpson Desert, and the Lake Eyre region generally, are under pastoral lease, indicating that stock can survive for considerable periods. And the tendency for accessions of surface and subsurface waters reaching the arid interior can only increase if the Australian plate continues its northward migration into the monsoon regions.

There has, as a direct and indirect result of human activities, been local intensification of aridity and marginal extension the deserts, but it is well to remember that deserts are overwhelmingly a function of the planetary pressure zones and wind circulation. They are moreover an ephemeral feature of the Earth's surface, for the unusual climatic conditions conducive to the formation of deserts occupy only a small proportion of geological time, though some argue that rarely have deserts been entirely absent from the Earth's surface.

However, though they may be temporary features in a geological sense, desert landforms and landscapes well illustrate the complexities of landscape interpretation, for all desert landscapes are palimpsest features in which contemporary and ancient features are intermixed. Such is the comparatively slow rate of activity of surface processes in the hot deserts that inherited landforms are everywhere prominent. Desert regions, more than most, bear the impact of events distant in time, as well as geologically recent episodes and present processes: the character of an arid land cannot be separated from its past.

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