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C. Rowland Twidale (Adelaide, South Australia)

Age and Origin of Longitudinal Dunes in the Simpson and other Sand Ridge Deserts

With 5 figures and 2 plates

The Australian dune deserts are dominated by sand ridges that are aligned roughly parallel with prevalent strong wind directions. The dunes stand up to 35 m above the adjacent corridors and plains, are characteristically asymmetrical in cross-section, and can be traced unbroken for scores and even a few hundreds of kilometres. Convergences, or Y-junctions, most of them opening to the south, are typical. The dunes are built of quartz sand, most grains carrying a pellicle of iron oxide which imparts the characteristic deep red colour to the dunes; there are also minor amounts of clay and carbonate. The sands are cross-bedded with alternating dips (in the Simpson for example where the dunes trend N.N.W., the foresets alternate between east- and west-dipping).

There are within the present dune areas sand ridges that are askew with respect to modern forms, and, beyond the confines of the contemporary arid zone, extensive dune fields now stabilised by vegetation.

The modern dunes appear to be of essentially Holocene age. In many places the dunes rest on late Pleistocene alluvia. They continue to advance over Pleistocene and older strata as well as late Holocene beds as for instance where they encroach upon or across modern flood plains or playas. Some dunes, and the cores and lower parts of others, may be of greater antiquity but most are younger than Pleistocene, for riverine and lacustrine conditions prevailed over wide areas of interior Australia at that time.

In some small measure the dunes are built of sand derived directly from weathered country rock (granite, sandstone, silcrete, A-horizon of laterite). But most of the sand has been through several cycles of transport and deposition and in an immediate sense the dunes are constructed of alluvial materials deposited by rivers in flood plains and playas. Thence it is drifted by the wind to form leeside mounds comparable to lunettes. As the wind passes over these source-bordering dunes intensified ephemeral vortices develop on the lee side where sand is deposited in tongues or fingers pointing downwind and located in the low velocity zones between the eddies. Some of the tongues of sand simply fade away but others grow and extend downwind under the influence of strong winds of a bidirectional regime to become part of the regional dune pattern.

In these ways the Australian sand ridge deserts evolved from and on late Pleistocene alluvial and lacustrine spreads located in tectonic and topographic depressions which are well developed in the Australian interiors. There is sufficient evidence to suggest that the mechanisms described are not peculiar to "the island continent" but that they have operated in some, at least, of the sand ridge deserts developed in other parts of the world.

Zusammenfassung: *Alter und Entstehung von Längsdünen in der Simpson-Wüste und in anderen Sandrücken-Wüsten.*

Die australischen Dünenwüsten werden dominiert von Sandrücken, die annähernd parallel zu den vorherrschenden Windrichtungen angeordnet sind. Die Dünen überragen die benachbarten

Prof. Dr. C. R. Twidale, The University of Adelaide, G.P.O.Box 498, Adelaide, South Australia 5001.

Gassen und Flächen um bis zu 35 m, sie sind im Querschnitt in charakteristischer Weise asymmetrisch, und man kann sie ununterbrochen über Dutzende und sogar einige Hundert Kilometer verfolgen. Konvergenzen oder spitzwinkliges Aufeinandertreffen in Form eines Y, das meist nach Süden geöffnet ist, sind typisch. Die Dünen werden aus Quarzsand aufgebaut, die meisten Körner tragen einen Überzug aus Eisenoxyd, der den Dünen die charakteristische tiefrote Farbe verleiht. Kleinere Ton- und Karbonatbeimengungen sind ebenfalls vorhanden. Die Sande sind kreuzgeschichtet mit wechselndem Fallen (in der Simpson-Wüste z. B., wo die Dünen in nordnordwestlicher Richtung streichen, alterniert das Fallen der Vorschüttsande zwischen östlicher und westlicher Richtung).

Innerhalb der heutigen Dünengebiete gibt es Sandrücken, die schräg zu den heutigen Formen verlaufen, und jenseits der Grenzen der rezenten ariden Zone existieren ausgedehnte Dünenfelder, die heute durch Vegetation stabilisiert sind.

Die aktiven Dünen scheinen im wesentlichen holozänen Alters zu sein. An vielen Stellen ruhen sie auf spätpleistozänen Aufschüttungen. Die Dünen schreiten weiter vor sowohl über pleistozäne und ältere Schichten als auch über spätholozäne Sedimente, das z. B. dort, wo sie auf rezente Flußniederungen oder Playas übergreifen. Einige Dünen und die Kerne und unteren Teile von anderen mögen ein höheres Alter besitzen, aber sie sind jünger als pleistozän, denn fluviale *(riverine)* und limnische Bedingungen waren in jener Zeit in vielen Gebieten des inneren Australiens noch vorherrschend.

In geringem Ausmaß bestehen die Dünen aus Sand, der direkt vom verwitterten Anstehenden stammt (Granit, Sandstein, Kieselkrusten, A-Horizont von Lateriten). Aber die meisten Sandkörner haben mehrere Zyklen von Transport und Ablagerung mitgemacht, und im augenblicklichen Zusammenhang werden die Dünen aufgebaut aus fluvialen Sedimenten, die in Flußniederungen und Playas abgelagert wurden. Von dort wird das Material vom Wind verfrachtet, um an der Leeseite Erhebungen zu bilden, die mit Lünetten zu vergleichen sind. Wenn der Wind über diese an ihre Materialquelle grenzenden Dünen zieht, entstehen verstärkte, kurzzeitige Wirbel an deren Leeseite, wo sich Sand in Zungen und fingerartigen Vorsprüngen ablagert, die sich in Windrichtung erstrecken und in den Zonen geringer Geschwindigkeit zwischen den Wirbeln liegen. Einige dieser Zungen laufen aus, aber andere wachsen und dehnen sich in der Windrichtung unter dem Einfluß starker Winde eines bidirektionalen Regimes aus und werden Teil des regionalen Dünenmusters.

In dieser Weise entstanden die australischen Längsdünenwüsten aus und auf Verbreitungsgebieten spätpleistozänen fluvialen und limnischen Materials, die sich in im Inneren Australiens wohl entwickelten tektonischen und topographischen Senken befinden. Es gibt ausreichende Belege, die darauf hindeuten, daß die beschriebenen Mechanismen keine Besonderheit des Inselkontinents darstellen, sondern daß sie zumindest in einigen der Längsdünenwüsten der Erde ebenfalls wirksam geworden sind.

Introduction

Longitudinal dunes, which can for convenience be defined, *pro tempore,* as sand ridges aligned in approximate parallelism with strong wind directions blowing from the same general quarter, are the most widely developed of all desert dunes. They occupy more than 70 % of the North African dune deserts, are dominant in the Arabian, Soviet and Australian arid zones, and are well developed in the Kalahari and the American Southwest. Moreover they are well preserved in the relic, stabilised, dune fields located at the southern margins of the Sahara and of the Australian deserts [see e.g. Grove 1958; Warren 1970; Twidale, Bourne & Smith 1976]. Yet despite or even perhaps because of, their prolific development and the attention that in consequence has been lavished on the forms by geologists and geomorphologists over the years, longitudinal sand ridges remain the most controversial of the common dune forms.[1])

[1]) In respect of another problem Mark Twain pointed out that "The researches of many commentators have already thrown much darkness on this subject, and it is probable that, if they continue, we shall soon know nothing at all about it!"

In the Australian context, debate has been concerned with three related aspects of the genesis of the dunes. First, many workers [Galloway 1965; Mabbutt 1967; Bowler 1976], and most recently Breed & Breed [1979] have argued that the main dune fields are of Late Pleistocene age, so that the sand ridges may have evolved under conditions rather different from those that now obtain. Folk (1971] implies that the dunes developed partly during the Pleistocene, partly in the Holocene, and yet others, a minority, have adduced evidence to suggest that the dunes are of Holocene age, that they are still active and that they are therefore to be explained in terms of modern environmental, particularly climatic, conditions [Wopfner & Twidale 1967; Twidale 1972 a; Twidale & Wopfner 1981].

Second, the mechanism or mechanisms of dune formation have generated considerable discussion, as has a third aspect of dune development concerned with the provenance of the materials of which the dunes are constructed. Obviously these two problems, the mechanism of formation and the source of sand, are closely related.

Age of the Australian dunefields

Just as there are reports of older sand ridges aligned in angular discordance with the modern dunes in the Soviet deserts [Féderovitch 1956, p. 125] and in Arabia [Glennie 1970, p. 90], so there is from several parts of the Australian arid zone the suggestion of remnants of older dune fields in which the sand ridges are disposed at slightly different orientations from the modern sand ridges [see e.g. Webb & Wopfner 1961; Wopfner & Twidale 1967]. In some areas now peripheral to the major dune fields and arid zone, old dunes are stabilised by vegetation and the component sand grains are not moved save when, through anthropogenic or other interference, the vegetation cover is depleted. Saltating sand grains can and do destroy plants downwind from the reactivated site so that there is a cumulative or positive feedback effect. Nevertheless these vegetated, fixed dunes are readily distinguished from those with crests that are normally bare and active.

Of what age or ages are the active sand ridges? In the Simpson Desert *(Fig. 1)* the sand ridges trend S.S.E. — N.N.W. and commonly continue without break for scores of kilometres *(Plate 1)*, though reticulate patterns are developed adjacent to some major rivers, and in many areas, notably Sturt's Stony Desert, sand ridges of great length stand in isolation.

Charles Sturt, after whom the famous stony desert, hamada or gibber plain was named, travelled through the southeastern part of the Simpson Desert in 1845. He noted that

> The basis of the country was sandstone, on which clay rested in a thin layer, and on this clay the sandy ridges reposed [Sturt 1849, I, p. 339]

and in essence many later workers have corroborated this observation. Looked at regionally, the 'clay' mentioned by Sturt in fact comprises various and varied lacustrine and riverine deposits. In the southern and eastern areas of the Simpson, where they are widely distributed, these sediments are fossiliferous. C14 determinations of shells and bones suggest a late Pleistocene-Holocene age [King 1956; Wopfner & Twidale 1967; Twidale 1972 a]. As they rest upon the alluvia, the dunes are in part clearly of Holocene, and possibly of middle and late Holocene age, though they are also contemporary or penecontemporary and continue to advance over late Pleistocene and Holocene alluvia in many places. They have also advanced to and across dry river channels.

In the northern and northeastern parts of the Simpson [Mabbutt & Sullivan 1968] some of the sand ridges rest on an alluvial substrate; others rest on a gibber composed of silcrete fragments. The silcrete hereabouts is of early-middle Tertiary (probably Miocene) age [Wopfner & Twidale 1967] so that the derived gravel must be of at least latest Tertiary age. Near the Hale River, what was termed the "subaeolian" floor, consists of river gravel which is "presumably an extension eastwards of Hale River alluvium" [Mabbutt & Sullivan 1968, p. 484]. Yeates [1971], describing the section at Hay River No. 4 bore, close to the centre of the Simpson dunefield, reports red aeolian sand overlying fluvial sand, pebbly sand and sandstone.

Thus during the late Pleistocene, when, according to the workers previously cited, a field of linear dunes was developing in central Australia, lacustrine and riverine conditions were in real-

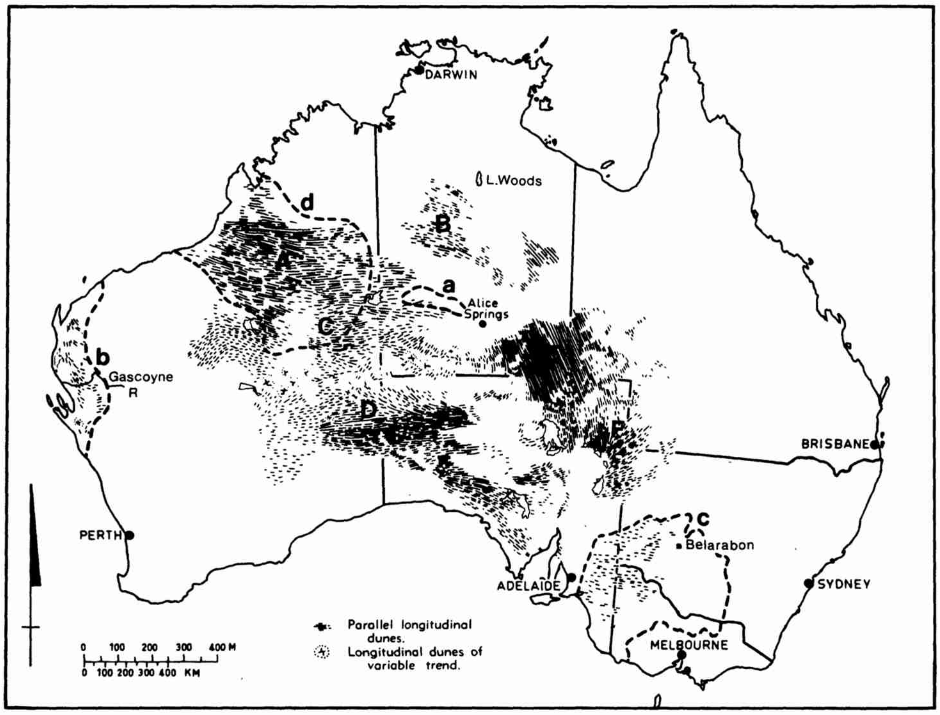
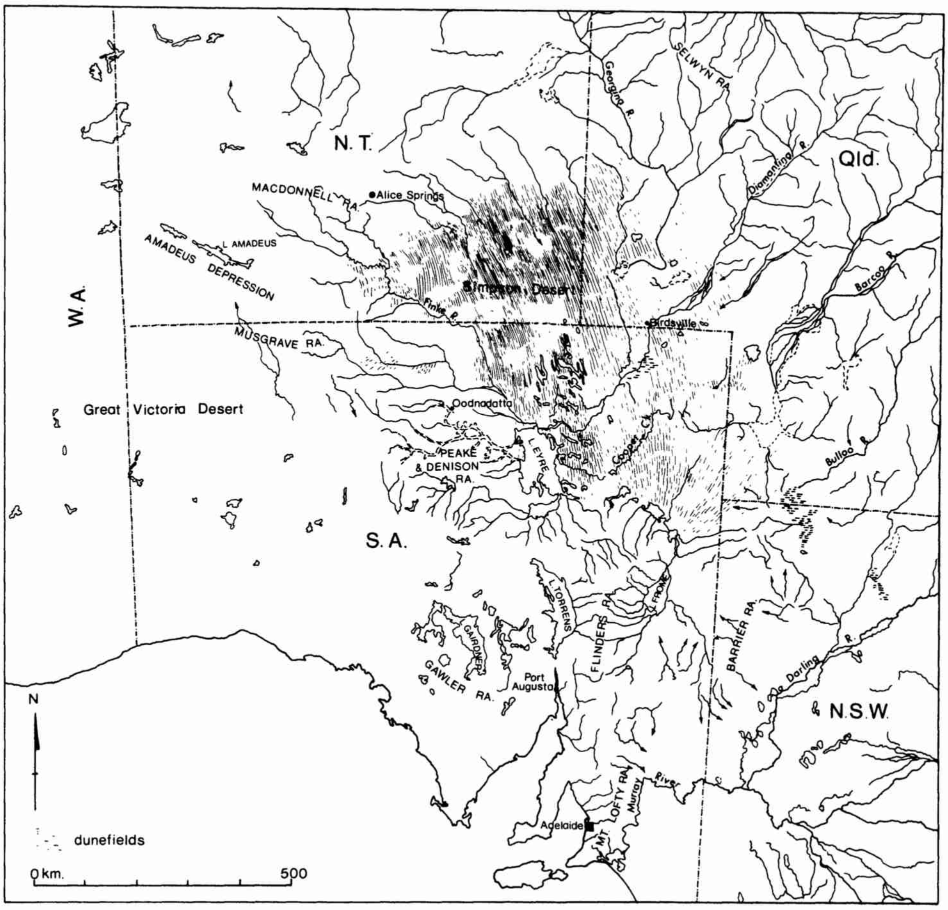


Fig. 1. Location maps showing Australian features, regions and locations mentioned in text: (a) — Australia; (b) — Simpson Desert and environs (p. 235 →).

ity prevalent. Between approximately 20.000 and 40.000 years B.P. the ancestral Lake Eyre, a body of water known as Lake Dieri [BROWNE 1945; DAVID 1950, pp. 617—618; LASERON 1954; LÖFFLER & SULLIVAN 1979] was at least 17 m deep [KING 1956] and was at least three times as extensive as its present area of 9.300 km^2, and was possibly as much as ten times as large [DAVID 1932, p. 95]. Lake Woods *(Fig. 1a)* was some 2.850 km^2 in extent (compared with its present 180 km^2) prior to the development of the present linear dunes [HILLS 1955].

A further consideration is that the late Pleistocene lake sediments exposed near Lake Eyre [KING 1956] were eroded by the wind, and elongate windrift dunes formed sometime after the late Pleistocene *(Fig. 2)*. This agàin implies Holocene aridity.

Also, the Pleistocene saw active dune development on the southern fringes of the present arid zone, on Eyre Peninsula, Yorke Peninsula, the Adelaide Plains, the Murray Basin and even extending to the western suburbs of Melbourne. Though difficult to date with precison the now vegetated and stabilised dunefields are, on the available evidence, of late Pleistocene age [TWIDALE, BOURNE & SMITH 1974, 1976; TWIDALE, LINDSAY & BOURNE 1978]. This, taken with the evidence of late Pleistocene lacustrine and riverine deposits and forms in the interior regions, implies a migration of the dune desert and not simply a contraction of the arid zone during the Holocene. Because, as is described below, similar stratigraphic sequences developed in other tec-



tonic settings, it is not possible to explain the late Pleistocene formations in terms of a general aridity, but with the lower part of the structural and topographic basin centred on Lake Eyre receiving run-off and underflow from the outer areas of the catchment.

With regard to regions other than the Simpson, it is unfortunate that, with rare exceptions, the geologists and drillers who have been responsible for most of the work and hence have had the greatest opportunity for making observations in arid Australia have been more concerned with other aspects of stratigraphy and structure. Relationships between superficial Quaternary units have been mentally noted but not recorded; the alluvium observed to underlie the dune sand is most frequently not readily dated; the drillers are almost invariably anxious to pass through the top few metres of weathered and recent materials into the "real geology" and frequently have not troubled to log the cores.

Nevertheless there is enough information to suggest that the superficial stratigraphy of the Simpson Desert region, where Holocene dune sand commonly rests on late Pleistocene riverine alluvium and lacustrine beds, is not atypical of the Australian sand regions as a whole.

Apart from general, imprecisely dated evidence of early Holocene or Pleistocene pluvials, an examination of geological maps of the Great Victoria Desert, the Gibson Desert, and the various dune fields of northern central Australia *(Fig. 1a)* shows that sand ridges commonly overlie and are still advancing over late Pleistocene or Holocene alluvia. CALLEN [1979] assigned the linear dunes of the Frome Embayment which in places rest on old lacustrine strata, to the Holocene. WASSON [1976] recorded sand ridges of late Holocene age resting on mid Holocene alluvium from the Belarabon area of northwestern N.S.W. MIRAMS [1964] mapped the sand ridges of the northern part of the Great Victoria Desert as of Holocene age, and as overlying calcrete and older alluvia and soils. In the Ngalia Basin, northwest of Alice Springs, HENSTRIDGE [1973] described linear dunes underlain by alluvial sandy clay, and A. F. TRENDALL (pers. comm. 5 May, 1980) reported that in the Gascoyne River area of Western Australia red sand dunes overlie Quaternary alluvium. CONDON [1954] regarded the main dune field of the Carnarvon Basin as of earlier Holocene age.

TRAVES & CASEY [1956] reported dunes encroaching on to lake (salina) beds in the Canning (Great Sandy) Desert of northwestern Western Australia, though both BRUNNSCHWEILER [1957] and VEEVERS & WELLS [1961] considered the dunes to be essentially inactive, and as having formed during a more arid phase of the Pleistocene. Most of the dunes are thus of Holocene age. But is it possible that FOLK, for example, is right in suggesting that the dunes are Holocene but extend back into the Pleistocene? It has after all been noted that though the dunes are active, the flanks are stabilised by vegetation. There are moreover lime nodules only a few centimetres beneath the crests. All this can be interpreted to imply that the core zones are stable and raises the possibility of their being older and possibly of (late) Pleistocene age.

But the evidence and argument weigh against this suggestion. First, the presence of lime nodules is not itself a guarantee or indication of even minor antiquity. Such nodules form in decades or even in a few years. It is not uncommon to find tree roots replaced by lime. For instance the roots of trees felled in about 1916 on a lunette bordering Kappakoola Swamp, on northwestern Eyre Peninsula, were fully replaced by lime within 10—15 years [SMITH, TWIDALE & BOURNE 1975]. Second, during the late Pleistocene large areas of central Australia were occupied by lakes and flood plains. Certainly the rivers flooded and the lakes filled with water from time to time during the Holocene [DULHUNTY 1975] and such ephemeral floodings continue from time to time both in the Australian and other deserts [e.g. BONYTHON & MASON 1953; BOBEK 1959]. But there is no widespread evidence of dunes of a consistently greater age than the widespread alluvial materials found in the Australian desert regions.

Two sets of sand ridges that have been dissected by rivers and separated by fluvial deposits have been described by R. H. TEDFORD and R. T. WELLS *(pers. comm.)* from the areas east and northeast of Lake Eyre. These areas are marginal to a tectonically active block that occupies the lower part of the Lake Eyre basin, which has been downfaulted in late- or post-Pleistocene time, and which is still actively subsiding [WOPFNER & TWIDALE 1967; WOPFNER 1968; YOUNGS & WOPFNER 1972]. Consequently, the effects of stream rejuvenation are marked. Also, ephemeral floods have a pronounced impact, in this, the focus of a catchment that covers about 1.3 million km^2 of central and northeastern Australia. It is easy to envisage that dunes were dissected and inundated by incising streams susceptible to flooding. That some dunes are dissected and buried by alluvium does not in this situation itself imply antiquitiy, and the question of their age awaits independent evidence.

Even so such sequences involving disturbed dune formations are rare. For the most part the dunes overlie early Holocene, Late Pleistocene or older strata. The dunes are in many areas still advancing, and at an appreciable rate [RATCLIFFE 1936, 1937]. In the Simpson Desert for instance where the dunes run to the N.N.W. station tracks running latitudinally are frequently diverted by the sand ridges. Tracks and roads are frequently blocked by drift. Dunes are manifestly advancing on to the southern margins of salinas *(Plate 1)* and over flood plains.

The modern activity of the dunes, and their Holocene age, cannot be questioned. Some dune cores are stable but even they commonly rest on Holocene materials. Thus the evidence points to the modern dune fields of central Australia being relatively youthful features of the landscape. Modern climatic data are thus relevant to their interpretation.

Origin of the sand ridges

STURT [1849, I, pp. 380—381] attributed the sand dunes of central Australia to wave action under marine conditions, but the dunes are of Holocene age and the ocean withdrew from the

Plate 1. Part of the Simpson Desert just east of Lake Eyre (approx. lat. 28° 55′S, 138° E) showing strongly developed sand ridges which extend on to the beds of salinas, on the lee shores of which mounds have formed [RAAF].

region in Late Cretaceous times and has not returned. The internal structures of the dunes clearly argue a constructional and aeolian origin (see below) and all recent workers have attributed the dunes to wind action under desert conditions. Even so there are considerable differences of interpretation. KING [1956] for example established that the dune ridges located near the margin of

Lake Eyre are of windrift type *(Fig. 2)*. They are due to wind erosion (i.e. they are comparable to yardangs), and are cut in lacustrine clays that carry a veneer of sand. KING went on to suggest that all of the sand ridges, not only in the Simpson but in the other Australian deserts also, are of this type [KING 1960]. Apart from those examined by KING, however, all the sand ridges so far subjected to close scrutiny are manifestly of depositional type.

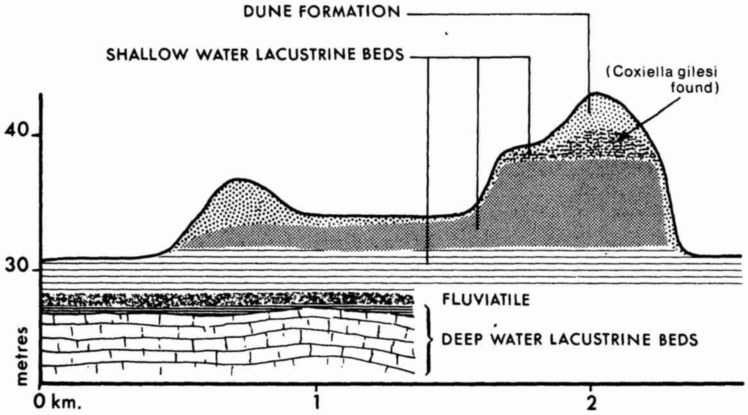


Fig. 2. Section through windrift dune located at the eastern margin of Lake Eyre (after KING).

Those who accept that the dunes have been deposited by the wind resort to various mechanisms in an endeavour to explain the forms. Here the dune forms and structures are first described. The origin of the dune material is discussed and this is followed by comments on the initiation of the dunes and their further development.

Description of sand ridges

The following comments concern the Simpson Desert in particular but it is believed that they apply in a general sense to other areas of longitudinal sand ridges.

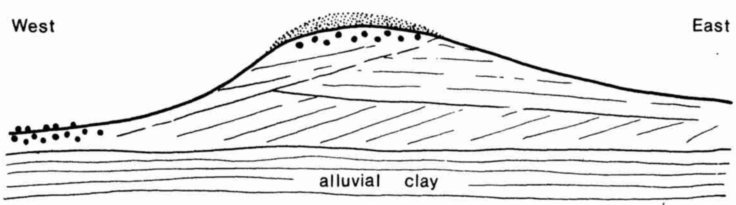


Fig. 3. Diagrammatic cross-section of a typical Simpson desert dune.

The Simpson Desert dunes consist of well sorted subangular to subrounded quartz grains that range in size between 0.05 and 1.2 mm [CARROLL 1946; WOPFNER & TWIDALE 1967]. Clay constitutes up to 5 % of the dunes and tends to be concentrated by illuviation in the cores of the ridges. Nodules of calcium carbonate are developed in some dunes (though not to the same extent as in the stable dunes of Eyre Peninsula for example) indicating that it is only the superficial sand that is in motion *(Fig. 3)*. Near the postulated source areas the sands are white to light brown in colour but only a few hundreds of metres downwind are a deep red colour, due to a pellicle of iron oxide (goethite and haematite) derived from the weathering of clays that are introduced either as dust [FOLK 1969, 1976 a; see also NORRIS 1969, WALKER 1979] or as pellets saltated from the alluvial flats with the sand grains [WOPFNER & TWIDALE 1967].

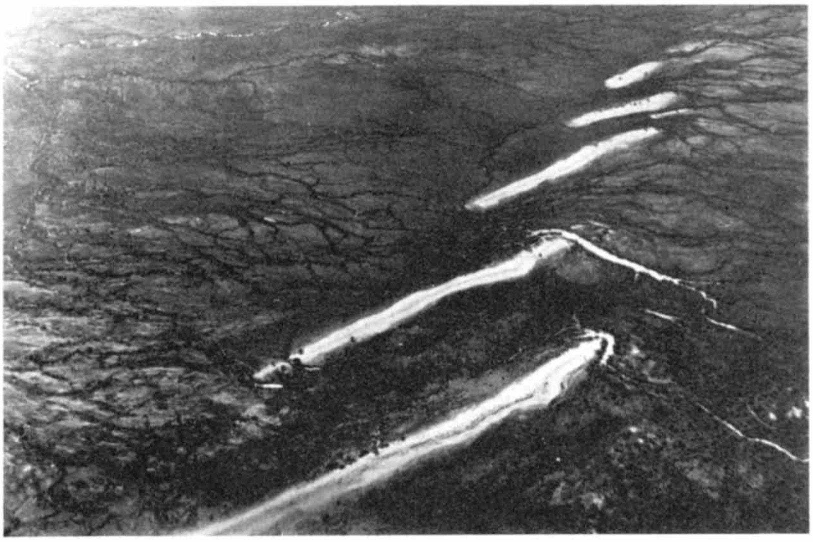


Plate 2. Dry meander loops and associated longitudinal dunes on the dry bed of Goyder Lagoon [C. R. TWIDALE].

Numerous sections show that the dune sands display planar crossbedding, the direction of dip of the foreset beds alternating between east and west and varying between 10° and 30° *(Fig. 3)*. These structures stand in marked contrast with the flat-lying bedding of the interdune areas [cf. MCKEE & TIBBITTS 1964].

The dunes are asymmetrical in cross-section with the eastern face usually being the steeper (the slip or avalanche face). Again however there are many exceptions and observations of the same sites under different wind conditions show that detailed dune morphology varies with the most recent strong wind direction. Only the crests and upper slopes of the dunes are active, the lower slopes, like the interdune corridors being vegetated and essentially stable. The dune cores too, appear to be static. Only the crestal zones are active or in motion: hence the carbonate nodules *(Fig. 3)*.

The Australian dune deserts differ from many others in the degree to which they are vegetated. Small trees, shrubs and grasses such as canegrass *(Zygochloa paradoxa)* and spinifex *(Triodia basedowii)* clothe the floors of the interdune corridors, and the grasses and shrubs extend on to the lower and middle slopes of the dune ridges. The vegetation cover in the Simpson and in other Australian deserts is both anomalous and important. It is anomalous because of the low average rainfall of the areas in which they occur. It may in part be a relic feature that was established during the late Pleistocene moister phase and which has persisted through to the present with the aid of the occasional rains that are received in every desert. The Australian arid zones are not as dry as many others, and though they average only between 150—250 mm per annum (which is nevertheless at least twice that received in Death Valley for example), the rainfall is more reliable than in many desert regions. Tropical and midlatitude lows frequently penetrate the interior and though they do not always generate rain, they sometimes do.

It is notable also that the permeable sands of the dune areas carry more vegetation than does the stony desert, presumably because of seepage and storage of water in the shallow subsurface. Only the higher, and drier zones of sand accumulation lack vegetation and are mobile. And of course, the saltating grains discourage the establishment of vegetation so that here too a reinforcement effect is operative. The vegetation that grows and survives has the effect of inhibiting the growth of distinct dune forms. The airflow near the ground is divided and diffuse, and saltation is disturbed. Sand is moved but is not accumulated in distinct forms, except in areas (as for instance in some river valleys) of prolific sand supply where small transverse and blowout (parabolic, U-dunes) are constructed.

Dune spacing varies considerably from area to area but there is a consistent relationship between dune height and spacing. The higher the dunes the fewer of them there are. Thus the volume of sand per unit area appears to be constant, but why dune spacing varies is not known. Certainly there is a tendency for the sand tongues developed in the lee of the mounds or source-bordering dunes to decrease in number. But what causes such changes both locally and regionally is a matter of conjecture. It may be that the smaller tongues are colonised and stabilised by vegetation. Possibly the occasional very strong winds sweep away minor ridges and concentrate the mobile material into a few large dunes, but whether such strong winds vary in incidence regionally or whether the present patterns represent the perpetuation of episodic events is not clear.

The ridges standing in isolation suggest that sand attracts sand to a marked degree. Once formed the ridges may persist because of positive feedback or reinforcement effects [TWIDALE, BOURNE & SMITH 1974; cf. SYKES 1918]. TSOAR [1978] for example claims that longitudinal dunes develop from sand strips or *zibar* [HOLM 1960] which not only act as obstacles but because of their rough surfaces also cause sand to aggregate. Clearly however this problem of dune spacing awaits further investigation.

Source of sand

Some of the sand is undoubtedly derived locally from the weathering of granite, arenaceous sediments, silcrete or laterite (A-horizon). In the northwest of the Simpson Desert, in the Tanami Desert of the central areas of the Northern Territory and in many other parts of the arid zone such sources are likely to have contributed substantially to dune building. But elsewhere this primary material has been transported and recycled not once but several times. Most of the dune sand is derived, in an immediate sense, from alluvia.

Thus many of the sand ridge deserts of the eastern part of the Australian arid zone lie within the Lake Eyre catchment [TWIDALE 1972 b], which is focussed on Lake Eyre. The bed of Lake Eyre stands some 15.5 m below sea level and is the lowest part of a basin with a long and continuing history of subsidence [WOPFNER & TWIDALE 1967; Twidale 1972 b] so that through the occasional run-off, underflow and subsurface migration of groundwaters the lower areas of the centripetal drainage basin receive more water from the outlying, higher rainfall, areas.

The dunefields of the Australian and other deserts are located in structural and topographic lows that receive more water than is suggested by the climatic data. During their present episodic periods of flow the convergent rivers transport large volumes of debris to the lower parts of the drainage basins, and during the late Pleistocene vast spreads of alluvia were deposited. These alluvia constitute the bulk of the raw material from which the wind has sifted and continues to sort the detritus from which mounds and dunes are built. Thus there is in train a cycle of fluvial transport and deposition followed by aeolian transport and deposition which effectively causes particles to be taken into the lower areas of drainage basins by rivers, and to be evacuated to the downwind outer areas by the wind. Some is later returned to the rivers (see *fig. 1b*).

Dune initiation

In the southern and eastern Simpson Desert longitudinal sand dunes are presently being formed in the lee of mounds [TWIDALE 1972 a] located on the northern margins of playas and flood plains. They range in size from minor ridges just a few score metres long and 2—3 m high, to large structures several kilometres long and standing up to 50 metres higher than the nearby lacustrine or riverine flats. Such large mounds border lakes Eyre and Gregory, and also occur marginal to Goyder Lagoon and the Diamantina flood plain in southwest Queensland. But whether large or small these mounds are located on the lee, that is the northern side of the flats.

Such leeside mounds, also known as source-bordering dunes and as lunettes have been described from southern Texas where they are known as clay dunes [COFFEY 1909] and from the Belarabon area of northwestern N.S.W. [WASSON 1976] where they are located on the eastern side

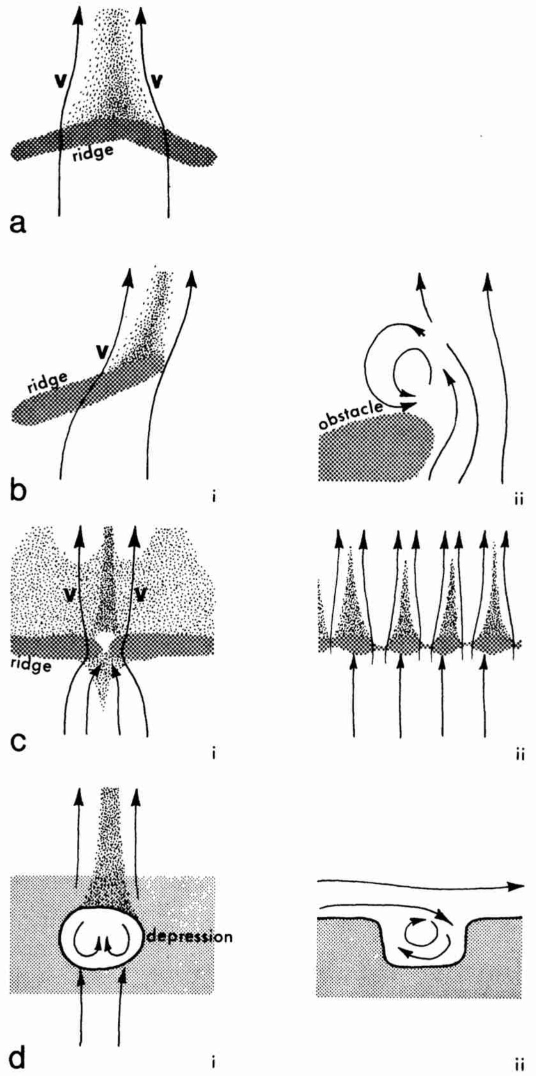


Fig. 4. Diagram showing changes in character of wind in lee of obstacles; in (a) (b) and (c) deflection and development of vortices related to positive relief feature (mound), and in (d) to a negative relief obstacle or depression.

of various meridional streams. Analogous forms and deposits evidently occur marginal to playas in southern California [MOTT & CARPENTER 1970]. In the Kalahari Desert of southwestern Africa WAYLAND [1953] reported that many of the pans or playas are bordered by dunes and both GROVE [1969] and LANCASTER [1978] described similar forms, which they call lunettes, from the southern edges of the lake depressions.

Lunettes are widely developed in southern Australia [see e.g. HILLS 1940; STEPHENS & CROCKER 1946; CAMPBELL 1968; BOWLER 1971] and they occur also in West Africa [BOULAINE 1954; TRICART 1954]. Though there has been considerable debate as to their origin it is now generally agreed [see CAMPBELL 1968; TWIDALE 1968, pp. 233—235] that they are derived from the sediment deposited in the lake basin or flood plain. The material is either deflated or saltated from the exposed flat and is trapped by vegetation bordering the bare area to form a mound. Alternatively, in lacustrine situations sediment is drifted by waves to the lee shore and deposited to form a beach whence it is blown a short distance downwind to form a dune or mound.

Such mounds are instrumental in the initiation of linear dunes because they act as transverse obstacles. Winds passing over them are deflected and develop short-lived but intense turbulence [TWIDALE 1972 a]. Distinct vortices develop and sand is deposited in the 'dead' or low velocity zones between adjacent vortices *(Fig. 4)*.

Sand ridges are developed in the lee of mounds in the Belarabon area of N.S.W. [WASSON 1976]; in the Umab Desert, in the western Kalahari Desert in southeastern Namibia; and according to one of GROVE's [1969] maps and the writer's observations also in the southwestern and western Kalahari.

The leeside mounds are positive topographic features. Longitudinal dunes are also initiated in relation to negative topographic obstacles [see ALLEN 1970, p. 40; TWIDALE 1972 a]. Thus on the bed of the usually dry Goyder Lagoon there are abandoned meander loops or 'billabongs' that eventually become dry to expose the sandy bed. The wind passing over the depression develops intense but short-lived turbulence in the shape of twin vortices known as Karman Trails *(Fig. 4)*. Again sand is deposited between the vortices in the form of a linear sand ridge *(Plate 2)*. Some of these remain near their source. Others have migrated downwind and are now remote from any obvious generating obstacle.

MELTON [1940] reached similar conclusions about the longitudinal dunes of the Moenkopi Plateau, in northeastern Arizona. The Plateau is capped by sandstone and the southwesterly wind, after crossing the deep valleys of the Little Colorado and its tributaries,

> sweeps upward through the canyon heads and northeastward across the plateau summit, picking up loose sand and scouring additional grains as it moves. The sand is deposited in dune form where the eddies occur, that is, above and behind the promontories which lie between headward-eroding canyons of the cliff face. [MELTON 1940, p. 121].

He goes on to state that "longitudinal dunes are unquestionably found downwind from some type of obstacle" [MELTON 1940, p. 122]. HACK [1941] denies that the Moenkopi dunes are lee dunes, but some at least appear to be located in the lee of valley heads and though, as BREED & BREED [1979, pp. 348, 350] point out, the source of the dune sand is debatable, MELTON's interpretation has much to commend it in general terms.

Thus sand ridges are clearly initiated in the lee of obstacles by ephemerally turbulent winds.

Further development

Dunes aligned in general parallelism with the prevailing strong (sand-moving) wind direction have been explained in terms of horizontal vortices and in terms of a bidirectional wind regime, with strong winds blowing from two distinct directions but from the same quarter. With regard to such bidirectional regimes TSOAR [1978, p. 130] has claimed that the two winds do not create an angle greater than 150°—180°, but according to FRYBERGER [1979] the relevant winds usually emanate from the same general quarter. BAGNOLD [1941, p. 223] at one time considered that seif and longitudinal dunes evolved from barchans under the influence of a bidirectional regime. MADIGAN [1946] claimed that no examples of the transition have been recorded and indeed there are no authentic barchans in the Australian deserts (there are barchanoid forms in some coastal areas but they are not mobile). Recently however seifs and barchans occurring in association and possibly genetically related have been described from Namibia and it is claimed that the former evolve under a bidirectional regime [LANCASTER 1980].

MADIGAN [1936] compared the Simpson Desert dunes to the *sastrugi* (or *zastrugi*) of Antarctica and envisaged them developing as blow-outs under the influence of a prevailing strong wind. Some organisation of the airflow is implied and BAGNOLD [1953], FÉDEROVITCH [1956] and GLENNIE [1970], have developed this theme, suggesting that linear dunes evolve under the influence of

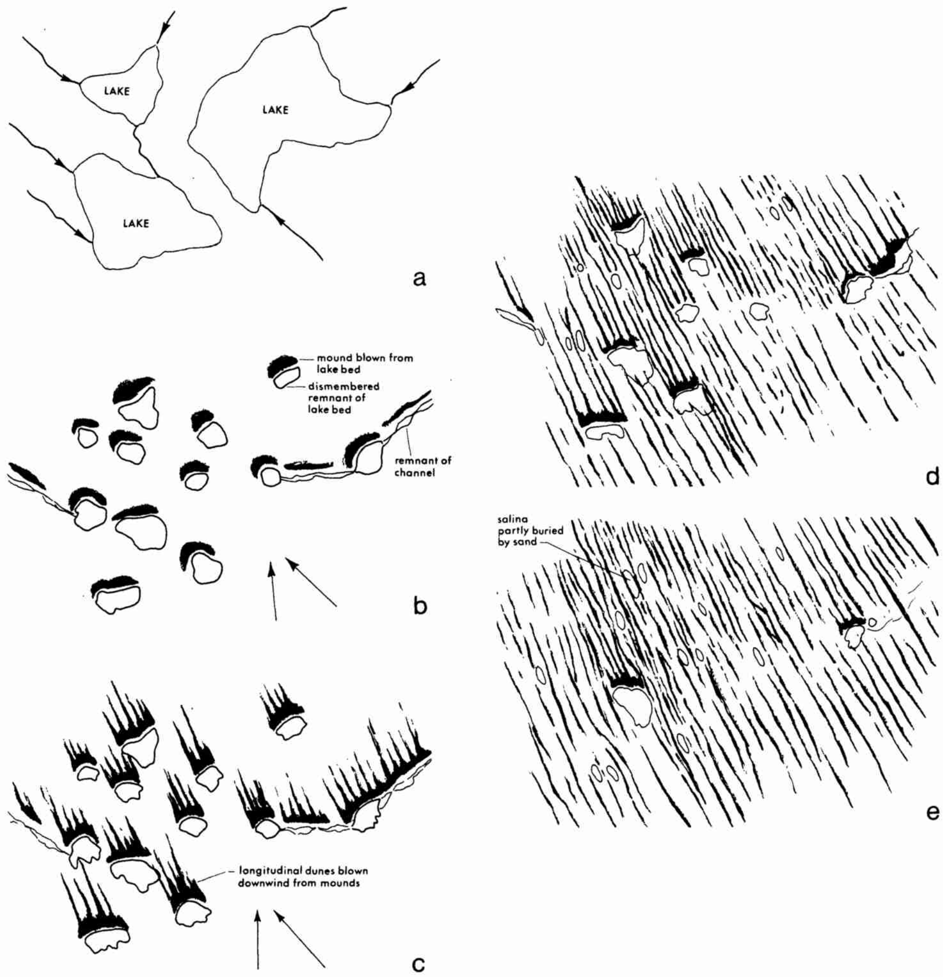


Fig. 5. Summary of dune development in the Simpson and other sand ridge deserts located in alluviated interior basins: (a) shows a late Pleistocene riverine and lacustrine plain, (b) and (c) stages in onset of aridity, dismemberment of drainage and initiation of dunes, (d) the spread of the dunes and masking of lake beds, and (e) the present situation.

long horizontal single or double (opposed clockwise and anticlockwise) spirals or vortices that sweep the sand laterally into dune ridges. This notion has been elaborated with characteristic enthusiasm by FOLK [1971, 1976 b, 1977; but see also LEEDER 1977].

As is made clear in the discussion of dune initiation, experimental work suggests that vortices are developed in the lee of obstacles (mounds, depressions) and that sand ridges are formed between these turbulent eddies. The dunes grow a short distance downwind in this way [cf. GLENNIE 1970, p. 59] but their internal structures indicate formation under a bidirectional regime (see below).

It is likely that in the Simpson Desert the modern wind regime is bidirectional [MADIGAN 1946; BROOKFIELD 1970], strong winds blowing from the southeast and from the southwest. The fields of longitudinal dunes in the western Kalahari [LEWIS 1936] develop in relation to winds from the north and northwest [FRYBERGER 1979], and a similar argument has been adduced in relation to the Canning Basin forms [VEEVERS & WELLS 1961].

The observed alternations of dip of the cross-bedding in the sand ridges are consistent with the development under such a regime as are the observed variations in location of the slip or avalanche slopes. The crossbars and diagonal arms of reticulate patterns are explicable in terms of transverse development under the influence of the strong winds from either southeast or southwest [WOPFNER & TWIDALE 1967; TWIDALE 1972 a].

On the other hand the sand ridges cannot be explained in terms of roller vortices, either single or double. The internal structures of the dunes for example are inconsistent with single vortices. The diagonal bars, the flat-lying bedding of the interdune areas and the consistent but varied asymmetry of the sand ridges are difficult to understand in terms of double vortices. Why should similar helicoidal forms produce such contrasted angles of deposition and slope? In any case the development of neither single nor double vortices has been demonstrated or even hinted at by field or experimental observations.

Conclusion

The field and experimental evidence support the suggestion that linear dunes are initiated by turbulent vortices induced by transverse obstacles, that their downwind extension takes place under the influence of bidirectional wind regime aided by reinforcement effects.

Similar conclusions have been reached in respect of longitudinal dunes in Israel [TSOAR 1978], the Kalahari, the Libyan Desert, West Africa and the Great Victoria Desert, Australia [FRYBERGER 1979].

The sand ridges are still active and their downwind snouts are mobile and advancing at an appreciable, though variable, rate. This material was deposited in the Holocene, but only the crests are now subject to drift. This situation may reflect late Holocene amelioration of climate following a more arid earlier Holocene phase, which in turn succeeded a widespread late Pleistocene climatic period during which extensive lacustrine and riverine plains developed in central and western Australia. Certainly this seems to be the case in the Simpson Desert *(Fig. 5)*.

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