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Abstract

The Innamincka Dome and associated low-gradient fan in the Strzelecki Desert is the product of Cenozoic crustal warping that has aided formation of an extensive array of palaeochannels, source-bordering transverse dunes and superimposed linear dunes. These dunes have impeded the course of Cooper Creek and provided a repository of evidence for Quaternary climate change as well as the interactive processes between transverse and linear dune formation. At Turra, Gidgealpa and sites nearby are extensive fluvial and aeolian sand bodies that date from marine isotope stages (MIS) 8-3 and the Last Glacial Maximum (LGM) and are now surrounded or buried by overbank mud. The sandy alluvium was deposited on the downstream slope of the dome by large channels transporting abundant bedload, subsequently blown northward to form transverse dunes from what were probably seasonally-exposed bars in a palaeoCooper system. Thermoluminescence (TL) and optically stimulated luminescence (OSL) ages demonstrate that the base of the dune complex is at least MIS 7 in age (~250 ka) but that it has been subsequently reworked by wind with additional sand blown from the river. Source-bordering dunes formed during a period of enhanced river flow and sand supply from ~120 to 100 ka, with another short episode of the same at ~85-80 ka and from ~68 to 53. The LGM was associated with enhanced flows and the supply of dune sediment, from 28 to 18 ka. Pronounced river flow and dune activity occurred in the early to mid Holocene, but there is no evidence of dunes being supplied from Cooper Creek since the LGM. The dunes forming the oldest basal sand units appear to be largely transverse in form and are aligned roughly parallel to adjacent east-west trending palaeochannels. Linear dunes have formed from and over these, and yield basal ages ranging from MIS 5 or MIS 4 but continuing to accrete and rework through to the Holocene. The study results in one of the few detailed chronological investigations of the interaction between transverse and linear dunes. It is apparent that long-distance sand transport has played no significant role in dune formation here for the linear dunes show no significant downwind decline in ages. Linear dunes appear to have accreted vertically from underlying transverse dunes. A wind-rift vertical accretion model with only minor lengthwise extension is the dominant mode of linear dune formation in this section of the Strzelecki Desert, the bulk of dune sediment being sourced from adjacent swales since the LGM.

Keywords

australia, strzelecki, dunes, bordering, late, quaternary, aeolian, fluvial, interactions, cooper, creek, fan, between, linear, desert, source, association, GeoQUEST

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ABSTRACT

The Innamincka Dome and associated low-gradient fan in the Strzelecki Desert is the product of Cenozoic crustal warping that has aided formation of an extensive array of palaeochannels, source-bordering transverse dunes and superimposed linear dunes. These dunes have impeded the course of Cooper Creek and provided a repository of evidence for Quaternary climate change as well as the interactive processes between transverse and linear dune formation. At Turra, Gidgealpa and sites nearby are extensive fluvial and aeolian sand bodies that date from marine isotope stages (MIS) 8–3 and the Last Glacial Maximum (LGM) and are now surrounded or buried by overbank mud. The sandy alluvium was deposited on the downstream slope of the dome by large channels transporting abundant bedload, subsequently blown northward to form transverse dunes from what were probably seasonally-exposed bars in a palaeo-Cooper system.

Thermoluminescence (TL) and optically stimulated luminescence (OSL) ages demonstrate that the base of the dune complex is at least MIS 7 in age (~250 ka) but that it has been subsequently reworked by wind with additional sand blown from the river. Source-bordering dunes formed during a period of enhanced river flow and sand supply from ~120 to 100 ka, with another short episode of the same at ~85–80 ka and from ~68 to 53. The LGM was associated with enhanced flows and the supply of dune sediment, from 28 to 18 ka. Pronounced river flow and dune activity occurred in the early to mid Holocene, but there is no evidence of dunes being supplied from Cooper Creek since the LGM. The dunes forming the oldest basal sand units appear to be largely transverse in form and are aligned roughly parallel to adjacent east–west trending palaeochannels. Linear dunes have formed from and over these, and yield basal ages ranging from MIS 5 or MIS 4 but continuing to accrete and rework through to the Holocene.

The study results in one of the few detailed chronological investigations of the interaction between transverse and linear dunes. It is apparent that long-distance sand transport has played no significant role in dune formation here for the linear dunes show no significant downwind decline in ages. Linear dunes appear to have accreted vertically from underlying transverse dunes. A wind-rift vertical accretion model with only minor lengthwise extension is the dominant mode of linear dune formation in this section of the Strzelecki Desert, the bulk of dune sediment being sourced from adjacent swales since the LGM.

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1. Introduction

The Strzelecki Desert, like many other dunefields across the globe, is dominated by linear, or longitudinal dunes. In addition to

the widespread occurrence of these linear aeolian landforms a number of transverse sand bodies exist in the central part of the dunefield on the Cooper Creek Fan. As such, the Strzelecki Desert is a repository of aeolian archives well removed from direct fluvial input and provides a suite of landforms that reflect a long history of fluvial and aeolian interaction. In recent years substantive luminescence chronologies for Australian (e.g. Fitzsimmons et al., 2007a) and African dunefields (e.g. Telfer and Thomas, 2007) have

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been published. While these studies have provided an essential chronological framework for such aeolian landforms, little is known of the climatic significance of such records. Questions such as, what dune erosion and deposition represents; and, how do these processes relate to periods of inferred aridity; are only beginning to be answered. This study presents a detailed assessment of source-bordering and linear dune construction on the Cooper Creek Fan near Innamincka (Fig. 1) over the last glacial cycle and investigates periods of dune building and its relationship to

water and sediment delivery via Cooper Creek to Lake Eyre, the depocentre of Australia's largest internally draining basin. As such, it aims to link formative processes of the aeolian landforms in the Strzelecki Desert to a derived luminescence chronology.

2. The development of linear dunes in central Australia

Dunefields on the Australian continent have most likely existed since the onset of intense aridification sometime during the period

Fig. 1. Locality map of the Cooper Creek Fan and adjacent terminal plays. 1–6 are dunes sites from Fitzsimmons et al. (2007a) and include: 1. Hesse; 2. Moolawatana; 3. Brumby 1; 4. Mulloora; 5. Tirari West; 6. Old Kalamurina.

of late Cenozoic cooling. The timing of this has been suggested to be after the beginning of the Brunhes Normal Chron at ~ 780 ka (Bowler, 1982; Zheng et al., 1998). Chen and Barton (1991) however interpreted the onset of pronounced aridity in central Australia at or before 1.6–0.9 Ma, but with particularly intense aridity occurring only since ca 500 ka (Gardner et al., 1987; Wasson and Clark, 1988). More recently, using ^{10}Be and ^{26}Al Fujioka et al. (2005, 2009) have suggested that stony deserts in Australia formed from 4 to 2 Ma while dunefields began to form around 1 Ma. Luminescence studies of the Australian dunefields have yielded thermoluminescence (TL) and optically stimulated luminescence (OSL) ages as old as 300–200 ka (Gardner et al., 1987; Nanson et al., 1988; Readhead, 1988; Nanson et al., 1992). However, erosion and deposition of dunes during phases of enhanced dune deflation/construction resets their luminescence characteristics and, as a consequence, luminescence dating of sand dunes rarely exceeds 200 ka except on the less active periphery of the arid zone and possibly at the base of some of the more centrally located dunes.

Research into the late Quaternary evolution of the central Australian dunefields is framed around their chronological development (Wasson, 1983b; Callen and Nanson, 1992; Nanson et al., 1992, 1995; Twidale et al., 2001; Lomax et al., 2003; Fitzsimmons et al., 2007a,b) and their sedimentological and stratigraphic characteristics (Wasson, 1983b; Pell and Chivas, 1995; Pell et al., 2000; Hollands et al., 2006; Bristow et al., 2007). In addition, other areas of research have focussed on formative controls of dune activity such as windspeed/direction, potential evapotranspiration and precipitation (Ash and Wasson, 1983; Wasson, 1989), and the changing role of vegetation in dune dynamics associated with varying CO_2 levels throughout the late Quaternary (Hesse et al., 2004). What has been demonstrated is the prevalence of dunefields that record a history up to nearly 300 ka, albeit some as old as 1 Ma (Fujioka et al., 2009), with little evidence for the long-distance transport of sand. Linear dunes have been shown to contain modest proportions of silt or clay pellets and often lack primary bedding structures, with minor lateral adjustments being the dominant positional change over the last glacial cycle (Bristow et al., 2007). Indeed, the internal asymmetry of linear dunes and the resultant implications for chronologies derived from such features has only received attention in the Australian dunefield recently (Hollands et al., 2006; Bristow et al., 2007; Fitzsimmons et al., 2007b). The timing and mode of formation of transverse and linear dunes on the Cooper Creek Fan (Fig. 1), along with an assessment of dune development and its' relationship to late Quaternary climate change, forms the primary focus of this paper.

3. Location and geological setting

Cooper Creek drains almost one quarter of the Lake Eyre basin, one of the world's largest internally draining arid basins with a total catchment area of $1.14 \times 10^6 \text{ km}^2$ (one-seventh of the Australian continent – Fig. 1). Cooper Creek originates in Queensland and terminates ~ 1500 km downstream in the Lake Eyre salt playa, a depocentre 15 m below mean sea level. The catchment is characterised by low-relief with headwaters reaching elevations of 500 m but with 70% of the catchment < 250 m in elevation, giving rise to a low-relief landscape with stream gradients of 0.1–0.2 m/km and a network of anabranching channels known as the 'Channel Country'.

The Channel Country and lower Cooper and Warburton Creeks are located on a complex sequence of nested, gently warped basins and associated near-horizontal sedimentary sequences that date from the Early Palaeozoic to the Cenozoic Lake Eyre (geological) Basin. The Innamincka Dome, the structure most influencing the Cooper Creek Fan being investigated here, is still

rising at a rate of at least 36 m Ma^{-1} (Nanson et al., 2008). Immediately downstream of this domal structure the Katipiri Formation forms the upper part of the fan sequence and is the most recently formally-described fluvial unit in the Lake Eyre Basin (Nanson et al., 2008).

3.1. Physiography of the Cooper Creek Fan and dune morphology

The Innamincka Dome forms the last topographic high prior to Cooper Creek debouching into the Strzelecki Desert and from there into the terminal Lake Eyre basin (Fig. 1). The dome reaches a height of approximately 250 m above the river plain north of Innamincka and 70 m in height above the gibber plains (desert surfaces mantled with stones) along the South Australia/Queensland border. At this point in the Cooper Creek catchment ($236,700 \text{ km}^2$) the entire flow passes through a series of bedrock-confined reaches on the southern margin of the dome before it flows into the Strzelecki Desert. In floods, such as the 1974 event, floodwaters are funnelled through bedrock reaches 0.25–1 km wide before emerging onto the Cooper Creek Fan immediately downstream of Innamincka (Fig. 1). The Cooper Creek Fan is an alluvial feature having a maximum westward regional slope of 0.00027 m/m , which is close to double the slope of the adjacent alluvial plains (Wasson, 1983a; Callen and Bradford, 1992). It is approximately $30 \times 22 \text{ km}$ and is characterised by east–west trending source-bordering dunes located on the northern margins of abandoned watercourses and contemporary floodways (Fig. 2). Contemporary drainage lines are distributary and fan-shaped and include the Cooper Creek channel which meanders westward with a branch draining north to Coongie Lakes. Strzelecki Creek flows southward on the western margin of the fan but only receives floodwaters once the stage height of Cooper Creek exceeds 9 m at the Innamincka gauge (Kotwicki, 1986) and which occurs about or somewhat less than once a decade. The fan is also characterised by a suite of dunes that have formed linearly from the east–west trending source-bordering dunes.

The Gidgealpa and Turra dune sites fall between the 'South Branch' of Cooper Creek and what is termed the Gidgealpa palaeo-channel which is still inundated in larger floods (Fig. 2). Floodplain morphology is generally extremely flat but exhibits low-relief gilgai patterning at the surface in areas with considerable shrink-swell clays (Dawson and Ahern, 1974; Fagan, 2001; Fagan and Nanson, 2004). The source-bordering dunes are generally east–west trending but often have an arcuate form, from which linear dunes extend northwards. The Cooper Creek Fan has moderately widely spaced (400–600 m) organised linear dunes and isolated irregular sub-parabolic dunes. (Fitzsimmons, 2007). Linear dune crests are 15–20 m above the floodplain and decrease in elevation in a northward direction and are often asymmetrical in cross-section (Fig. 3c). They are generally sparsely vegetated but often only have small areas of active dune crests. On the base and lower slopes of the dunes canegrass (*Zygochloa paradoxa*) and several *Acacia* spp with other desert shrubs grow, while forbes and grasses on the upper slopes vary annually and seasonally in terms of cover density. At the northern end of both Gidgealpa and Turra the active nose of the dune is migrating onto the Cooper floodplain. Inter-dune swale topography is highly variable with the presence of what we term inter-dune ridges. These east–west trending features may be 5–8 m above the lowest part of the swale and are often laterally semi-continuous and are offset on the eastern and western sides of the linear dune (Fig. 3a,b).

3.2. Climate and hydrology of the Cooper Fan

The principal synoptic influences on rainfall in the Lake Eyre drainage basin are in the form of moist tropical air incursions that

Fig. 2. Gidgealpa and Turra source-bordering and linear dunefields; (a) dune distribution map taken from an enhanced satellite image derived from Landsat 5 TM – 25 m pixel (Geocoded – 1995) and Landsat 7 ETM 12.5 m pixel (Geocoded – 2000). A – Gidgealpa transect, B – Turra transect, EDB – East Dog Bite Lake, NDB – North Dog Bite Lake. The triangle denotes the location of initial investigations at Gidgealpa. (b) Digital elevation model derived from SRTM data of the Gidgealpa complex showing a gradation of elevation from high areas (white) to areas of lower elevation (dark). Note the presence of the transverse dune at the downwind (southern) end and mid-way along the length of the dune complex (white dashed line) and the presence of the arcuate line of claypans (black dashed line). (c) Wind rose diagram from Moomba 1992 – present with shading of windrose varying from 0 to 3 (black) to >9 m/s (dark grey) and concentric circles representing % of time exceeded.

pass over the northern tablelands and eastern Great Dividing Range during the summer months (Allan, 1990). Mean annual rainfall decreases markedly from about 400 to 500 mm in the northeast of the basin to about 100 mm near Lake Eyre, with the coefficient of variability of mean annual rainfall among the highest recorded in Australia (Kotwicki, 1986; Kotwicki and Isdale, 1991) and indeed the world (McMahon et al., 2008). Mean annual evaporation (Class A Pan) grades progressively from about 2400 mm yr⁻¹ in the northeast to more than 3600 mm yr⁻¹ near Lake Eyre. Mean daily maximum temperatures at Moomba (1990–2006), 50 km southwest of the study area (Fig. 2) are 28.9 °C but with a maximum recorded daily temperature of 49.6 °C and a mean daily minima of 14.9 °C. Annual rainfall at Innamincka (1889–present) has averaged 171 mm yr⁻¹, with an average monthly rainfall for January and August of 27.4 and 6.5 mm, respectively. Wind direction is dominated by the south-east quadrant with the strongest winds

from the south (Fig. 2), broadly in accordance with the orientation of the region's linear dunes.

The mean annual runoff for Cooper Creek is characterised by high streamflow variability with long periods of low or zero flow and occasional periods of extremely high discharge with high C_v values (hydrologic variability) by world standards (1.61 and 2.20, respectively) (Knighton and Nanson, 1994a, 2001). The largest flood on record occurred in January–February 1974, with a maximum daily discharge of 6360 m³ s⁻¹ at Innamincka and occurred with simultaneous flooding of all major watercourses in the Lake Eyre drainage basin and the subsequent inundation of Lake Eyre to its highest recorded level. One of the prominent hydrological characteristics of Cooper Creek is the magnitude of transmission losses of floodwaters, with up to 60–75% of flow lost as secondary channels and floodplains are inundated for the ~450 km upstream of Innamincka (Knighton and Nanson, 1994). Similar losses almost

Fig. 3. Longitudinal profiles of Turra and Gidgealpa linear dunes. Note the varying vertical exaggeration of $40\times$ VE and $100\times$ VE, respectively. (a) Turra linear dune with downhole % silt + clay. (b) Gidgealpa linear dune with downhole % silt + clay. Note the topographic variability of swales downwind. (c) Selected cross-sections along Gidgealpa dune.

certainly apply for the study area downstream of Innamincka where Cooper Creek distributes its floodwaters into the Strzelecki Desert and into a series of terminal lakes, the largest and most distal being Lake Eyre.

4. Field and laboratory methods

Two east–west trending source-bordering dunes were chosen for investigation, each with north–south trending linear dunes that extend downwind (Fig. 2). Locations were selected based on the pronounced nature of the source-bordering dunes, whilst linear dune selection was based on representative length, with Gidgealpa dune representing one of the longest linear dunes (8 km) and Turra being one of the shorter (2.5 km). Transects were undertaken parallel to the linear orientation and extended from the adjacent upwind floodplain, along the length of the dune crests and onto the floodplain on the downwind side. Selected cross-sections were surveyed along with inter-dune swale topography. Holes were augered by hand or mechanically along the crest of these transects whereas the floodplains were drilled using a truck-mounted Gemco 210D drill rig. In addition, a number of floodplain pits (maximum depth of 5 m) were examined using a tracked excavator.

Sediment was collected from all holes at 1–2 m intervals for particle size analysis using a Malvern laser particle size analyser with the clay fraction analysed by a Horiba Cappa-700. X-ray diffraction was used for the identification of minerals in the clay-size sediments using a Philips PW 1150 diffractometer with a copper broad focus X-ray tube at 40 keV and 30 mA. Standard particle size parameters are presented along with colour determinations using a Munsell colour chart. A stereoscan 440 scanning electron microscope (SEM) was used to examine surface characteristics of aeolian and fluvial sediment samples.

4.1. Luminescence sampling and dating procedures

Chronological techniques employed within this study include both thermoluminescence (TL – Table 1) and optically stimulated luminescence (OSL – Tables 2 and 3). The analytical procedures for TL and OSL dating at the Wollongong and CSIRO laboratories have been thoroughly described in previous publications with full details of the TL procedures given in Shepherd and Price (1990), Nanson et al. (1991) and recently in McIntosh et al. (2009) and full details of the OSL technique provided in Olley et al. (2004). Fifty-seven quartz samples have been dated with TL using a multi-grain (90–125 μm)

Table 1
Thermoluminescence (TL) data for the Gidgealpa and Turra dunes and associated fluvial deposits.

Reference @ sample depth (m)	Sample No.	Temp. plateau region (°C)	Palaeodose (Gray)	K content (% ± 0.005)	Moisture content (% ± 3.0)	U + Th specific activity (Bq/kg)	Annual radiation (Gy/ka ⁻¹)	TL age (ka)
<i>Gidgealpa dune</i>								
Gidge1-2 @ 3	W2248	300–500	24.1 ± 1.7	0.410	2.0	22.4 ± 0.7	1.02 ± 0.03	23.6 ± 1.8
Gidge1-4 @ 6.9	W2249	300–500	64.2 ± 6.4	0.375	3.6	22.2 ± 0.8	0.96 ± 0.02	66.9 ± 6.9
Gidge2H1 @ 1.2	W4024	300–500	28.2 ± 1.6	0.565	2.1	29.3 ± 0.9	1.37 ± 0.03	20.5 ± 1.2
Gidge2H1 @ 3.0	W4025	300–500	25.3 ± 2.8	0.400	1.8	24.0 ± 0.8	1.06 ± 0.03	23.8 ± 2.7
Gidge2H1 @ 5.8	W4026	300–500	71.3 ± 3.1	0.990	15.6	69.8 ± 1.7	2.22 ± 0.06	32.1 ± 1.6
Gidge2H2 @ 2	W4022	275–500	3.3 ± 0.3	0.400	0.8	27.0 ± 0.8	1.13 ± 0.03	2.9 ± 0.3
Gidge2H2 @ 4	W4023	300–500	10.3 ± 0.6	0.375	1.3	25.0 ± 0.8	1.04 ± 0.03	9.9 ± 0.6
Gidge2H2 @ 6	W3997	300–500	15.7 ± 0.9	0.425	2.5	22.9 ± 0.7	1.02 ± 0.03	15.5 ± 1.0
Gidge2H2 @ 8	W3998	300–500	27.6 ± 1.7	0.400	3.3	28.7 ± 0.9	1.08 ± 0.03	25.6 ± 1.7
Gidge2H2 @ 10	W3999	300–500	50.9 ± 2.7	0.450	4.1	20.9 ± 0.7	0.96 ± 0.03	53.1 ± 3.2
Gidge2H2 @ 12	W4000	300–500	62.1 ± 4.2	0.455	4.9	26.7 ± 0.9	1.14 ± 0.03	54.5 ± 3.9
Gidge2H2 @ 14	W4001	300–500	56.6 ± 3.4	0.355	3.1	24.5 ± 0.8	0.92 ± 0.02	61.6 ± 4.0
Gidge2H2 @ 15.6	W4002	300–500	112.0 ± 5.0	0.740	9.6	48.0 ± 1.3	1.65 ± 0.03	67.8 ± 3.0
Gidge2H3 @ 2.0	W4076	275–500	9.2 ± 0.8	0.340	0.7	20.2 ± 0.6	0.93 ± 0.03	9.9 ± 0.9
Gidge2H3 @ 2.0	W4114	300–400	11.2 ± 0.6	0.375	0.8	18.7 ± 0.6	0.92 ± 0.03	12.2 ± 0.8
Gidge2H3 @ 6.0	W4077	300–500	102 ± 10.0	0.450	3.8	32.7 ± 0.9	1.18 ± 0.03	86.3 ± 9.0
Gidge2H3 @ 8.0	W4061	300–500	122 ± 7.0	0.465	6.2	31.2 ± 1.0	1.16 ± 0.03	105 ± 6.0
Gidge2 gully @ 3	W4059	300–500	20.6 ± 1.0	0.315	1.3	21.4 ± 0.7	0.92 ± 0.03	22.4 ± 1.2
Gidge2H4 @ 2	W4078	275–500	9.0 ± 0.4	0.420	1.0	23.3 ± 0.8	1.08 ± 0.03	8.4 ± 0.5
Gidge2H4 @ 4	W4062	275–500	8.8 ± 0.6	0.260	0.6	11.4 ± 0.4	0.65 ± 0.03	13.7 ± 1.0
Gidge2H4 @ 6	W4079	300–500	26.5 ± 1.8	0.400	2.3	21.4 ± 0.7	0.96 ± 0.03	27.5 ± 2.0
Gidge2H4 @ 8	W4063	300–500	58.1 ± 3.2	0.395	2.3	23.7 ± 0.8	0.98 ± 0.03	59 ± 3.7
Gidge2H4 @ 10	W4080	300–500	69.7 ± 2.9	0.395	2.6	25.6 ± 0.8	1.00 ± 0.03	69.4 ± 3.5
Gidge2H4 @ 12	W4064	300–500	94.3 ± 5.3	0.365	3.4	23 ± 0.8	0.90 ± 0.03	104 ± 7
Gidge2H5 @ 4	W4075	275–500	9.8 ± 0.7	0.380	1.7	21.3 ± 0.6	0.97 ± 0.03	10.2 ± 0.7
Gidge2H5 @ 6	W4060	275–450	9.8 ± 0.7	0.295	1.4	17.1 ± 0.6	0.78 ± 0.03	12.6 ± 1.0
Gidge2 east inter-dune @ 8	W4089	300–500	198 ± 11	0.455	3.1	23.5 ± 0.7	1.03 ± 0.03	192 ± 12
Gidge2 west inter-dune @ 4	W4090	325–500	285 ± 16	0.540	5.4	29.7 ± 0.9	1.25 ± 0.03	228 ± 13
Gidge2 east swale @ 2	W4115	300–500	c. 419 ± 22	0.800	9.5	42.6 ± 1.2	1.71 ± 0.03	c.245 ± 13
Gidge2 east swale @ 4	W4116	300–500	c.402 ± 22	0.555	2.7	34.5 ± 1.1	1.40 ± 0.03	c.288 ± 17
Gidge2 west swale @ 2	W4113	300–500	269 ± 18	0.525	3.9	22.1 ± 0.7	1.13 ± 0.03	239 ± 17
<i>Turra dune</i>								
Turra2-2 @ 5	W2476	300–500	21.1 ± 1.9	0.365	2.9	25.7 ± 0.8	1.01 ± 0.03	21.0 ± 1.9
Turra2-3 @ 9	W2477	300–500	24.2 ± 2.5	0.370	4.4	25.0 ± 0.8	0.95 ± 0.03	25.4 ± 2.5
Turra6-2 @ 5	W2478	300–500	2.8 ± 0.4	0.305	0.6	15.1 ± 0.5	0.76 ± 0.03	3.7 ± 0.6
Turra6-3 @ 10	W2479	300–500	123 ± 10	0.605	8.2	43.9 ± 1.1	1.49 ± 0.03	82.1 ± 7.0
Turra4-2 @ 5.2	W2480	300–500	4.4 ± 0.4	0.385	2.6	25.2 ± 0.6	1.03 ± 0.03	4.3 ± 0.4
Turra4-3 @ 10	W2481	300–500	164 ± 19	0.720	12.7	47.5 ± 1.5	1.60 ± 0.03	103 ± 12
Turra1-1 @ 2.7	W2672	300–500	24.8 ± 2.0	0.320	1.2	25.4 ± 0.7	0.99 ± 0.03	25.0 ± 2.2
Turra1-2 @ 5.7	W2673	300–500	50.1 ± 4.7	0.435	2.3	31.8 ± 1.0	1.21 ± 0.03	41.4 ± 4.0
Turra1-3 @ 8.7	W2674	300–500	124 ± 18	0.410	2.8	27.8 ± 0.9	1.07 ± 0.02	116 ± 17
Turra3-2 @ 5	W2675	300–500	5.4 ± 0.5	0.280	0.6	8.7 ± 0.3	0.60 ± 0.03	8.9 ± 0.9
Turra 3 @ 10	W2676	300–500	158 ± 46	0.420	2.8	24.0 ± 0.7	0.99 ± 0.02	158 ± 46
Turra5 @ 4	W3971	275–500	8.0 ± 0.5	0.335	0.8	18.8 ± 0.6	0.88 ± 0.03	9.1 ± 0.9
Turra3 @ 5	W3972	275–500	12.0 ± 0.6	0.375	1.2	20.8 ± 0.6	0.95 ± 0.03	12.6 ± 0.7
Turra3 @ 7.2	W3973	300–500	14.3 ± 0.8	0.385	0.9	23.2 ± 0.7	0.99 ± 0.03	14.5 ± 0.9
Turra3 @ 9.9	W3974	300–500	45.2 ± 2.2	0.850	7.9	51.0 ± 1.6	1.89 ± 0.06	24.0 ± 1.4
<i>Fluvial</i>								
EDBL1-1 @ 3.85	W2246	300–500	72.6 ± 6.5	0.240	0.7	21.5 ± 0.7	0.83 ± 0.03	87.5 ± 8.3
NDBL1-1 @ 3.7	W2247	325–500	86.7 ± 8.5	0.600	0.5	25.7 ± 0.8	1.31 ± 0.03	66.3 ± 6.7
Gidge2H1 @ 7.5	W4027	300–500	139 ± 9.0	0.530	1.7	24.5 ± 0.7	1.18 ± 0.03	118 ± 8.0
Gidge Trench 1 @ 4.75	W4087	300–500	143 ± 10.0	0.500	4.7	32.9 ± 0.9	1.27 ± 0.03	112 ± 9.0
Gidge Trench 4 @ 4.3	W4088	300–500	72.4 ± 4.8	0.185	0.4	12.4 ± 0.4	0.58 ± 0.03	124 ± 10
TurraPC4-1 @ 2.8	W2470	300–500	103 ± 10	0.590	1.5	33.8 ± 1.0	1.45 ± 0.03	71.2 ± 6.8
TurraPC2-1 @ 2.45	W2471	300–500	95.6 ± 6.8	0.715	4.2	48.1 ± 1.4	1.82 ± 0.03	52.5 ± 3.8
TurraPC2-2 @ 4.55	W2472	325–500	146 ± 21	0.730	5.0	43.8 ± 1.3	1.72 ± 0.03	84.9 ± 12.1
TurraPC3-3 @ 3.50	W2473	325–500	97.2 ± 17.2	0.495	0.9	31.1 ± 1.0	1.30 ± 0.03	74.7 ± 13.3
TurraPC3-6 @ 8	W2474	300–500	81.5 ± 8.9	0.215	3.2	18.8 ± 0.6	0.69 ± 0.03	118 ± 14
TurraPC3-7 @ 9.2	W2475	325–500	201 ± 47	0.400	1.8	17.9 ± 0.5	0.87 ± 0.03	231 ± 54

multiple aliquot technique (combined additive-regenerative technique) and eight samples have been dated using single grain OSL (180–212 µm). Environmental dose rates have been calculated using a range of dosimetry techniques including high-resolution gamma spectrometry (OSL fluvial samples), thick source alpha and beta counting (TL and OSL aeolian samples), whilst flame photometry, neutron activation and XRD have been used to

determine mean K% values. Field moisture contents, plus an assumed error have been used in all cases. We have assumed secular equilibrium in the uranium/thorium decay chain and the limited number of samples analysed using the high-resolution gamma spectrometry confirms this to be a valid assumption.

Our previous experience with luminescence dating in central Australia (e.g. Nanson et al., 2005; Hollands et al., 2006; Maroulis

Table 2

Single grain optically stimulated luminescence (OSL) data for the fluvial sediments in the Gidgealpa floodplain.

Sample	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{40}K	(Gy ka $^{-1}$)	σ_d (%)	De (Gy)	Age (ka)
GT1	10.9 $\pm$ 0.9	10.3 $\pm$ 0.2	11.1 $\pm$ 1.2	14.2 $\pm$ 0.3	161 $\pm$ 4	1.1 $\pm$ 0.09	17	130 $\pm$ 10	118 $\pm$ 13
GT2	7.87 $\pm$ 1.19	8.89 $\pm$ 0.16	11.2 $\pm$ 1.1	11.3 $\pm$ 0.2	149 $\pm$ 4	1.01 $\pm$ 0.08	20	120 $\pm$ 7	119 $\pm$ 12
GT3	5.67 $\pm$ 0.86	4.96 $\pm$ 0.13	9.08 $\pm$ 1.17	6.17 $\pm$ 0.17	60 $\pm$ 2	0.61 $\pm$ 0.05	40	62 $\pm$ 10	102 $\pm$ 19
GT4	5.07 $\pm$ 0.4	4.3 $\pm$ 0.08	3.58 $\pm$ 0.5	5.01 $\pm$ 0.09	46 $\pm$ 1	0.46 $\pm$ 0.04	50	16 $\pm$ 2	35 $\pm$ 5
GT5	3.78 $\pm$ 0.36	3.47 $\pm$ 0.07	4.39 $\pm$ 0.48	3.99 $\pm$ 0.18	31 $\pm$ 1	0.41 $\pm$ 0.03	49	9 $\pm$ 2	22 $\pm$ 5
GT6	4.1 $\pm$ 0.41	4.06 $\pm$ 0.08	5.91 $\pm$ 0.56	4.75 $\pm$ 0.17	62 $\pm$ 2	0.53 $\pm$ 0.04	30	45 $\pm$ 5	85 $\pm$ 12

Note: Dosimetry for all sample derived from high-resolution gamma spectrometry.

et al., 2007; Nanson et al., 2008) has shown that, in the main, TL dating remains very suitable for dating aeolian samples whereas single grain OSL dating is more appropriate for fluvial samples. This is primarily a function of partial bleaching in fluvial samples and microdosimetry in heterogeneous stratigraphic units. Material for TL dating was obtained directly by sub-sampling from the drillhead at the surface into light-proof bags at 1–2 m intervals to depths of 15+ m. Given the limited occurrence of vertical exposures in the aeolian sediments only two samples were collected for comparative analyses from a small eroded gully at Gidgealpa. This was to assess the degree of residual palaeodose in a modern sample and the similarities between multi-grain techniques such as TL and single aliquot OSL with single grain OSL.

In contrast to aeolian samples, fluvial samples are more likely to contain a mixture of grains with different palaeodoses. Any luminescence technique, whether OSL or TL, which examines more than one grain at a time will therefore likely overestimate the age due to the averaging effect inherent in large aliquot or multi-aliquot dating. We have therefore used single grain OSL for dating fluvial deposits, with samples collected from trenches using horizontally driven cores. Financial constraints however, have meant that only a proportion of fluvial samples could be collected and dated in this way, hence we have also included the TL results from a further 11 fluvial samples. These results however should be considered as indicative only, as they may be overestimates resulting from the heterogeneous bleaching of material during fluvial transport.

Single grain OSL palaeodose distributions from fluvial samples often display so-called overdispersion, where the spread in the distributions is greater than what can be explained by measurement uncertainties alone. For fluvial samples this overdispersion is typically due to partial or heterogeneous bleaching during transport. Following Olley et al. (2004) we have determined the overdispersion parameter σ_d using the central age model (CAM) of Galbraith et al. (1999), and where σ_d has exceeded 20%, the minimum age model (also of Galbraith et al., 1999) has been used to calculate the sample palaeodose. Where σ_d is less than 20%, the sample burial dose is taken as the weighted mean, calculated using the CAM, of the single grain palaeodoses.

5. Results

5.1. Dune sedimentology

Sediment samples from the Turra and Gidgealpa dunes indicate the dominance by quartz (90–95%) and occasional feldspars, with muscovite and calcite being the principle additional mineral and illite being the dominant detrital clay mineral. Near the surface, dune sediment has a mean particle size of 180–200 μm (2.52 ϕ) with sediments in the dune having a bimodal distribution with a primary peak between 200 and 300 microns (Fig. 4). Sorting down profile decreases with depth as a function of an increase in the percentage of silt and clay (Fig. 3a,b). These fines could result from sand-size mud aggregates blown into the dunes and then disaggregating and eluviating towards the base, or more simply windblown dust alighting on the dunes and doing the same. Particle size characteristics from the adjacent fluvial landforms (sandy palaeochannels and floodplain muds) indicate a greater variability with a mean particle size of 185–500 μm (1.01–2.39 ϕ) and a greater standard deviation than the aeolian dune sediments (but not statistically significant, $p > 0.05$). The fluvial sediments indicate that many of the sand units share a similar size mode (200–400 μm) to the adjacent aeolian sands (Fig. 4), a strong indication that adjacent alluvium was the source for the transverse and linear dunes formed on the Cooper Creek Fan. No evidence of pedogenic horizons (palaeosols) were identified in any of the drill-hole data with only minor carbonate enrichment encountered in the basal sections of drill-holes where the aeolian sediment overlies the fluvial facies.

5.2. Gidgealpa dune and associated paleochannels

The Gidgealpa dune is a surprisingly complex feature. At first glance it appears to consist of a simple transverse dune in the south that acted as a source for a series of linear dunes and sandy intervening swales trailing northwards (downwind) (Fig. 2). The transverse dune is superimposed with the start of the northward trending linear dunes. Closer inspection reveals what appear in the swales to be a series of relatively small transverse inter-dune ridges

Table 3

Single grain optically stimulated luminescence (OSL) data for two aeolian samples at Gidgealpa dune.

Sample	Alpha (Gy ka $^{-1}$)	Beta (Gy ka $^{-1}$)	Gamma (Gy ka $^{-1}$)	Total dose (Gy ka $^{-1}$)	Palaeodose					
					σ_d (%)	De (Gy) CAM	De (Gy) MAM	De (Gy) FMM	FMM (#/%)	Age (ka)
GA4	0.03 $\pm$ 0.01	0.48 $\pm$ 0.03	0.34 $\pm$ 0.01	1.05 $\pm$ 0.07	17	0.07 $\pm$ 0.01	0.07 $\pm$ 0.06	–	–	0.07 $\pm$ 0.06
GA3	0.03 $\pm$ 0.01	0.40 $\pm$ 0.03	0.27 $\pm$ 0.01	0.87 $\pm$ 0.07	41	17.8 $\pm$ 1.2	–	–	–	20.4 $\pm$ 2.0
								21.13 $\pm$ 0.62	3/85	24.2 $\pm$ 1.9

Note: Single grain analysis using a 240 $^{\circ}\text{C}/10$ s preheat and 160 $^{\circ}\text{C}/5$ s cutheat. GA4 is a well-stratified modern sample taken at 0.5 m depth and GA3 is a late Pleistocene sample (see W4059/Table 1 for TL results). CAM – central age model (Galbraith et al., 1999). For GA4 the unlogged central age model of Arnold et al. (2009) has been used. MAM – minimum age model (Galbraith and Laslett, 1993). For GA3 the unlogged minimum age model of Arnold et al. (2009) has been used. FMM – Finite mixture model (Galbraith and Green, 1990; Roberts et al., 2000) where # is number of components and % is percentage of data within that component. Single aliquot data for GA3 (45 aliquots, 0.5 mm mask, 90–125 μm) yields a palaeodose of 19.7 $\pm$ 0.6 Gy (22.1 $\pm$ 1.8 ka). Dosimetry for both samples derived from thick source alpha counting and beta counting.

Fig. 4. Particle size distributions from aeolian and fluvial sediments in the Gidgealpa area; (a) aeolian sediment from Gidgealpa, hole 2; (b) floodplain and channel sands taken from trenches upwind of Gidgealpa dune.

separating a sequence of clay pans spaced along each swale. In other words, the elevation of the floor of each swale undulates lengthwise but in a way not unrelated to undulations in adjacent swales (Fig. 3). The overall pattern of these alternating low interdune ridges and claypans is a sequence of concentric east–west arcs roughly parallel to the transverse dune (Fig. 2).

The luminescence results from the Gidgealpa transect reveal a long history of dune construction. The assessment of the “modern” sample taken from a stratified section at 0.5 m depth shows no evidence of a significant residual palaeodose signal (Fig. 5a) with the sample yielding a palaeodose value of 0.07 ± 0.06 Gy (with an estimated modern age of 70 ± 60 years, Table 3). The late Pleistocene sample in contrast comes from the same stratigraphic section but from an unstratified unit at 2.7 m depth (separated from the above sample by a diffuse boundary at 0.9 m). The single grain OSL results from this sample (Fig. 5b) indicate palaeodoses that range from 3 to 32 Gy (σ_d is 41%). Despite the presence of five to seven grains with half the palaeodose of the bulk of the population the sample yields a central age estimate of 20.4 ± 2.0 ka, which overlaps within 1σ of the single aliquot estimate of 22.1 ± 1.8 ka and of the TL estimate of 22.4 ± 1.2 ka (Tables 1 and 3). Using the finite mixture model (Galbraith and Green, 1990; Roberts et al., 2000) identifies the presence of one dominant sub-population with a palaeodose of 21.1 ± 0.6 Gy (Fig. 5b) constituting 85% of the data. The remaining data stems from grains that yield lower palaeodoses and constitute minor

Fig. 5. Single grain characteristics of two aeolian samples from Gidgealpa dune, see Table 3. (a) Palaeodose distribution of a stratified young sample taken at 0.5 m depth. (b) Radial plot of single grain OSL D_e determinations for late Pleistocene aeolian sample W4059. Note the presence of intruded young grains, but with 85% of the data falling into the palaeodose sub-population of 21 Gy. Each dose equivalent (D_e) estimation for a given grain is plotted as a point with its precision (x-axis) and standardised log dose (y-axis). The palaeodose for each grain is read by tracing a line from the y-axis origin through the point to the radial scale. The shaded band shows the palaeodose estimate for the dominant sub-population whilst the black dashed lines represent minor sub-populations as determined by the finite mixture model.

sub-populations of 3.4 ± 0.5 and 8.6 ± 0.7 Gy (4 and 11%, respectively). Using the dominant sub-population yields a single grain age of 24.2 ± 2.0 ka, a value that overlaps within 1σ of the single aliquot and TL estimates. We interpret the presence of a small proportion of grains (10–15%) with smaller palaeodoses within the unstratified late Pleistocene aeolian deposit as grain intrusion as a result of bioturbation processes (plants or animal disturbance).

Whilst this single/multi-grain comparative analysis is limited in its scope it provides useful evidence to suggest that modern aeolian samples are well-bleached at the time of deposition, but that through time some minor mixing may introduce grains with younger and older palaeodoses from units above and below the one sampled. We have used the good agreement between the single grain and multi-grain techniques to confirm the suitability of TL for dating the dunes within this study. This is predicated on the assumption that other aeolian samples will display equivalent degrees of bioturbation, an assumption that requires further systematic single grain analysis of aeolian sediment in the Australian dunefields. Previous comparisons between multi-grain techniques for aeolian samples in the south-west Kalahari have also shown good correspondence between multiple-aliquot TL and single aliquot OSL (see review by Chase, 2009).

Fig. 6. Dune cross-section of swale and inter-dune ridge at Gidgealpa dune. White dashed line highlights location of transverse inter-dune ridge while black dashed line shows location of transverse claypans (see Fig. 2).

A total of thirty-one TL ages were obtained from the east–west trending transverse dune in the south, a ~10 km long northward trending linear dune and from the two swales on either side of the linear dune. The oldest TL ages of 239 ± 17 (W 4113) and $ca\ 245 \pm 13$ to 288 ± 17 (W4115 and W4116 are almost at TL saturation; Table 1) come from the base of two adjacent swales beneath two claypans (Fig. 6 transect B). The two inter-dune ridges north of these claypans yielded TL ages of 192 ± 12 and 228 ± 13 ka (W4089 and W4090) (Fig. 6). The core of the linear dune is towards the middle of its length and is 105 ± 6 and 105 ± 7 ka (Fig. 7) (W4061 and W4064) and interestingly appears to be slightly inset within the older adjacent swales with their claypans and inter-dune ridges.

Basal ages for the deepest hole (Fig. 7, hole 2) is in the southern transverse dune component of the dune complex and yielded TL ages between 67.8 ± 3.0 and 53.1 ± 3.2 ka (W3999–W4002) of MIS IV–III. It occurs below the elevation of the adjacent swales at the head of the linear dune but is represented as a dune core, elevated above the swale in the downwind section of Gidgealpa (Figs. 2 and 7). Overlying this unit is an aeolian sequence that dates between 27.5 ± 2.0 and 12.6 ± 1.0 ka with the most upwind end of Gidgealpa dune yielding TL ages that centre around the LGM (hole 1, W4024–W4025). These MIS II ages stem from an aeolian unit that reveals little to no bedding but has been dated at both Gidgealpa sites and at the Turra dune (described below). Fig. 7 demonstrates that the upper 2–4 m of both the transverse and linear components of the Gidgealpa dune complex yielded predominantly early Holocene ages with the upper metre (undated) showing the only signs of intact stratigraphy. The results for the Gidgealpa transect show no evidence for downwind younging for the middle or upper part of the dune.

A series of trenches were excavated at the upwind end of Gidgealpa dune to investigate the stratigraphic relationships between the underlying fluvial sequences (Katipiri Formation) and the construction of the linear dunes (Fig. 8). Trench 1 is on the

upwind end of Gidgealpa dune adjacent to hole 1. The upper 2.5 m of this sequence exhibits well sorted horizontally laminated fine sand interpreted to be aeolian in origin, overlying a thin fluvial sand with a lower sharp boundary to a massive 1.5 m thick mud unit. This floodplain mud overlies an indurated finely laminated cross-bedded fluvial sand unit which yielded an OSL age of 118 ± 13 ka (GT1) and a TL age of 112 ± 9 ka (W4087) which are within one sigma of the TL age of 118 ± 8 (W4027) from the basal fluvial sands from hole 1 (Fig. 8). Trench 2 occurs on the most upwind limb of Gidgealpa dune and is dominated by fluvial facies underlying 0.5 m of surface aeolian sediment. The upper part of the fluvial unit comprises an upward-fining sequence with muds and channel sands indurated with gypsum and ferricrete. Low-angle cross beds with a north–westerly dip indicate a channel migrating in essentially the same direction as the present Cooper Creek. The basal cross-bedded sands yielded an OSL age of 119 ± 12 ka, 2 m deeper but almost identical in age to that of the basal sands in Trench 1 (GT2, Table 2).

Trench 3 occurs on the floodplain of the Gidgealpa palaeo-channel immediately adjacent to Gidgealpa dune and contains nearly 3.5 m of blocky floodplain mud overlying indurated fluvial sands of the Katipiri Formation with an OSL age at 4.5 m of 102 ± 19 ka (GT3, Table 2). The stratigraphic relationship between the fluvial sands in Trenches 2 and 3 is unknown as both basal ages overlap within two sigma. This may therefore represent one fluvial unit underlying both trenches or alternatively the elevation difference of the fluvial sands may suggest an unconformity between the fluvial successions in these two trenches (Fig. 8). The fluvial sands in Trenches 1, 2 and 3 overlap chronologically with dune sediment dated from the basal and middle section of Gidgealpa dune (Fig. 7). This provides useful evidence indicating the links between active river channels in MIS 5 and the contemporaneous formation of dunes adjacent to such channels.

The floodplain mud thins southwards towards Trench 4 where only 1.5 m of mud overlies a trough cross-bedded sand unit

Fig. 7. Chronology of Gidgealpa linear dune; (a) thermoluminescence (TL) ages along with isochrones; (b) cross-sections along Gidgealpa dune; (c) marine isotope stages with summary of dune deposition ages.

representing a bar sequence with an OSL age from the basal sands of 35 ± 5 ka (GT4, Table 2). Despite the clear bedding the distribution of palaeodoses shows considerable scatter (Fig. 9d) suggesting partial bleaching of the alluvial unit with a TL age from the same unit of 124 ± 10 (W4088). If the OSL minimum age is a good representation of the true depositional age then this fluvial sand unit falls within errors of the source-bordering dune dated in hole 1 (Fig. 8). This would suggest a direct link between the fluvial sands and the adjacent dune development. A similar argument can be put for the OSL age of 22 ± 5.2 ka (GT5) from basal unconsolidated cross-bedded of fluvial sands in Trench 5 (Table, 2, Fig. 8). This LGM age corresponds directly with equivalent aged aeolian deposits in both the Gidgealpa and Turra source-bordering dunes and along their associated northward trending linear dunes (Fig. 7). It would appear that Cooper Creek was supplying sand during the LGM and

that this fed contemporaneous dune formation north of the channel. The thin floodplain mud capping this trench indicates one of the more recent positions of the palaeo-Cooper in the area.

Trench 6 indicates an increased thickness of floodplain muds in a southward direction overlying an upward-fining bar sequence with steeply dipping (30°) cross beds yielding an OSL age of 85 ± 12 ka (GT6, Table 2, Fig. 8). The stratigraphy in this trench again indicates a north–westerly migrating Cooper Creek with corresponding late MIS 5 dune sediment dated in Gidgealpa dune (Fig. 7) and in both Turra aeolian and fluvial successions (see next section).

5.3. Turra dune and associated palaeochannels

Turra dune is a 2.5 km linear dune immediately east of the Gidgealpa dune (Fig. 2). Like Gidgealpa, the basal part of Turra dune

Fig. 8. Stratigraphy of floodplain trenches upwind of Gidgealpa dune (T1–T6) along with OSL and TL ages (grey and black symbols respectively) from fluvial sands and the overlying aeolian units. All stratigraphic sections are from western faces. Auger hole 1 from Fig. 7 is plotted in its true position relative to Trench 1.

is MIS 5 and older, ranging from 158 ± 46 to 103 ± 12 ka (Table 1, W2481, W2674, W2676). This MIS 5 basal core appears to extend the length of the dune with a TL age from a depth of 10 m of 82.1 ± 7 ka (Table 1, W2479). Turra dune differs to Gidgealpa in that it records no depositional evidence of the extensive MIS 4 aeolian unit recorded along the length of Gidgealpa dune. Rather, the upwind end of Turra dune (i.e. the southern end) records some depositional evidence in MIS 3 with a TL age of 41.4 ± 4 ka (Table 1, W2673) underlying the bulk of the dune that records sediment accumulation throughout MIS 2 (Table 1, Fig. 10). MIS 2 is represented in Turra dune with TL ages ranging from 12.6 ± 0.7 to 25.4 ± 2.5 ka (W2672, W2476–W2477, W3972–W3974) and the most upwind segment of the dune recording dune accumulation centred around the LGM. (Table 1, Fig. 10). The Holocene record for Turra dune exhibits a more variable history of accumulation than Gidgealpa dune with TL samples from 4 to 5 m depth yielding TL ages of 9.1 ± 0.9 to 8.9 ± 0.9 ka (W2675, W3971, Table 1, Fig. 10). TL ages from comparable depths in other downwind locations of the dune yielded TL ages of 4.3 ± 0.4 to 3.7 ± 0.6 ka (holes 4 and 6 in Fig. 10; Table 1, W2478 and W2480). While Bristow et al. (2007) have used this as evidence to infer dune elongation of over one kilometre in 9 ka, additional chronological evidence presented here and the correction of some of their auger hole locations suggests some localised blowouts and reworking between about 9 and 3.5 ka in the northern-most kilometre of the dune. There is no clear downwind linear progression.

A drill-hole transect on the floodplain immediately upwind (south) of Turra dune also highlights the chronostratigraphic relationship between the underlying fluvial successions (Katipiri Formation) and dune construction. Fluvial sands underlying the muddy floodplain range from 231 ± 54 ka at a depth of 9 m below the floodplain surface to 52.5 ± 3.8 ka at a depth of 2.5 m (Table 1, W2471 and W2475, Fig. 11) and generally provide good correspondence between the fluvial and aeolian successions. A fluvial sand from drill-hole 3 (Fig. 11) yielded a TL age of 118 ± 14 ka dune

(W2474, Table 1), matching both the dated aeolian sequences within Turra dune and both fluvial and aeolian sequences within Gidgealpa. A TL age of 84.9 ± 12.1 ka from drill-hole 1 at 4.5 m (W2472, Table 1, Fig. 11) also agrees well with the late MIS 5 dated aeolian sequence at Turra and Gidgealpa dune. Almost identical ages from this late MIS 5 fluvial sand unit have been obtained from Gidgealpa Trench 6 (Fig. 8) and at East Dog Bite Lake (W2246, Fig. 2, Table 1). MIS 4 fluvial sand bodies have been dated on the Turra transect at drill-hole 3 and 4 with TL ages of 74.7 ± 13.3 and 71.2 ± 6.8 ka (W2473, W2470, Fig. 11, Table 1) and at North Dog Bite Lake (W2247, Fig. 2, Table 1) and match closely the dated aeolian sequences in the upwind section of Gidgealpa dune (Fig. 7).

6. Discussion

6.1. Linear dune formation: evidence of significant downwind sand transport?

Despite linear dunes being widespread across the deserts of the world and indeed on other planets such as Venus and Mars, there is disagreement on how they form (see Lancaster, 1982), although it has been widely assumed that they extend linearly downwind. Bagnold (1941) and others (e.g. Tsoar, 1978) have suggested that they can form as a function of elongation of one arm of a barchan dune or alternatively with the blowing out of the nose of a parabolic dune (King, 1960). The downwind development of linear dunes behind an obstruction or downwind of a transverse dune has also been suggested (Warren, 1972; Tsoar, 1978) and in Australia, Twidale (1972) used the presence of dunes extending over playa surfaces as evidence that downwind extension was the primary mechanism for linear dune development. However, there are at least two types of linear dunes, with seif dunes essentially bare of vegetation and having crests that meander downwind, probably in response to bimodal wind directions. In contrast, broad crested linear dunes occur in Australia and are usually non-meandering

Fig. 9. Radial plots of single grain OSL De determinations for samples GT1–GT6.

and vegetated, generally increasing in clay content with depth. Bedding structures are commonly absent (Hollands et al., 2006; Bristow et al., 2007), probably because large bedforms are not involved in their formation and the smaller flow structures are destroyed by bioturbation. This makes it difficult to determine any formative wind direction and suggests that they have remained at least partially vegetated while forming.

Hollands et al. (2006) suggested that the linear dune downwind extension model may not always be the most appropriate and their work in the Simpson Desert suggested three possible scenarios for linear dune development. Their *long-distance*

transport extension model could apply with an abundant sediment supply and sufficient wind; the dunes would elongate downwind thereby becoming younger in that direction. Their *wind-rift extension model* could apply where sediment was sourced locally from the swales and is deposited in the lee of the advancing dune 'nose', a process that would also result in linear dunes declining in age downwind but with sand being transported only a short distance. Their *wind-rift vertical accretion model* would occur where the dune grows mostly vertically and uniformly along its length, with sediment supplied from the adjacent swales. In this case the morphology would be determined and oriented by the

Fig. 10. Chronology of Turra linear dune; (a) thermoluminescence (TL) ages along with isochrons. (b) Marine isotope stages with summary of dune deposition ages. See Fig. 7 for key.

wind but the dune itself would show few signs of advancing or declining in age downwind. Their work in the northern part of the Simpson Desert led them to conclude that little evidence existed for downwind extension with one group of dunes extending just 2 km over a period of 15 ka (Hollands et al., 2006). The bulk of the dunes in their study area appeared to have been formed by wind-rift vertical accretion.

The results for Gidgealpa and Turra dunes represent one of the most intensive chronological assessments of individual linear dunes in Australia. Gidgealpa shows no clear evidence of a downwind decline in the age of this 8 km long linear dune (Fig. 7). The

2.5 km Turra dune shows much the same but with a possible 500 m extension at its northern-most portion between about 9 and 3.5 ka, a rate of $\sim 100 \text{ mm a}^{-1}$. The basal age of sand at about the middle of Gidgealpa dune is in the order of 250 ka (auger hole 3 in Fig. 7) indicating that the base of this landform has been stable for a very long time. If this old sand was the source for that presently at the northern-most tip of the complex then this would represent a very slow rate of transport of about 20 mm a^{-1} , and then only if the sand was *actually* transported along the dune (the long-distance transport extension model of Hollands et al., 2006). Should the wind-rift extension model be the mechanism then even these

Fig. 11. Drill-hole transect of the floodplain upwind of Turra dune.

modest estimates would greatly overstate the extent of sediment transport. Paradoxically, however, there is a close correspondence in the age of the aeolian sediment to its fluvial source (Figs. 7–11). This means that the sand must have been deflated and blown rapidly northwards from the palaeochannels that lie several kilometres to the south. While transverse source-bordering dunes may well form as a result of such rapid sand transport, albeit over relatively short distances, our evidence suggests that these broad crested linear dunes are probably wind-rifted and essentially vertically accreted. They are not a landform that appears to be capable of significant downwind sand movement. This process of linear dune formation is similar to that presented by Rubin and Hesp (2009) where they describe linear dunes in the Qaidam Basin in China which form downwind of transverse dunes, becoming cohesive as the sediment incorporates mud and evaporates from the adjacent playas. Linking this type of dune construction to the late Quaternary aeolian record is therefore critical in determining the validity of such chronological records for palaeoclimatic analysis (Lancaster, 2008) and is discussed in the following sections.

6.2. The links between sediment delivery and dune construction on the Cooper Fan

The Lake Eyre basin appears to have been becoming increasingly arid during the mid to late Quaternary (Nanson et al., 2008). Results from this study highlight the antiquity of aeolian sediment on the Cooper Creek Fan, extending back over at least 250 ka. They also reveal the highly complex composite and polycyclic nature of transverse and linear dunes on the Cooper Creek Fan. These aeolian features are inherently linked to sediment delivery from the palaeo-Cooper. Their development reflects periods of large flows and considerable bedload supply, but probably during a period of gradually increasing aridity and seasonality with the dry seasons suitable for sand deflation and source-bordering dune formation. However, the dunes also reflect periods of mobilisation at times when there would have been no contribution of sand from the adjacent river. Separating the phases of source-bordering dune accumulation and subsequent stabilisation and the mobilisation of the linear dunes is discussed below.

The base of the linear dunes investigated yielded four MIS 5 TL ages of 105 ± 6 , 105 ± 7 (Gidgealpa) and 103 ± 12 , 116 ± 17 ka (Turra) and these correspond well (within age uncertainties) with three OSL ages from fluvial deposits representing the Katipiri Formation of 119 ± 11 , 118 ± 13 and 102 ± 19 ka and two TL ages from fluvial deposits of 118 ± 8 and 112 ± 9 ka from palaeochannels south (upwind) of both dune complexes. This suggests that, as recently proposed by Nanson et al. (2008), mid to late MIS 5 was a period of significant sediment delivery to the Cooper Creek Fan. Given the magnitude of the errors with both the OSL and TL it is not possible to clearly determine whether the dunes formed concurrently to sediment delivery from the palaeo-Cooper or whether they formed soon after. Given the vastly different sediment load of the MIS 5 palaeochannel to the contemporary muddy floodplain it is reasonable to assume that larger more competent rivers than today delivered coarse sand to the Cooper Creek Fan, but at a time of strongly seasonal flows allowing for deflation and sediment supply to the dunes immediately downwind.

Sandy alluvium of the Katipiri Formation underlying the contemporary muddy floodplain at Gidgealpa and Turra also yields ages of 85 ± 12 , 84.9 ± 12.1 (TL), 74.7 ± 13.3 (TL) and 71.2 ± 13.3 ka (TL). The early part of this phase accords well with sediment accumulation on the Gidgealpa dune at 86.3 ± 9 ka and, as shown by Maroulis et al. (2007), with sediment accumulation on source-

bordering dunes on Cooper Creek upstream of the Innamincka Dome (Durham and Chookoo dune, respectively) between 87 and 84 ka. Interestingly, there is no evidence for source-bordering dune accumulation in quite a large time gap between 84 and 70 ka, either above or below the Innamincka Dome. The next period of source-bordering dune formation is recorded from the upwind (southern) section of the Gidgealpa dune complex from 67.8 ± 3 to 53.1 ± 3.2 ka along with subsequent linear dune formation/mobilisation ~ 6 km immediately north in this same time interval (Fig. 7). Equivalent aged fluvial deposits are recorded on the Turra transect from 71.2 ± 6.8 to 52.5 ± 3 ka (TL).

The next most obvious phase of coeval river and dune activity on the Cooper Creek Fan was MIS2. This period, and specifically the LGM, has been demonstrated to be $7-9^\circ\text{C}$ colder than present in central Australia (Miller et al., 1997), and a time interval often interpreted to be arid. The most recent palaeochannel south of Gidgealpa dune dates at 22 ± 5 ka and is supported by evidence of enhanced discharges through the Innamincka Dome between 28 and 18 ka (Nanson et al., 2008). There are seven aeolian ages in the Gidgealpa and Turra dunes that correspond to this period of enhanced flow. The prevalence of LGM aeolian depositional records in Australia has previously been interpreted as evidence of cold and arid conditions (e.g. Fitzsimmons et al., 2007a) and an interval of increased windiness (e.g. Ash and Wasson, 1983) accompanied with playa deflation (Magee and Miller, 1998). However, evidence presented here demonstrates a depositional history of higher discharges, somewhat equivalent to that during previous MIS stages albeit probably of shorter duration (Nanson et al., 2008). This provides compelling evidence of an LGM in central Australia that was cold but with strong seasonality characterised by significant water and sediment delivery in a 'wet' season and pronounced dune deposition in the dry season. Nanson et al. (2008) also record enhanced flow through the Innamincka Dome in the early to mid Holocene, however, the lack of any identifiable associated palaeochannels near the Gidgealpa or Turra dunes suggests that the numerous Holocene aeolian ages in these dunes reflect reworking of existing dunes rather than the addition of new material since the LGM.

Transverse dunes (lunettes) formed largely of sand east of Lake Frome have been OSL dated by Fitzsimmons et al. (2007a,b) but, on the basis of the presence of a small amount of pedogenic mud they interpreted them as evidence of salinity and aridity. Cooper Creek abounds in pedogenic mud transported now and in the Quaternary in fresh water (e.g. Rust and Nanson, 1989). If Lake Frome's lunettes are regarded simply as evidence of full lake phases, as sandy lunettes normally are (e.g. Bowler, 1983), with water supplied from Cooper Creek, then Fitzsimmons et al.'s (2007) chronology of lunette formation at 111 ± 6 to 105 ± 6 ka, 57 ± 5 and 22 ± 2 ka fits well with that proposed here for episodes of pronounced fluvial activity.

6.3. The ambiguity of aeolian chronologies in deciphering the climatic record

Luminescence chronologies from aeolian successions are being increasingly used to discern late Quaternary climate change across the globe (e.g. O'Connor and Thomas, 1999; Duller and Augustinus, 2006; Telfer and Thomas, 2007), in particular periods of aridity and associated dune activity (e.g. Partridge, 1993; Stokes et al., 1997; Munyikwa, 2005; Fitzsimmons et al., 2007a) where palaeosol development is generally inferred to represent more humid conditions. However, what dune deposition in deserts actually represents climatologically is difficult to determine. Indeed, Chase (2009) in his recent assessment of the 219 luminescence ages from the Kalahari has questioned whether the dune record is an

indicator for aridity and surmises that aridity is the unlikely dominant forcing mechanism for dune activity in southern Africa.

To investigate this we examine the most complete aeolian records from the Australian dunefields. Firstly, desert dunes need to be separated into those that are source-bordering and therefore fed with sand from rivers and lakes at times of higher water input, and those that are essentially a product of aridity and associated aeolian erosion and transport. Source-bordering dunes can in fact reflect humid periods of sand accumulation, and also arid phases when an existing dune is partially or wholly reworked. Dune sediments are obviously best preserved if periods of dune activity (determined largely from chronostratigraphies derived from the deposition of dune sand) are followed by a humid phase leading to the stability (i.e. palaeosol development) and preservation of the dated unit. This is true of source-bordering as well as aridity-controlled dunes. Dune sediments, however, do not provide unequivocal evidence as to what causes a depositional episode (nor the associated erosion episode that provided the aeolian material). Such processes may be controlled by immediately local factors (e.g. the presence of localised dune blowouts), broader local factors (e.g. sediment supply from a river or lake) or regional trends in climate (and resulting vegetation).

As a means of addressing this issue we present two age-depth profiles for Gidgealpa dune along with the other most robust age-depth profiles from previously published datasets for the Strzelecki and Tirari Deserts (Fitzsimmons et al., 2007a), all within a 300–400 km radius of each other. This provides a means of comparing the accumulated depth of dune sediment over comparable time periods (acknowledging that it represents a stacked but incomplete record). This method weights the dating to the volume of material that accumulates over each period of the record; it acts to filter out the significance of ages that represent little volume change. Such profiles for the most complete aeolian records of the Strzelecki Desert are compared in Fig. 12a and demonstrate the variability in accumulation rates between dunes in the same dunefield within the same time interval (see Fig. 1 for location of sites). Three of the five age-depth profiles compared in this figure are linear dunes developed on transverse ridges (Gidgealpa hole 2, hole 4 and Moolawatana) with the other two being more simple linear dunes. If linear dunes were good indicators of regional climatic processes then it would be assumed that age-depth profiles between dunes, but within the same dunefield, would show similarities (potentially representing regional dune activation – see Fitzsimmons et al., 2007a). The lack of similarity is shown by statistically different slopes in age-depth models for dunes within the Strzelecki Desert (Fig. 12b).

The variability presented in Fig. 12a clearly shows that neither the simple linear dunes or the composite transverse/linear ridges share the same accumulation patterns. The only similarities presented in this comparison is for within-dune accumulation rates for Gidgealpa dune. Furthermore, the age-depth profiles for the composite transverse/linear ridges show considerable differences that may reflect differing source locations with Gidgealpa dune being located at the proximal head of Cooper Creek Fan in contrast to Moolawatana being located adjacent to the distal lake basins (Fig. 1). This notion of differing dune types recording differing degrees of dune deposition has recently been examined in the Kalahari Desert where considerable intra-dunefield variability has been demonstrated (Telfer and Thomas, 2007; Stone and Thomas, 2008). The degree of variability in dune accumulation rates between linear dunes within the same dunefield also occurs when dunes from within the Strzelecki Desert are compared against those from the Tirari Desert (essentially a continuation of the same dunefield) (Fig. 12c). As can be seen, accumulation rates differ both within the Tirari desert and compared against those of the Strzelecki. This suggests that there has been considerable variation

Fig. 12. (a) Vertical accretion rates for the Strzelecki Desert derived from TL chronology of Gidgealpa dune (this study) and OSL chronology and palaeosol location (wavy symbol) from Fitzsimmons et al. (2007). See Fig. 1 for location of sites. (b) Vertical accretion rates for the Strzelecki Desert expressed as linear regressions with 90% confidence intervals. (c) Vertical accretion rates for the Tirari Desert derived from Fitzsimmons et al. (2007).

in morphological responses of linear dunes (erosion and deposition) to the same climatic periods of the last glacial cycle.

Broad correlation between dune construction and water/sediment delivery on the Cooper Creek Fan can be made with other

aeolian archives from Southern Hemisphere deserts over the last glacial cycle. This is most pronounced in MIS 4 and MIS 2. Fitzsimmons et al. (2007a) present a peak in aeolian activity in the Strzelecki and Tirari deserts that occurred between 73 and 66 ka, which agrees well with dunefields in the Kalahari where dune mobilisation occurred between 77 and 76 ka (Telfer and Thomas, 2007) and between 73 and 63 on the western margin of South Africa (Chase and Thomas, 2007). Whilst it would appear that source-bordering and linear dune construction on the Cooper Creek Fan (occurring from 67 and 53 ka) record might proceed such a Southern Hemisphere period of aeolian activity, the climatic significance is less clear. In Australia the peak in glaciation in the southeast Australian highlands occurs after the pronounced peak in aeolian activity (around 59 ka, Barrows et al., 2001) while the Tasman Sea dust record registers an increase in dust concentration from approximately 74 ka but with the peaks occurring around 61 and 52 ka (Hesse, 1994). The Antarctic ice cores also register the MIS 4 peak in dust around 68 ka (EPICA, 2006), towards the end of this period of dune mobilisation. As such, whilst broad correlations can be made between aeolian records the palaeoclimatic implications for factors such as wind strength/speed, precipitation and aridity are equivocal.

Recent work by Stone and Thomas (2008) from the Mariental–Stampriet region in the southern Kalahari Desert demonstrate the importance of sampling resolution for determining periods of aeolian activity, with defined intervals appearing when sampling resolution is reduced. This notion of sampling resolution more than likely has important implications for existing research in the Australian dunefields for two reasons. Firstly, there are fewer than ten individual linear dunes in the Strzelecki and Tirari Deserts where detailed records exist (more than four samples per dune, Fig. 12). Secondly, of these records mean sampling resolution is 1.75 m, potentially allowing for more readily discernible periods of aeolian activity, but which are an artefact of resolution. We believe that examining and separating dune chronologies based on dune type, along with an assessment of the effects of sampling resolution holds good promise for palaeoclimatic research in the Australian dunefields. This approach is currently being investigated for other Southern Hemisphere dunefields (Stone and Thomas, 2008; Chase, 2009) and is an important step in critiquing the validity of aeolian archives for palaeoenvironmental research. Detailed single-grain analyses of both dune sediment and palaeosols, linked to the internal stratigraphy, is ultimately the future for determining how aeolian dunes are formed and their significance in the late Quaternary climatic record.

7. Conclusion

We demonstrate with a TL and OSL chronology that dune sands on the Cooper Creek Fan in the Strzelecki Desert are up to 250 ka (MIS 7) in age but have mostly been added to or reworked at times between MIS 5 and the LGM. They have been derived from adjacent fluvial sands of the Katipiri Formation, now buried by a muddy floodplain overburden, that dates from time periods broadly corresponding to those for the dunes. Unlike the mud-dominated channels and floodplains of today, these fluvial sands represent more competent rivers transporting abundant bedload. At these times of water and sediment delivery onto the Cooper Creek Fan, source-bordering sands were blown northward out of the river channels in the initial phase of linear dune development. Sand deposition during dune development over the last glacial cycle was most likely linked directly to sediment delivery from the palaeo-Cooper under a strongly seasonal flow regime that exposed extensive sandbars on the channels. The accumulation of these aeolian landforms does not represent phases of pronounced aridity.

Indeed, we demonstrate considerable intra-dunefield variability when the best available aeolian chronologies for the central deserts of Australia are compared, suggesting there has been considerable variation in morphological responses of linear dunes to the same climatic periods of the last glacial cycle.

Source-bordering dunes formed during periods of enhanced river flow and sand supply on the Cooper Creek Fan from ~120 to 100, ~85 to 80 ka and from ~68 to 53. The linear dunes that form immediately downwind of these source-bordering features date from mid MIS 4/early MIS 3 through to MIS 2. The LGM was also associated with enhanced flows and sediment delivery to the Cooper Creek Fan and the associated supply of dune sediment from 28 to 18 ka. There is however, no evidence of dunes being supplied from Cooper Creek since the LGM and we suggest that the Holocene cap of the linear dunes has been 'quarried' from old deposits in the transverse dunes still visible in the swales.

While considerable sand has been blown out of the channels to form extensive dune complexes over the surface of the Cooper Creek Fan (Fig. 2), wind-driven northward migration of this sand has been very slow with surficial linear dunes exhibiting limited or no northward migration. Clearly, long-distance transport of sand has played no role in the formation of linear dunes on the Cooper Creek Fan. We suggest that a wind-rift extension or wind-rift vertical accretion model is the dominant mode of formation for the stabilized linear dunes in this section of the Strzelecki Desert with the bulk of sediment supplied from adjacent swales.

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