Alluvial evidence for major climate and flow regime changes during the middle and late Quaternary in eastern central Australia

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Abstract:
As a low-gradient arid region spanning the tropics to the temperate zone, the Lake Eyre basin has undergone gentle late Cenozoic crustal warping leading to substantial alluvial deposition, thereby forming repositories of evidence for palaeoclimatic and palaeohydrological changes from the Late Tertiary to the Holocene. Auger holes and bank exposures at five locations along the lower 500 km of Cooper Creek, a major contributor to Lake Eyre in the eastern part of the basin, yielded 85 luminescence dates (TL and OSL) that, combined wit a further 142 luminescence dates from northeastern Australia, have established a chronology of multiple episodes of enhanced flow regime from about 750 ka to the Holocene. Mean bankfull discharges on Cooper Creek upstream of the Innamincka Dome at 250–230 ka or oxygen isotope stages (OIS) 7–6 are estimated to have been 5 to 7 times larger than those of today, however, substantially less reworking has occurred during and after OIS 5 than before. Lower Cooper Creek appears to have similarly declined. In the Tirari Desert adjacent to Lake Eyre there is evidence of widespread alluvial activity, perhaps during but certainly before the Middle Pleistocene, yet the river became laterally restricted in OIS 7 to 5. While the Quaternary has been characterised by a dramatically oscillating wet–dry climate, since oxygen isotope stage OIS 7 or 6 there has been a general decline in the magnitude of the episodes of wetness to which the eastern part of central Australia has periodically returned. During the last full glacial cycle, Cooper Creek's periods of greatest runoff and sand transport were not during the last interglacial maximum of OIS 5e (132–122 ka) but later in OIS 5 when sea levels and global temperatures were substantially below those of 5e or today. Fluvial activity returned in OIS 4 and 3, but not to the extent of mid and late OIS 5; strongly seasonal but still powerful flows transported sand and fed source-bordering dunes in OIS 5 and 3. This chronology of fluvial activity in the late Quaternary broadly coincides with that for rivers of southeastern Australia and suggests that the wet phases in eastern central Australia have not been governed as much by the northern monsoon as by conditions in the western Pacific close to the east coast both north and south. Flow confinement within the Innamincka Dome has locally amplified Cooper Creek's energy, and here evidence exists for short but high-magnitude episodes of flow during the Last Glacial Maximum and in the early to middle Holocene, conditions that were capable of forming large palaeochannels but that were not long-lived enough to rework the river's extensive floodplains elsewhere along its length.

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Introduction

Cecil Madigan (1946), geographer, scientist and explorer, described the Simpson Desert as the "dead heart" of Australia, adopting the term from Gregory (1906) who undertook fossil-collecting expeditions on Warburton Creek near Lake Eyre in 1901-02 (Fig. 1). These fossils, along with the alluvial record of the basin, provide evidence for episodes in the Quaternary when large powerful rivers crossed a wetter continent and filled Lake Eyre (e.g. Nanson et al., 1992, 1998; Magee et al., 1995,2004) and the rivers and lakes supported a diverse ecology of now mostly extinct marsupial, avian and reptilian megafauna (Tedford and Wells , 1990).

Central Australia has undergone truly remarkable shifts in climate and flow regime during the late Cenozoic with climatic variation achieving its maximum amplitude and frequency during the Quaternary. The purpose of this paper is to present stratigraphic evidence for the spatial distribution, magnitude and chronology of these changes in the arid centre of Australia, specifically northeast of Lake Eyre along the course of one of the lake's major contributories, Cooper Creek (Fig.1). This part of the lake basin has a long accretionary record for the late Cenozoic, a period that coincided with generally drying conditions globally. Unlike the world's high latitude and high altitude areas that were so severely impacted by the direct effects of

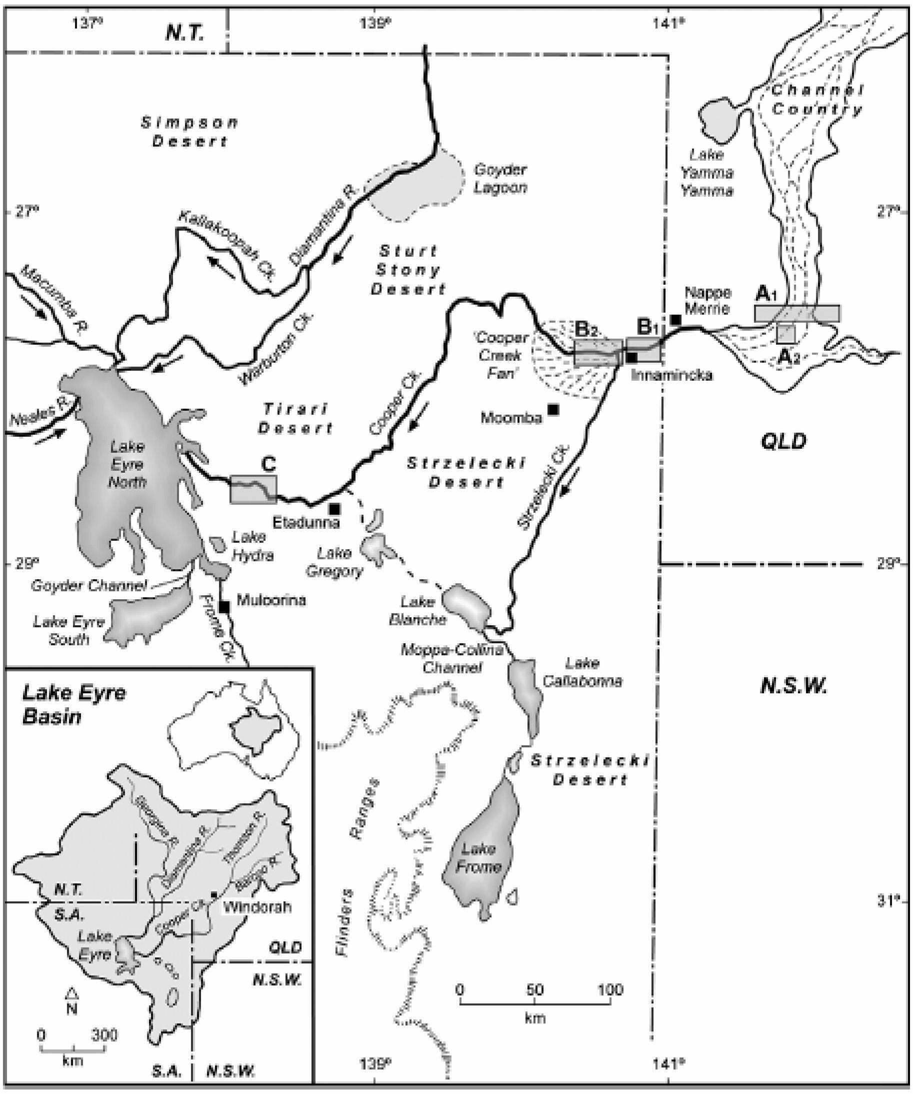


Fig. 1. The study areas along Cooper Creek, located as A1, A2, B1, B2 and C. The inset map shows the Lake Eyre basin within Australia.

glaciation, the Quaternary over much of Australia has represented essentially a continuum with what was happening during the preceding Tertiary, albeit that the wet-dry variability became more dramatic. Environmental changes in arid Australia as far back as the Middle Pleistocene now lie within the range of luminescence sedimentary dating. The Lake Eyre basin presents a long and comprehensive alluvial history of Australia's “dead heart” and, as such, offers detailed insights into past environmental changes in this now largely dry continent. Important questions remain to be answered. Just how wet was Australia at times during the Quaternary, what has controlled the wet-dry cycles over this period, and has there been an overall drying trend in the mid to late Quaternary? The stratigraphic alluvial record along the lower ~500 km of Cooper Creek is interpreted here as a proxy for changes in rainfall and runoff in the eastern part of central Australia.

2. The Lake Eyre basin

Latitudinally spanning the tropics to the temperate zone and characterised by a centripetal drainage system, the 1.14 million km^2 Lake Eyre basin (Fig. 1) forms a shallow depression that preserves an extensive array of fluvial, aeolian and lacustrine deposits recording climate and flow regime changes, evidence that is particularly detailed for the past ~300 ka. At present, strongly seasonal dryland rivers in the eastern Lake Eyre basin, including Cooper Creek and the Diamantina and Georgina Rivers, direct monsoon floodwaters through a low-gradient region of western Queensland known as the Channel Country (Fig. 1). Here the landscape is characterised by an intricate array of fluvial and aeolian landforms that include extensive and commonly dry muddy floodplains with braided and reticulate surficial channels and occasional aeolian dunes interspersed with entrenched anabranching channels and permanent waterholes (Nanson et al., 1986; 1988; Rust and Nanson, 1986). Downstream of Innamincka on Cooper Creek and from Goyder Lagoon on the Diamantina–Georgina Rivers (Fig. 1), these rivers are remote and difficult to access so have been less well studied. Yet every decade or so, usually requiring a La Nina event, floodwaters reach Lake Eyre, the basin's depocentre. With an area of 9355 km^2 and its floor 6 to 15 m below sea level, this lake is one of the world's largest salt playas.

Formed by the confluence of the Barcoo and Thomson Rivers and fed from the western slopes of the Great Dividing Range, Cooper Creek has a catchment area of 306 000 km^2. In terms of the geomorphology and Quaternary history (e.g. Nanson et al., 1986, 1988, 1992; Rust and Nanson,1986; Knighton and Nanson,1994a; Fagan and Nanson, 2004; Maroulis et al., 2007), hydrology (Kotwicki, 1986; Kotwicki and Isdale, 1991; Knighton and Nanson, 1994b, 2000, Knighton and Nanson, 2001), floodplain sediments and soils (Nanson et al., 1986; Rust and Nanson, 1989; Maroulis and Nanson, 1996) and aquatic ecology (e.g. Kingsford et al.,1999; Puckridge et al., 2000), Cooper Creek is the most intensively described Channel Country system. Furthermore, Lake Eyre has also been subject to detailed palaeoenvironmental study (Magee et al., 1995; 2004; Magee and Miller, 1998; Nanson et al., 1998; DeVogel et al., 2004) and, to a lesser extent, so too have the streams entering the western side of the lake (Croke et al., 1996, 1998).

2.1. Climate and hydrology

The arid climate of the Lake Eyre basin displays long hot summers interrupted by short cool winters with marked diurnal temperature variations. The principal synoptic influences on present rainfall in the Lake Eyre drainage basin are in the form of incursions of moist tropical air that pass over the northern tablelands and eastern Great Dividing Range during the summer months (Allan, 1990). Mean annual rainfall decreases markedly from about 400–500 mm in the northeast of the basin to about 100 mm near Lake Eyre, with the variability of rainfall, among the highest recorded in Australia, being caused by vagaries of tropical cyclone and monsoon–trough conditions (Kotwicki, 1986; Kotwicki and Isdale, 1991). Mean annual evaporation (Class A Pan) grades progressively from about 2400 mm/a in the northeast to more than 3600 mm/a near Lake Eyre. Mean daily maximum temperatures (1972–1999) at Moomba, near the centre of the Lake Eyre basin (Fig. 1), are 37.5 °C in January and 19.2 °C in

July, with mean daily minimums in the same months, 23.3 °C and 6.3 °C, respectively. Annual rainfall at Moomba (1972–2005) has averaged 206 mm/a with a mean monthly maximum of 40.0 mm in January and a mean monthly minimum of 8.6 mm in August.
Cooper Creek's mean annual runoff is characterised by high streamflow variability with long periods of low or zero flow and occasional periods of extremely high discharge. Mean annual runoff decreases over a downstream distance of ~420 km from 3.05 km^3 at Currareva to 1.26 km^3 at Nappa Merrie (Fig. 1), with high C_v values (hydrologic variability) by world standards (1.61 and 2.20, respectively) (Puckridge et al., 1998; Knighton and Nanson, 1994a, 2001).
On Cooper Creek, the largest flood on record occurred in January– February 1974, with maximum daily discharges of 25,000 m^3/s at Currareva (near Windorah) and 5800 m^3/s at Nappa Merrie (Fig. 1). This topical climatic event resulted in the simultaneous flooding of all major watercourses in the Lake Eyre drainage basin and the subsequent inundation of Lake Eyre to its highest recorded level. The dominance of this flood at both Currareva and Nappa Merrie contrasts with the mean annual flood which is relatively small at both stations (96.7 m^3/s at Currareva and 40.0 m^3/s at Nappa Merrie) and generates extremely steep relative flood magnitude ($Q/Q_{2.33}$) curves (Knighton and Nanson, 1994a, 2001). These data illustrate the enormous transmission losses between Currareva and Nappa Merrie as the river progresses towards the increasingly arid centre of the basin.

2.2. Soils and vegetation

Heavily cracked clays (vertisols) with a high proportion of smectite (montmorillonite) dominate the present Cooper Creek floodplain in the Channel Country and, because of the abundance of dunes, to a lesser extent downstream of the Innamincka Dome. These self-mulching soils form a low-relief gilgai surface pattern and their low-density sand-sized mud aggregates play a vital role in the development of braid-like channels on the floodplain surface (Nanson et al., 1986, 1988; Rust and Nanson, 1989; Maroulis and Nanson, 1996; Fagan and Nanson, 2004).

Coolabah (Eucalyptus microtheca) and river red gum (E. camaldu-lensis) form a narrow riparian woodland that dominates the anastomosing channels and waterholes (billabongs). At places on the floodplains and on the base and lower slopes of the dunes, sandhill canegrass (Zygochloa paradoxa) and several Acacia spp., with other desert shrubs grow. Forbes and grasses on the upper slopes of the dunes vary annually and seasonally in terms of cover density. Lignum (Muehlenbeckia florulenta) is common along the channels and adjacent to the many permanent waterholes.

2.3. Geology

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 Cainozoic Lake Eyre Basin (Tedford et al., 1986; Wells and Callen, 1986; Wrecker, 1989; Krieg et al., 1990; Alley, 1998) (Fig. 2). Based on observations in southeastern Australia, their deformation is likely to be ongoing today (Sandiford, 2003) and their basin histories are essential to understanding the arrangement of the contemporary drainage systems and the division of the depositional settings investigated here.

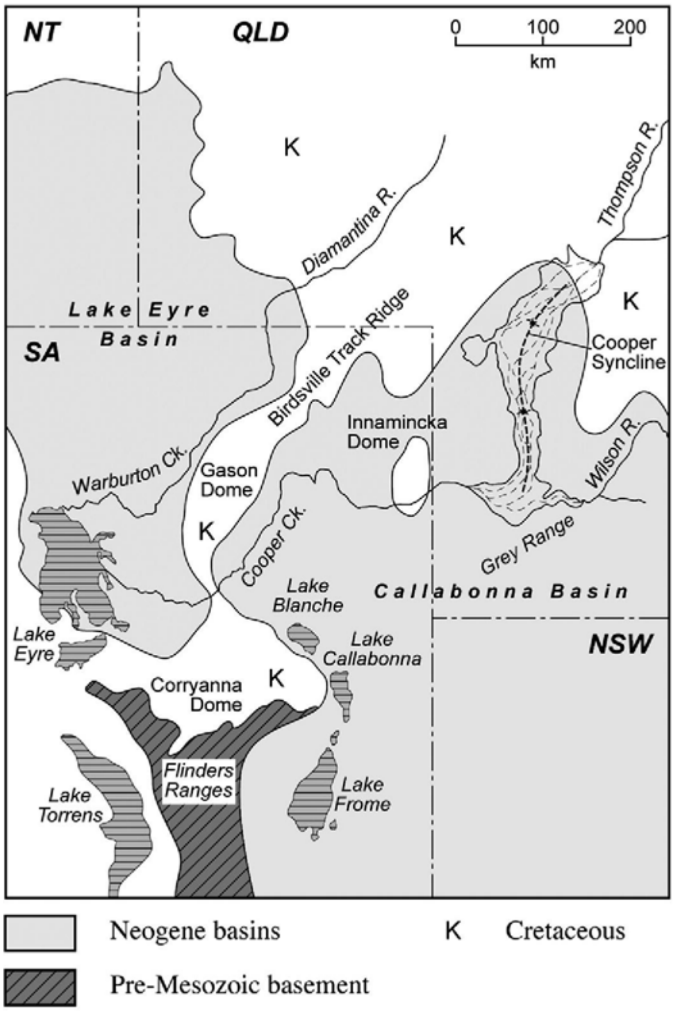


Fig. 2. The Cretaceous and Neogene geology of the relevant field area within the Lake Eyre basin (from Wells and Callen, 1986; Alley, 1998).

2.3.1. *The Mesozoic*

The modern landscape has been greatly influenced by the structural and lithological features of the Eromanga Basin (Early Jurassic-Late Cretaceous), a broad intracratonic structure of mostly terrestrial clastic strata (with a thin Early Cretaceous marine transgression) upturned on its eastern margin. Deformation of this basin occurring during the mid-Tertiary resulted in the development of extensive northwest to northeast-trending anticlines that control the broad topography and drainage patterns of the present surface. In western Queensland, Cooper Creek flows south along one of the intervening depressions, the extensive north-trending Cooper Syncline (Fig. 2). Northwest of the Grey Range, it takes an abrupt turn westward along the Wilson Depression, passing through the Innamincka Dome between Nappa Merrie and Innamincka where it enters South Australia. The continuing rise of the dome across the river's path has contributed upstream to the spectacular array of low-gradient floodplains, channels and waterholes that have been described in detail by Nanson and co-workers, and downstream west of Innamincka township to the low-gradient 'fan' of interrelated channels, terminal lakes and source-bordering dunes described by Coleman (2002).

Despite having an alluvial connotation, the 'Channel Country' of western Queensland is predominantly an erosional landscape of broad shallow valleys between structural highs that are formed mostly of Late Cretaceous Winton Formation, a terrestrial mudstone and lithic sandstone representing a period of northward regional drainage (Senior, 1968). The ridges are commonly pedogenically silicified and characterised by low highly-fretted erosional escarpments, mesas and extensive gibber-strewn pediments. The wide intervening low-gradient floodplains receive their fine-grained alluvia from weathered finer Cretaceous sediments and their shrinking-swelling clays from the Cainozoic basalts in northwestern Queensland.

2.3.2. The Cainozoic

This period has been characterised by a wide range of environmental conditions revealed in a time-series of sub-basins illustrating a generally drying trend through to the late Quaternary. Unconformably overlying the Winton Formation along the Cooper Creek valley in western Queensland is the Glendower Formation (Senior et al., 1978) (termed Eyre Formation in South Australia), a partly silicified fluviatile arenite with lesser conglomerate, and with arenaceous components becoming finer, swampy and more laminated downstream. Late Palaeocene to Middle Eocene in age, it represents a warm wet phase of deposition in the Lake Eyre basin, a landscape dominated by river systems, including the precursor to Cooper Creek, forming deposits over 100 m thick with carbonaceous clays (swamp deposits) farthest southwest. Slight warping east of Lake Eyre during the Oligocene created the Corryanna and Gason Domes and associated Birdsville Track Ridge that separated with an uplifted silicified surface (Sturts Stony Desert) the westward Lake Eyre and eastward Callabonna Basins (Wells and Callen, 1986) (Fig. 2). Upstream of this doming in the Callabonna Basin the Namba Formation, and downstream of it, nearer the present lake, the equivalent Etadunna Formation are Late Oligocene to Early Miocene in age and represented a drier phase of shallow freshwater lakes.

The Tirari Formation is interpreted as representing the next stage of increasing aridity towards the Quaternary. It is characterised by a red-brown or brick-red mudstone and muddy sandstone with interstitial gypsum nodules and rhizomorphs and capped with a massive gypsum crust. Magnetically reversed, the upper part is interpreted as older than the Brunhes-Matuyama boundary (~780 ka; Tedford and Wells, 1990). However, with its base magnetically normal, it is probably Late Pliocene or Early Pleistocene in age (Gilbert Chron 3.9-3.4 Ma; Tedford et al., 1992). It is interpreted as a fan-delta system of channels representing a period drier than previously but substantially wetter than much of the Quaternary, with extensive floodplains, expanded lacustine sediments and abundant megafauna present. It probably ended under strongly evaporative conditions with elevated saline watertables and gypsum formation (Tedford et al., 1986).

The Early to Middle Pleistocene is represented by ongoing alluviation with deposition of the Kutjitara Formation (Wells and Callen, 1986), fluvial channels cut and filled into the Tirari Formation with coarser, more poorly sorted medium to fine sands and red mudstone that is less intensely gypcreted than the Tirari Formation. It has aeolian and lacustrine facies near Lake Eyre. This is overtopped with Middle to Late Pleistocene Katipiri Formation, mostly unconsolidated, white fine sand showing festoon cross-stratification sets interspersed with mud drapes, with thin basal conglomerates formed of clasts of gypsum- and carbonate-cemented lithic fragments and some older rocks (Tedford et al., 1986). It is similar to Kutjitara Formation but less weathered.

The abundant fossil remains of marsupial and reptilian megafauna presented in the Tirari, Kutjitara and Katipiri Formations (Wells and Callen, 1986; Krieg et al., 1990; Tedford and Wells, 1990) indicate that these animals utilised periods of greatly enhanced pluvial conditions during the mid to late interglacials and interstadials to occupy the now-arid Australian interior via the river corridors and lake systems. They survived until ~46 ka, a date broadly coincident with the arrival of humans who have been attributed as the cause of megafaunal extinction continent-wide (Roberts et al., 2001). The Katipiri Formation (named in South Australia as the Katipiri Sands by Stirton et al. (1961), although essentially the same unit extends up Cooper Creek into western Queensland) is the focus of this paper. It has been intensively studied stratigraphically (Wells and Callen, 1986; Tedford et al., 1986; Tedford and Wells, 1990; Tedford et al., 1992; Magee, 1997) and provides a remarkable repository of evidence for Middle to Late Pleistocene climate and flow regime changes (Nanson et al., 1986, 1988; Rust and Nanson,1986; Nanson and Tooth,1999; Maroulis et al., 2007).

3. Study sites in geological context

In the context of the domes and basins through which Cooper Creek passes, Middle to Late Pleistocene alluvial sequences are examined here at five separate locations along the creek. First, in a vertical sequence of what is essentially the Katipiri Formation beneath the Shire Road (Site A_1, Fig.1), alluvium trapped in the Cooper Syncline upstream of the rising Innamincka Dome (Fig. 2) is described and dated from the Early and Middle Pleistocene to the Holocene. Second, at Chookoo nearby (Site A_2, Fig. 1), two distinct fluvial units overlie an older one again and have given rise to associated source-bordering dunes during the Late Pleistocene (Maroulis et al., 2007). At a third location within the Innamincka Dome (Site B_1, Fig. 1), augering revealed the approximate dimensions of Holocene palaeochannels and evidence of the magnitude of Last Glacial Maximum (LGM) channel activity. At the fourth location, the Katipiri Formation is exposed by migration of a meander bend of Cooper Creek at Tilcha Waterhole and Wills Grave on the ‘Cooper Creek Fan’ downstream of the Innamincka Dome in the northwestern part of the Callabonna Basin (Site B_2, Figs.1 and 3a). At the fifth location, we examine both the Tirari and Katipiri Formations on lower Cooper Creek in the Tirari Desert in the Lake Eyre basin, east of Lake Eyre and downstream of the Gason and Corryanna Domes (Site C, Figs. 1 and 3b). These diverse locations provide tectonically emplaced windows through which to view the chronology and magnitude of flow regime change during the Pleistocene along middle and downstream Cooper Creek in the now-arid Lake Eyre basin.

4. Luminescence and U series dating

A large amount of the chronostratigraphic work was undertaken in this study using TL while various optically stimulated luminescence (OSL) dating methods were still being developed (large aliquot, multiple and single aliquot and single grain).

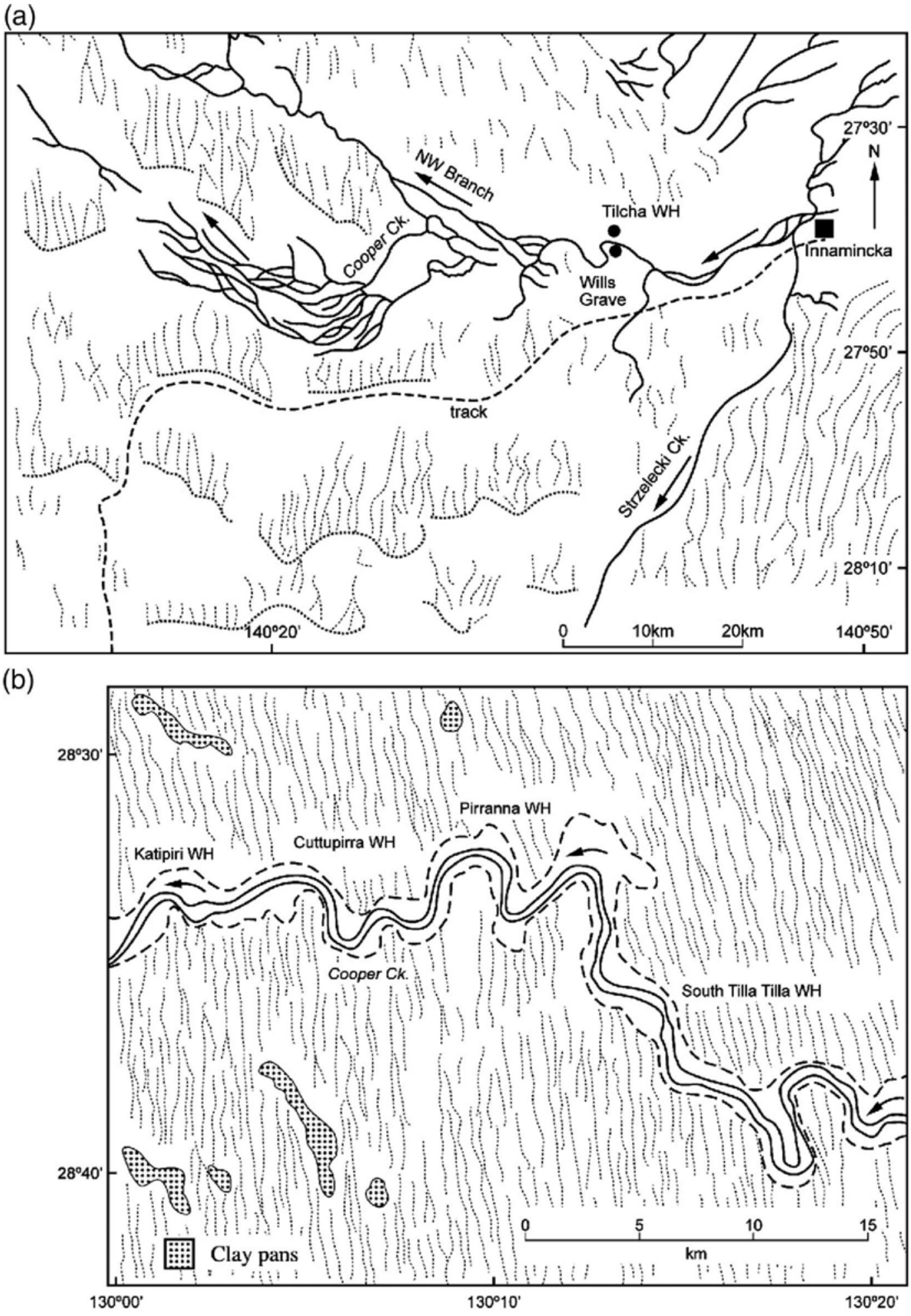


Fig. 3. a. The path of Cooper Creek in the Strzelecki Desert downstream of Innamincka (Area B2 in Fig. 1) showing the locations of Tilcha Waterhole (WH) and Wills Grave. b. The incised channel of lower Cooper Creek in the Tirari Desert showing the extensive adjacent linear dunefield and the locations of Katipiri, Cuttapirra, Parranna and South Tilla Tilla Waterholes (Area C in Fig. 1). source-bordering dunes are dark dotted lines and northward aligned linear dunes are lighter dotted lines.

Although usually not a problem for aeolian samples in desert areas with abundant sunlight, TL can suffer from incomplete bleaching for sediments transported under water. As a consequence two comparative studies involving 11 OSL analyses and 10 TL analyses have been undertaken to establish if the TL data obtained from alluvium within the Cooper Creek floodplain are indeed comparable to OSL determinations from the same sample or location.

One of the comparative studies (upper floodplain material near site A_1) was conducted using large aliquot OSL analyses of material isolated from the same samples as used for the TL analyses, whereas the other study (alluvial sands at site B_2) was undertaken using single grain OSL dating of additional samples collected from the same strata and at the same location sampled for TL analysis (although not identical samples). The TL data for all samples is shown in Table 1 and the results of the TL/OSL comparisons are presented in Table 2.

Sample Location	Sample no.	Temperature plateau region (°C)	Palaeodose (Gy)	K content (%)	Moisture content (%)	U+Th specific activity (Bq/kg)	Annual radiation (mGy/year)	TL age (ka)
Shire Road transect	W2030	300–500 Sloping	19.8±1.7	0.750±0.005	3.2±3	47.8±1.4	1875±32	10.5±0.9
	W2031	300–450	30.8±2.7	0.305±0.005	14.5±3	24.4±0.8	808±24	38.1±3.5
	W2032	300–450	34.9±3.1	0.355±0.005	1.4±3	22.4±0.6	986±51	34.5±3.6
	W2033	300–500	37.2±3.8	0.215±0.005	7.6±3	18.2±0.5	638±25	58.3±6.3
	W2034	325–500	230±22	0.205±0.005	19.8±3	20.5±0.6	568±22	405±43
	W2035	325–500	399±64	0.270±0.005	18.0±3	29.8±0.8	779±14	512±83
	W2036	325–500	564±41	0.280±0.005	19.0±3	29.3±0.9	762±13	740±55
	W2037	300–500	71.2±6.5	1.050±0.005	6.5±3	65.8±1.3	2464±30	28.9±2.6
	W2296	300–500	37.5±4.4	0.305±0.005	0.5±3	21.8±0.7	894±28	41.9±5.1
	W2038	325–500	117±10	0.600±0.005	19.3±3	54.5±1.5	1514±28	77.5±6.6
	W2039	325–500	178±20	0.385±0.005	15.4±3	53.1±1.4	1388±20	133±15
	W2040	275–500	30.4±2.7	1.150±0.005	10.7±3	79.0±2.3	2590±54	11.3±1.0
	W2041	325–500	97.7±8.4	0.165±0.005	0.3±3	13.1±0.4	534±27	183±18
	W2044	325–500	135±16	0.285±0.005	0.5±3	12.5±0.4	685±26	197±24
	W2045	325–500	106±10	0.315±0.005	2.3±3	17.7±0.5	772±26	137±14
	W2046	325–500	311±119	0.200±0.005	19.2±3	27.6±0.9	685±23	454±174
	W2047	300–500	36.3±3.6	1.000±0.005	8.1±3	74.3±2.3	2517±39	14.4±1.4
	W2048	300–500	305±149	0.800±0.005	2.3±3	41.9±1.3	1800±31	169±83
	W2049	300–500	158±30	0.900±0.005	11.1±3	82.8±2.6	2499±41	63.1±12.2
	W2050	325–500	>218±26	0.650±0.005	6.7±3	38.9±1.2	1486±29	>147±18
	W2051	300–500	139±10	1.050±0.005	10.4±3	78.6±2.3	2586±38	53.9±4.0
	W2052	300–500	358±54	0.600±0.005	16.0±3	88.9±2.7	2180±39	164±25
Cullyamurra Waterhole and Lake Marroocutchanie	W2250	325–500	138±18	0.500±0.005	7.6±3	33.9±0.9	1268±27	109±14
	W2580	275–500	7.7±1.0	0.023±0.005	0.2±3	10.3±0.3	384±26	20.1±2.9
	W2581	275–500	9.2±0.8	0.500±0.005	2.6±3	43.0±1.4	1523±32	6.0±0.5
	W2582	300–500	66.9±5.8	0.650±0.005	6.9±3	86.6±2.7	2403±43	27.8±2.5
	W2583	275–500	2.9±0.4	0.325±0.005	0.7±3	17.0±0.5	836±27	3.5±0.5
	W2584	300–500	13.7±1.0	0.420±0.005	3.6±3	38.2±1.2	1283±30	10.7±0.8
	W2669	300–500	7.0±0.9	0.205±0.005	0.5±3	17.1±0.4	717±27	9.7±1.3
	W2670	300–500	26.7±3.0	0.600±0.005	6.5±3	40.1±1.1	1456±25	18.3±2.1
	W2671	300–500	24.2±2.9	0.115±0.005	17.0±3	13.6±0.4	386±11	62.5±7.7
	W3482	300–500	17.0±0.8	1.2±0.05	13.9±3	75.4±2.3	2562±59	6.6±0.4
	W3483	300–500	67.3±3.2	0.9±0.05	7.9±3	54.8±1.0	2038±56	33.0±1.8
	W3484	300–500	6.0±0.3	0.85±0.05	5.3±3	51.6±1.5	1988±60	3.0±0.2
	W3485	275–500	5.6±0.5	0.70±0.05	3.9±3	46.2±1.4	1741±60	3.2±0.3
	W3486	300–500	5.1±0.4	0.430±0.005	1.7±3	25.7±0.7	1127±27	4.5±0.4
	W3487	300–500	58.3±2.7	0.65±0.05	3.7±3	31.5±1.0	1402±59	41.5±2.6
Tilcha Waterhole	W2232	300–500	14.7±1.0	0.435±0.005	5.6±3.0	23.9±0.7	1028±26	14.3±1.0
	W2233	300–500	29.8±2.4	0.550±0.005	1.7±3.0	34.9±0.8	1393±28	21.4±1.8
	W2234	300–425	27.9±2.0	0.550±0.005	2.2±3.0	35.6±1.1	1387±26	20.1±1.5
	W2235	300–500	23.5±2.2	0.320±0.005	0.8±3.0	19.2±0.6	801±23	29.4±2.8
	W2237	300–500	62.6±5.7	0.425±0.005	2.3±3.0	31.7±0.8	1128±20	55.5±5.1
	W2239	300–500	66.9±4.8	0.270±0.005	0.8±3.0	15.4±0.4	620±12	108±8
	W2240	300–500	55.5±5.2	0.210±0.005	2.5±3.0	10.9±0.3	463±13	120±12
	W2464	300–500	40.0±3.5	0.420±0.005	1.7±3.0	28.9±0.9	1110±28	36.1±3.2
	W2465	300–500	55.5±4.8	0.375±0.005	2.2±3.0	24.5±0.7	956±27	58.0±5.3
	W2467	300–500	55.6±4.6	0.230±0.005	3.0±3.0	14.7±0.5	574±13	97.0±8.4
	W2468	300–500	61.1±6.9	0.145±0.005	3.0±3.0	10.8±0.3	402±13	152±18
	W2469	300–500	50.9±4.25	0.090±0.005	3.0±3.0	11.2±0.4	349±13	146±13
	W2677	300–500	54.8±4.3	0.380±0.005	1.0±3.0	24.4±0.8	974±24	56.3±4.6
Wills Grave	W2574	275–500	14.1±1.3	0.125±0.005	0.3±3	13.2±0.4	537±27	26.2±2.7
	W2575	300–500	23.4±2.8	0.120±0.005	5.1±3	15.9±0.5	514±25	45.5±5.9
	W2576	275–500	17.2±1.4	0.110±0.005	0.2±3	10.6±0.3	481±26	35.9±3.5
	W2577	300–500	21.6±2.6	0.070±0.005	0.6±3	9.9±0.3	391±26	55.3±7.6
	W2578	325–500	151±35	0.190±0.005	14.2±3	20.7±0.7	604±24	250±60
	W2579	275–500	16.3.±1.7	0.100±0.005	0.2±3	9.8±0.3	454±26	35.9±4.3
Lower Cooper Creek	W803	300–500	121±11	0.41±0.01	0.5±3	21.8±4	1035±77	117±14
	W804	300–500	147±7	0.16±0.01	0.4±3	17.0±4	669±77	220±27
	W805	300–500	>299±67	0.23±0.01	1.0±3	17.4±4	745±76	>400±98
	W806	300–400	32.9±1.8	0.05±0.01	0.6±3	15.9±4	1013±77	32.5±3.0
	W807	300–500	58.3±3.0	0.13±0.01	0.8±3	10.7±4	506±77	115±18
	W808	sloping	74.0±4.0	0.21±0.01	0.3±3	13.1±4	645±77	115±15
	W809	300–500	>239±34	0.17±0.01	0.9±3	10.3±4	539±77	>440±90
	W810	300–500	>246±49	0.41±0.01	2.0±3	9.7±4	775±76	>320±77
	W811	300–500	>246±36	0.41±0.01	11.4±3	18.0±4	850±68	>290±48
	W812	300–500	116±7	0.47±0.01	0.5±3	20.5±4	1075±77	108±10
	W813	300–500	60.8±3.3	0.12±0.01	0.3±3	8.8±4	460±77	132±23
	W814	300–475	67.9±3.8	0.26±0.01	0.7±3	11.9±4	670±77	101±13

Table 1

TL ages for alluvial and aeolian sequences

Table 2

A comparison of TL and OSL ages for samples collected from near site A_1 and from Site B_2

TL laboratory number	TL Palaeodose (Gy)	TL Dose rate (Gy ka^{-1})	TL Age (ka)	OSL Palaodose (Gy)	OSL Dose rate (Gy ka^{-1})	OSL Age (ka)
Site A_1				Large aliquot		
W2839	40.1±2.8	1.97±0.06	20.4±1.6	49±2.0	2.32±0.13	21.1±1.4
W2844	11.9±1.0	2.33±0.06	5.3±0.5	11±0.5	2.62±0.28	4.2±0.3
W2845	14.1±1.1	1.94±0.06	7.3±0.6	14±0.5	2.30±0.24	6.1±0.6
W2846	15.2±1.2	1.74±0.06	8.8±0.7	15±0.5	2.00±0.22	7.5±0.6
W2849	15.0±0.3	2.47±0.06	6.1±0.5	23±1.2	3.15±0.21	7.3±0.5
W2850	13.4±1.3	2.36±0.06	5.7±0.6	21±1.5	2.92±0.21	7.2±0.5
Site B_2				Single grain		
W2239	66.9±4.8	0.62±0.012	108±8	80±5	0.65±0.04	123±11
W2467	55.6±4.6	0.57±0.013	97±8	70±5	0.65±0.04	108±11
W2240	55.5±5.2	0.46±0.013	120±12	65±5	0.41±0.03	159±17
W2468	61.1±6.9	0.40±0.013	152±18	48±5	0.39±0.03	123±16
W2469	50.9±4.3	0.35±0.13	146±13	98±4	0.77±0.05	127±11

Note that the analyses from site A_1 are based on single samples analysed for TL and OSL, whereas the OSL ages from site B_2 are based on additional samples which date the same unit but are not exact sample duplicates (see Fig. 8).

The TL procedures in the University of Wollongong laboratory have been described elsewhere (Nanson et al., 1991) and are not repeated here. Sample preparations for OSL analyses were designed to isolate pure extracts of appropriately sized quartz grains. Treatments were applied to remove carbonates, feldspars, organic matter, heavy minerals and acid soluble fluorides, all of which are contaminants that can interfere with the analysis procedure. For the six samples collected from near site A_1 palaeodoses were determined on 5 mm aliquots of 180-212 urn quartz, using the single aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000). The reported OSL palaeodose is the weighted average of 24 individual aliquot determinations. The dose rate data for these samples was collected using thick source alpha counting (for U and Th) in combination with flame photometry (for K) was used for determination of dose rate. Dose rates have been calculated based on the assumption of secular equilibrium in the ^{238}U and ^{232}Th chains, using the conversion factors of Stokes et al. (2003). For the OSL samples collected at site B_2 burial doses were determined via single grain analysis using methods and instrumentation described in detail in Olley et al. (2004). Dose rates were calculated from radionuclide activity concentrations measured using high resolution gamma spectrometry (Murray et al., 1987). The high resolution gamma spectrometry revealed no secular disequilibrium for these samples, providing support for our assumption of secular equilibrium used in dose rate calculations based on thick source alpha counting.

For all OSL samples cosmic dose rates were calculated from Prescott and Hutton (1994). (3-attenuation factors were taken from Mejdahl (1979) and the effective internal a dose rate (applied to all samples) has been estimated using an a-efficiency 'a' value of 0.04 ±0.02 (as measured previously for quartz grains from southeastern Australia, e.g. Bowler et al., 2003). An assumed long term water content of 5 ± 5% has been used to adjust dry dose rates. Differences in calculated dose rate evident in Table 2 are primarily the result of the use of different p attenuation factors consistent with the larger grain size used for OSL. There were also small differences in measured radionuclide content, consistent with sampling variation, and in techniques used for uncertainty assignation and propagation.

For the TL/OSL comparison, what were assumed to be relatively young samples were initially chosen from near site *A^* because any residual luminescence acquired in periods prior to the last episode of transport and luminescence bleaching would be more apparent in younger age determinations. These young sandy mud samples were collected on the Cooper Creek floodplain approximately 2 km northeast of Goonbabinna Waterhole from auger holes under conditions of total light exclusion and later divided in dim red light in the OSL darkroom for separate analyses in the University of Wollongong TL and OSL laboratories. The TL/OSL pairs from near site A_1 show remarkable correspondence (Table 2). A series of five additional OSL samples was collected and dated from a vertical section of clean alluvial sand at Tilcha Waterhole (Fig. 3a) that have been previously dated by us in the range of ~97 to ~152 ka with TL (Table 1). For the sandy mud samples, in three of the six cases (W2839, W2845, W2846), the error margins overlap whereas in the remaining three cases (W2844, W2849, W2850) they very nearly do, for all pairs lie within ±12%. In other words, there is no evidence of any systematic differences between the TL and OSL determinations. It is worth noting that at this site both the OSL and TL analysis techniques are based on large aliquots, and therefore any grain to grain variation in dose is likely to be equally masked in both cases. Single grain OSL dating was therefore subsequently applied to five additional samples collected from a vertical section of clean alluvial sand at Site B_2 (Tilcha Waterhole — Figs. 3a, 7 and 8) that has been previously dated by us in the range of ~97 to ~152 ka with TL (Table 1). The single grain OSL dates all fall within this range. The general correspondence between the single grain OSL dates and the TL dates indicates that for Cooper Ck samples luminescence techniques (whether OSL or TL) which rely on large aliquots are not adversely affected by the presence of significant proportions of unbleached grains. These results indicate that TL and OSL (large aliquot or single grain) techniques appear to be acceptable for differentiating late Quaternary stratigraphic units and depositional events along Cooper Creek.

U series dating was applied in two instances by Dr Steve Short, at the time from Australian Nuclear Sciences and Technology Organisation at Lucus Heights, Sydney, and the methods used have been described in Nanson et al. (1991).

5. Site investigations along Cooper Creek

Alluvial evidence for flow regime changes have been investigated at five locations along the middle and lower reaches of Cooper Creek, from the Shire Road near Naccowlah to near its terminus in Lake Eyre (Sites A_1 to C, Fig. 1).

5.1. Location A1; Shire Road

A series of eight auger holes was sunk to depths of 7 to 35 m at variable intervals along a 14 km transect of the Cooper Creek floodplain (Fig. 4). In addition, three trenches were excavated to depths of ~7 m immediately adjacent to three of the auger holes to obtain stratigraphic evidence, described in detail elsewhere (Maroulis, 2000). The truck-mounted solid augering system limited the precision of the stratigraphic detail that could be obtained from below the level of the excavated pits, however, samples were withdrawn and removed from the auger tip at each 1–2 m of auger length, and these provided a guide to the general sedimentary character of this wide and deep floodplain section.

The floodplain consists of 0.5–5.0 m of surficial massive sandy mud that dates from essentially modern at the surface to b10 ka at its lower contact with sand (~1.5 m) near the main channel on the western side of the floodplain, and to N60 ka at the sand contact (~4 m) near the eastern side (the oldest basal age obtained for this surficial floodplain mud was ~100 ka obtained on the Durham Road transect ~25 km to the north; Maroulis, 2000). Although commonly deposited as pelleted bedload (Maroulis and Nanson, 1996), no flow structures have been preserved because of the self-mulching character of these muds. These contemporary channels and waterholes are entrenched in this upper mud unit and transport virtually no sand today (Knighton and Nanson, 1994a,b; 2000).

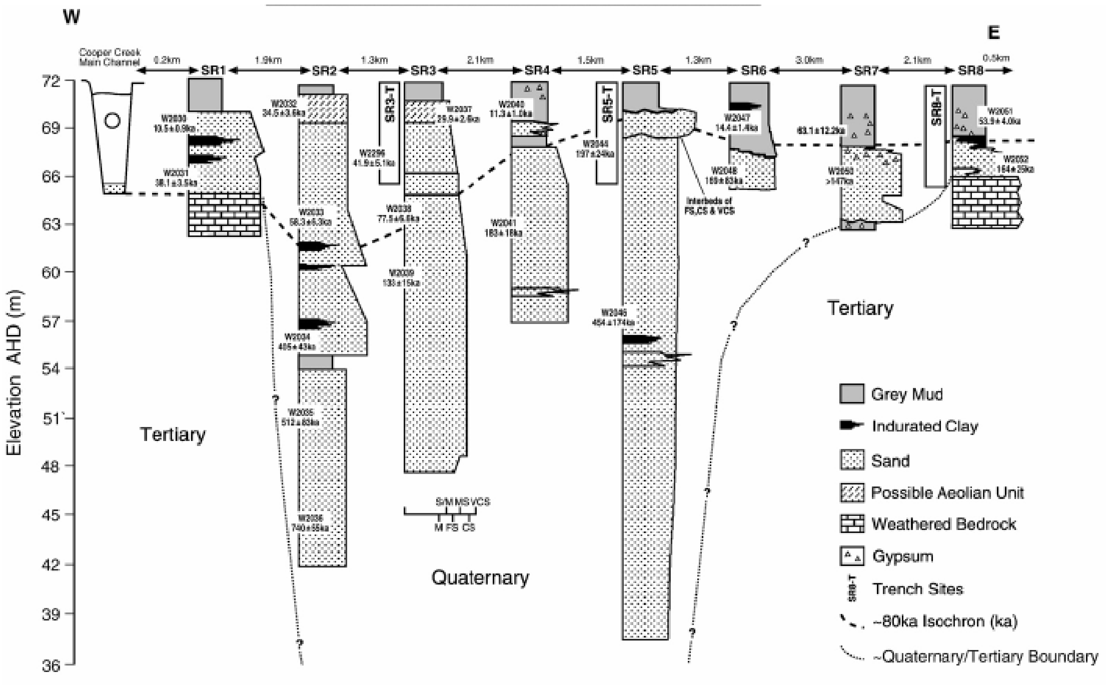


Fig. 4. The stratigraphy of the Shire Road transect (Area A1 in Fig. 1).

Below the mud down to the limit of augering (~35 m) consists of coarse to fine sand, occasional mud lenses, Fe–Mn stained units and some fine gravel. The oldest ages in the upper 6–7 m of the sand body occur at the eastern end of the transect (197±24 to 164±25 ka) whereas at the western end there is clear evidence of reworking to depths of ~12 m since ~80 ka.

On the older eastern end of the transect, the basal muds and uppermost sands are partly indurated with abundant calcrete and gypcrete. The individual strata are thin, have sharp erosional reactivation surfaces and display limited bedding structures, evidence of flashy fluvial processes probably associated with the valley side well away from the main flow. In contrast the much younger western end of the transect is substantially less indurated. Trench SR3-T towards the western side of the floodplain shows an upward fining laterally-accreting greyish-brown to very pale brown sand body. Palaeocurrent directions 60° to 120° away from downvalley and laterally-accreting bar surfaces indicate a strongly sinuous laterally migrating system. The base of the trench consists of large-scale festooned cross-bedded fine-medium sand, some minor calcrete rhizomorphs and scattered pebbles, and TL dates at 41.9±5.1 ka (W2296). This grades up to very fine sand formed of large trough cross-beds and climbing ripple sets. The upper part consists of very well-sorted fine sands (possibly aeolian) and TL dated at 29.9±2.6 ka (W2037) in the adjacent auger hole (SR3). The base of the floodplain clay capping is at 1 m.

TL dates from the alluvial fine sands on the western side of the floodplain include those of 10.5±0.9 ka (W2030) and 38.1±3.5 ka (W2031) at SR1, 58.3±6.3 ka (W2033) at SR2, andat 41.9±5.1 (W2296) and 77.5±6.6 ka (W2038) at SR3. In combination these suggest that western side of the floodplain above 10–12 m has been reworked and filled since marine oxygen isotope stage (OIS) 5, as illustrated with the 80 ka isochron in Fig. 4, and that fluvial activity has contracted here over the last full glacial climate cycle.

Below this upper part, thick units of coarse to medium sand, some with sequences fining upward to fine sand, date from 183±18 ka (W2041) to 133±15 ka (W2039) at 12–9mdepth,toasoldas740±55ka (W2036)at27mdepth, with intermediate dates of 512±83ka(W2035), 454±174 ka (W2046) and 405±43 ka (W2034) between 21 and 15 m in depth. Only occasional mud lenses interrupt an otherwise uniform and essentially unconsolidated sand body extending to over 30 m in depth. The presence of mud intraclasts and balls within the sand indicates that the associated channels probably had muddy banks and fine overbank floodplains that were reworked by this laterally and vertically accreting system.

At a depth of 27 m below the Shire Road the alluvium is at 45 m Australian Height Datum [AHD]. This means that it is a remarkable 6 m below the bed of Cooper Creek (51 m AHD) at the Burke and Wills Bridge near Nappa Merrie, some 95 km downstream where the river enters the bedrock constriction of the Innamincka Dome. Clearly, sand accretion even well upstream of the Shire Road, is essentially a product of upwarping in the dome since the Brunhes–Matuyama reversal (~780 ka), and probably before that as well. TL ages plotted against depth at Shire Road suggest a relatively uniform accretion rate of about 0.036 mm/a from 27 m to the floodplain surface on the eastern side of the floodplain. However, on the reworked western side it has accreted from ~12 mdepthat~130 ka to the surface nearly three times more rapidly at ~0.092 mm/a.

As well as accumulating alluvium upstream, Cooper Creek over this period must also have been incising into the dome. At this stage, neither the rate of incision nor the rate of uplift is known. However, assuming Cooper Creek was in a state of mass–balance equilibrium and able to move all the sediment load supplied from upstream, other than that trapped because of the rising dome (in other words, none of the upstream accretion is due to flow incompetence regardless of uplift), the long term uplift rate must have exceeded the rate of incision (denudation) by 0.036 mm/a. The sediment accretion rate of ~0.092 mm/a since OIS 5 on the western side of the floodplain probably represents a cut and fill adjustment within the longer term overall uplift trend. We are currently undertaking a cosmogenic isotope analysis of the denudation rate of the dome in order to determine its rate of uplift.

This entire Shire Road sequence can be considered to be equivalent to the Katipiri Formation in South Australia (Stirton et al., 1961) that we describe and date in detail below. The depth of alluvial sand beneath the Shire Road shows Cooper Creek to have been a much more powerful system, and certainly more laterally active than it is today. A large palaeochannel near Naccowlah Waterhole near the Shire Road was identified, partly excavated and dated as being 250– 230 ka (OIS 8–7) by Rust and Nanson (1986; their Fig. 5). Its width was ~500 m, mean depth ~4.5 m, wavelength ~4 km and bend radius of curvature ~2 km. The slope of the sinuous channel over that part of the floodplain would have been 8 cm km^{-1} (i.e. somewhat less than the valley slope) and Manning's n at bankfull for a wide sand-bed system can be assumed to have been about 0.025. From these data an approximate bankfull discharge of ~2200 m^3s^{-1} can be calculated. Knighton and Nanson (2000)have estimated the present mean annual flood discharge at Meringhina Waterhole 35 km upstream of the Shire Road (the only nearby location where the entire flow of Cooper Creek up to bankfull passes through a single channel) to be ~330 m^3s^{-1} and, from their paper, the dimension of that waterhole and a Manning's equation calculation suggest a bankfull discharge of about 410 m^3s^{-1}. This suggests that channel-forming flows during OIS 7 were some 5 to 7 times those of present Cooper Creek. While periods of sandy fluvial activity during OIS 5 at the Shire Road were more powerful than anything subsequently, only episodes prior to OIS 6 saw reworking of the entire floodplain. OIS 5 and later phases were capable of only working the western part of the floodplain at this location. Alluvial reworking of the floodplain at the Shire Road section continued as far as 2–3 km from the present channel until about 40 ka (SR3 in Fig. 4). Two hundred metres east of the main channel there is evidence of alluvial reworking during the early Holocene, suggesting conditions then were somewhat more energetic than in the present system which is essentially a tree-lined and laterally stable system of anabranches with cohesive muddy banks. Stratigraphic evidence from near Longreach on the Thomson River (a major tributary to Cooper Creek in its upper catchment; Fig. 1) suggests that the main channel contracted to its present very low energy state during the middle and late Holocene (Nanson et al., 1988, their Fig. 10). Similar evidence is presented below for Cooper Creek within the

Innamincka Dome.

The Shire Road transect reveals a chronostratigraphy of Cooper Creek from the Middle Pleistocene to the Holocene, with evidence that fluvial activity prior to OIS 5 was significantly more energetic than anything that has occurred subsequently. OIS 5 was only moderately active and subsequent phases of fluvial activity were even less so.

5.2. Location A2; Chookoo

In a recent study of source-bordering dune development at Chookoo, 10 km south of the Shire Road on the western side of the floodplain (Fig. 1), Maroulis et al. (2007) identified several periods of pronounced fluvial activity. The actual luminescence ages are listed in their paper but are summarised here in Fig. 5 as units of oxygen isotope stage (Fig. 5). Augering here was limited to the upper 15 m of the floodplain. Below about 10 m depth occurs an extensive unit of medium to coarse sand dating from OIS 8 to 6 (~270 to ~160 ka). Above this an OIS 5 unit (~105 to ~80 ka) inset with alluvial fine to medium sands that essentially represent two units (Fig. 5), the first dated in OIS 4 (~65 ka) and the second in OIS 3 (~50 ka). Source-bordering dunes were derived from active sandy channels in late OIS 5 (~85–80 ka) and mid OIS 3(50–40 ka), but none apparently during OIS 4. After ~40 ka sand–channel activity largely ceased and the flood-plains and channels were inundated with mud, isolating the dunes as emergent features on the floodplain. They concluded that the formation of source-bordering dunes occurred along large sandy meandering rivers with beds seasonally exposed to the prevailing southerly winds. The provision of abundant aeolian sand appears to have required seasonally wetter conditions and more powerful rivers than exist under today's seasonal but much drier climate. Global temperatures in late OIS 5 and in OIS 3 were significantly below those of the present, therefore the flows appear to be the product of cooler seasonally-wet conditions. The limited size and distribution of such dunes on Cooper Creek suggest that aeolian conditions were localised on particular bends, relatively short lived and probably characterised the end of a fluvial phase.

In summary, stratigraphic evidence from the Shire Road and Chookoo transects suggests that fluvial episodes in the Middle and Late Pleistocene on Cooper Creek were much more powerful than those of today. Flows appear to have declined in intensity from OIS 6 to OIS 5 and 3, with flows sufficient to feed sand to source-bordering dunes largely ceasing in late OIS 3 (~40–35 ka). Evidence for some minor fluvial activity by a sand-transporting river in the Holocene at the Shire Road transect is not replicated at Chookoo, probably because by the Holocene the active system appears to have greatly reduced in size, and Chookoo is some 3 km away from what remains of the primary channel (Goonbabinna Waterhole).

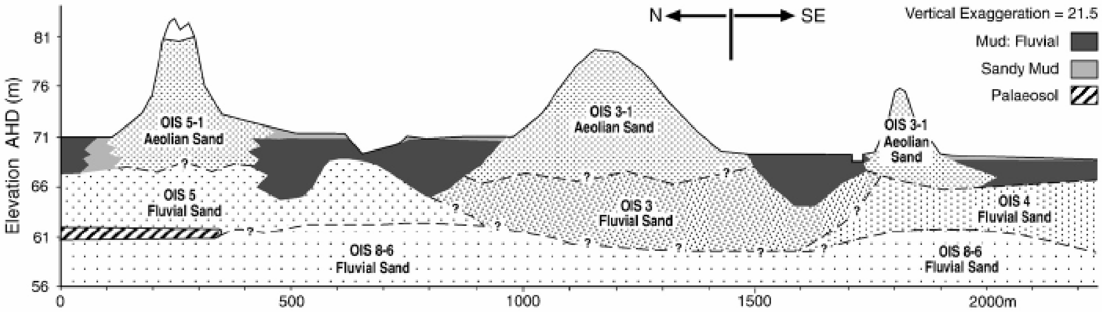


Fig. 5. A summary transect at Chookoo Dunes (Area A2 in Fig. 1) showing the aeolian units and underlying alluvial units divided by luminescence ages into oxygen isotope stages (after Maroulis et al., 2007).

5.3. Location B1; Innamincka Dome

The post OIS 3 record is relatively poorly represented along most of Cooper Creek because by the onset of OIS 2, discharges had clearly declined from the earlier maxima that left such widely distributed deposits in Stages 5 and 3. Furthermore, the limited energy these reduced flows had must have been dispersed over extensive flood-plains that in Queensland exceed 60 km in width. However, as Cooper Creek reaches South Australia it enters the Innamincka Dome near Nappa Merrie (Figs.1 and 2) where it becomes greatly confined; large floods are in places restricted in width to just a few hundred metres! Consequently, the dome can act as a local amplifier, concentrating the energy of Cooper Creek. At a cross section at the upper end of Cullyamurra (Cullamurra) Waterhole, some 15 km upstream of Innamincka Township, the floodplain is only ~800 m wide and Cooper Creek exits a fully confined bedrock reach (Fig. 6). Because of this, there is little opportunity for lateral migration and the chronstratigraphic data in Fig. 6 should therefore be indicative of the palaeochannel dimensions.

Luminescence ages from four auger holes have identified two episodes of alluvial activity here (Bowman, 2003). It appears that there was a large channel in OIS 3, its deposits yielding alluvial TL ages below the level of the Holocene channel of about 42 to 33 ka, similar to ages from alluvial sands within 3 km east of the main Cooper Creek channel at the Shire Road transect and at Chookoo. A large early to mid Holocene channel appears to have been reduced in size in the late Holocene to form the present waterhole. Another section of auger holes several kilometres downstream of that described here has also been shown by Bowman (2003) to illustrate contraction of a large channel in the period from about 8–7 ka to 3 ka. This early to mid Holocene activity may also relate to that dated at ~10 ka about 200 m east of the main Cooper Creek channel on the Shire Road transect (Fig. 4).

From augered and TL dated transects, Bowman (2003) estimated the width of the mid Holocene channel to have been 400 m while the mean depth was bedrock controlled and therefore similar to the present 9.5 m. The likely cross-sectional area was therefore about 3800 m^2. Using a Manning's n calculated for the present waterhole (0.028) and a HEC-RAS modelled water surface slope of 0.0002, the bankfull discharge is estimated here to have been ~8600 m^3s^{-1} or ~8.6 times the present bankfull discharge of ~1000 m^3s^{-1}. A sensitivity analysis undertaken by varying Manning's n values from 0.025 and 0.032, and water surface slopes from 0.00017 to 0.00025, produces bankfull discharges between 7 and 11 times the present. These are substantially larger than increases of 5 to 7 times present Cooper Creek based on Meringhina Waterhole near the Shire Road for the fluvially more active OIS 8–7 period. However, with flows jetting out of a confined bedrock reach immediately upstream of the alluvially flanked Cullyamurra Waterhole, it is very likely that moderate increases in Holocene discharges were capable of a much greater channel enlargement here than would larger flows in the unconfined setting near the Shire Road. Suffice to say that early to mid Holocene discharges were considerably larger and more powerful than those of today.

However, it seems such events may have been very infrequent, perhaps catastrophic, but not necessarily representing a wholesale upward shift in the flow regime, as this was not a period represented by significant Holocene reworking of Cooper Creek floodplain beyond the Innamincka Dome (Nanson et al., 1988; 1992).

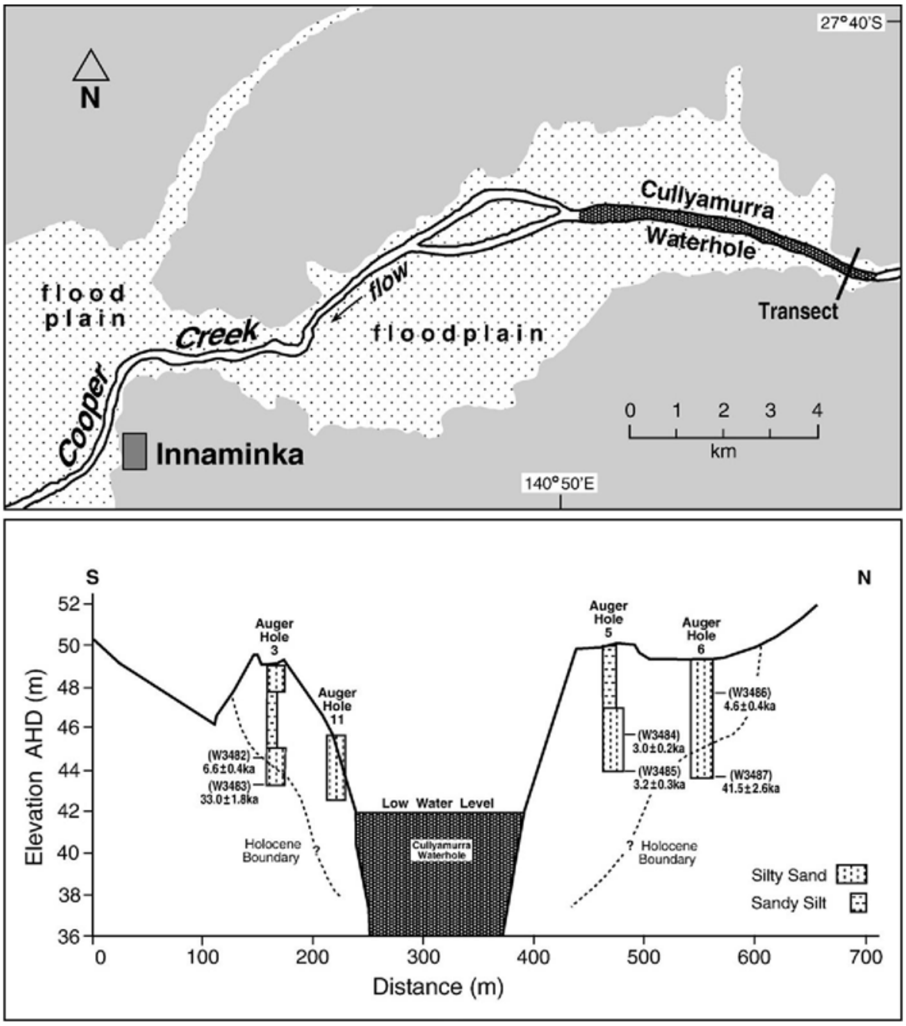


Fig. 6. Confinement of Cooper Creek and its floodplain within the Innamincka Dome (Area B1 in Fig. 1), showing the location of the stratigraphic section at the upstream end of Cullyamurra Waterhole.

Also within the Innamincka Dome, Coleman (2002) obtained TL dates of 27.8±2.5 ka (W2582), 20.1 ±2.9 ka (W2580) and 18.3±2.1 ka (W2670) from a substantial channel infill at a cross section some 5 km downstream that is shown in Fig. 6. These dates show that there must also have been enhanced discharges through the dome at and just before the LGM, a time traditionally seen as markedly arid in the Lake Eyre basin (e.g. Magee et al., 2004). This episode also probably consisted of infrequent events rather than an overall change in the flow regime, similar to that which occurred later in the Holocene. These LGM episodes of extreme floods were also unable to rework the floodplain beyond the effect of the energy-amplifying dome. We are currently undertaking further investigations of the alluvium within the Innamincka Dome, as it appears to be a location sensitive to recording changes in the Cooper Creek basin not yet seen to be recorded elsewhere on the floodplain during the LGM and in the Holocene.

5.4. *Location B2; Tilcha Waterhole*

Tilcha Waterhole on 'Cooper Creek Fan' is ~17 km downstream from Innamincka where Cooper Creek exits its confinement in the Innamincka Dome. (Figs. 1, 2 and 3a). Immediately opposite Wills Grave, a large meander bend on Cooper Creek is slowly eroding its right bank and exposing a ~22 m high section of basal fluvial sands and overlying aeolian dune deposits (Figs. 7 and 8). At the base of this section, slightly indurated 10-50 cm thick sets of yellowish brown trough cross-beds of medium sand yielded a TL age of 146 ±13 ka (W2469). This is overlain by well-sorted smaller (<20 cm) sets of pale brown medium sand trough cross-beds that dated at 152±18 ka (W2468). It is likely that these ages, along with the nearby OSL ages of 127 ±11 ka and 123 ±16 ka, are slight underestimates, as the moisture content at this depth is likely to have fluctuated due to intermittent rises in the watertable. This lowest visible portion of the section above water level to ~41.7 m AHD appears to be an OIS 6 fluvial sequence.

The next unit consists of a thin (< 10 cm) lag of pebbles topped with a thin layer of well-sorted very pale brown fine sand. The pebbles appear to form the base of the OIS 5 deposit. Overlying them is a sequence of mud balls, some armoured with small pebbles, topped by a1m thick coset of trough cross-bedded pale brown medium sand (sets 25-30 cm) that TL dates at 120±12 ka (W2240) and 97.0±8.4 ka (W2467) and OSL dates at 108±11 ka and 123±11 ka. This OIS 5 unit fines upwards into 3.6 m of poorly sorted brownish yellow and very pale brown, trough cross-bedded sets (10-30 cm) of fine sand giving a TL date of 108 ± 8 ka (W2239), and capped with 2 m of massive blocky floodplain mud.

The remainder of the section above ~49 m AHD is formed of aeolian units separated by palaeosols. Aeolian Unit 1 consists of 1.0 m of poorly sorted very pale brown fine-grained laminated sand giving a TLage of 56.3 ±4.6 ka (W2677). Accumulation continued as a vertically accreting palaeosol marked by 1.6 m of very poorly sorted pale brown very fine-grained sand characterised by wind ripples, root channels and carbonate rhizomorphs that gave TL ages of 58.0±5.3 ka(W2465) and 55.5±5.1 ka (W2237). Aeolian Unit 1 is capped by a 0.9 m thick hard calcrete.

Aeolian Unit 2 starts at 52.2 m AHD and consists of~1 m of poorly sorted fine red sand with a TL age of 36.1 ±3.2 ka (W2464). This is overlain by 0.5 m of poorly sorted yellow fine cross-bedded dune sand (orientation 245°) indurated with calcrete and giving a TL age of 29.4± 2.8 ka (W2235). It is capped with a thin palaeosol with wind ripples oriented 170° and a few carbonate rhizomorphs.

Aeolian Unit3 extends from54.4to58.0mAHD.Itconsistsof3.8mof dune cross-bedded sets (20–50 cm) of very poorly sorted yellow, brownish yellow and pale brown sandorientatedat320–340°. They give TL ages of 20.1±1.5 ka (W2234) and 21.4±1.8 ka (W2233) and contain a few carbonate rhizomorphs and carbonate leisegangs. There is evidence of reactivation surfaces and sand accretion around palaeovegetation (grasses). This is capped with a 0.85 m thick poorly sorted fine sandy palaeosol that gave a TL age at 0.5 m depth of 14.3±1.0 ka (W2232) but may have been contaminated by bioturbation with surface material. The overlying 3–4 m of still partly active dunes have been dated nearby as Holocene (Coleman, 2002).
The section at Tilcha Waterhole represents active fluvial deposition during OIS 6 and 5, followed by at least three phases of aeolian activity in OIS 3 and 2. Interestingly, no OIS 3 fluvial deposits are present on this side of the river, for reasons apparent below.

(a)

(b)

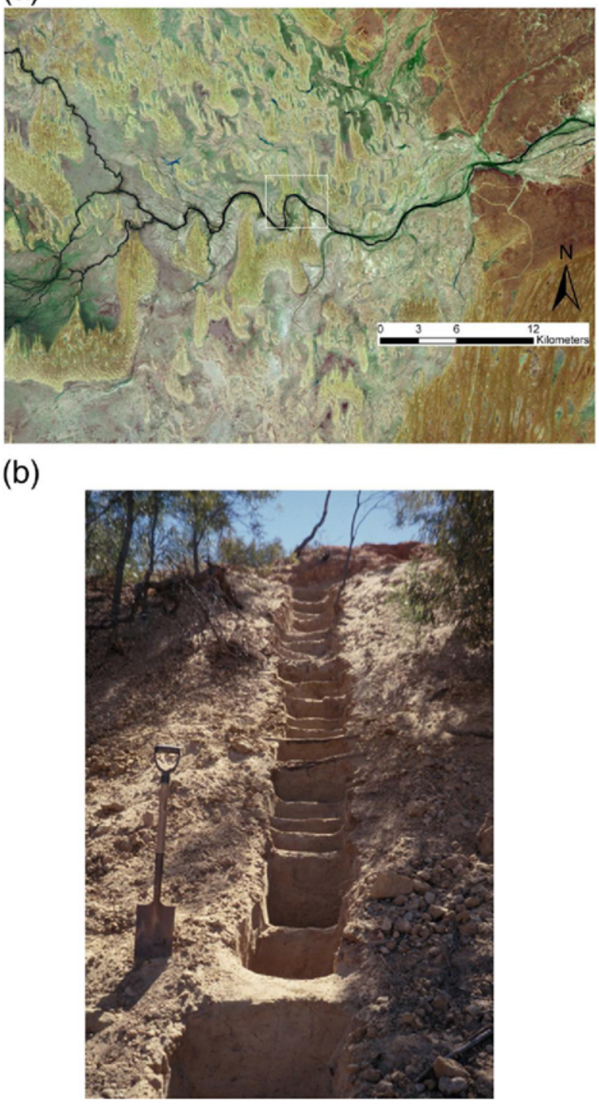
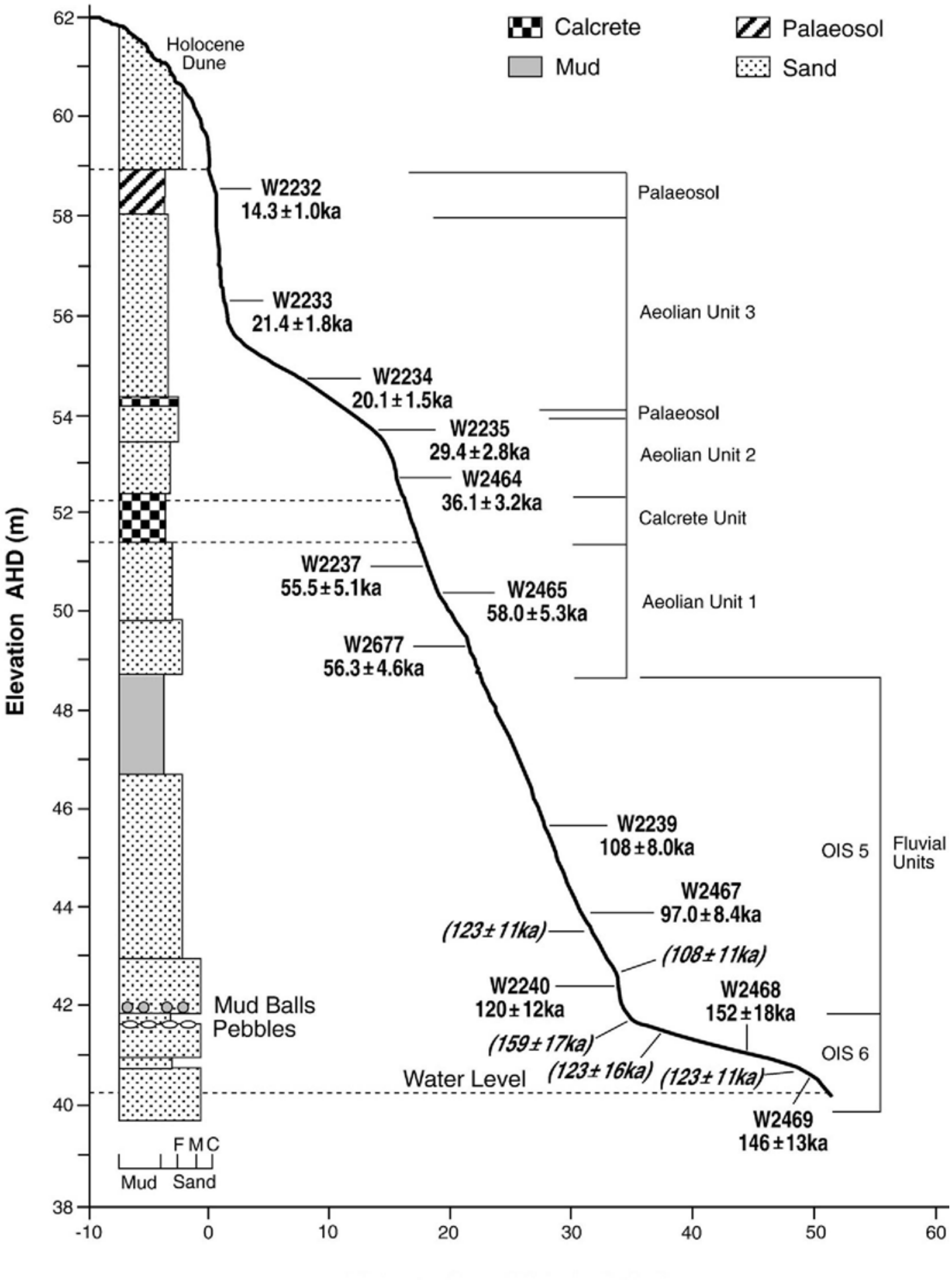


Fig. 7. a. Satellite image of Cooper Creek as it exits into the Strzelecki desert. Note the presence of linear dunes that interrupt the path of the Cooper and the presence of east– west trending arcuate source-bordering dunes. Flow is from right to left. The white box indicates the location of the trench in B, and associated stratigraphic section in Fig. 8. The image is an enhanced satellite image derived from Landsat 5 TM—25 metre pixel (Geocoded—1995) and Landsat 7 ETM 12.5 metre pixel (Geocoded—2000). b. Tilcha Waterhole and the stratigraphic section from the right bank presented in Fig. 8.



Distance from Waterhole (m)

Fig. 8. The stratigraphic section and associated TL dates on the northern bank of Tilcha Waterhole (Figs. 3a, 7a). Single grain OSL dates are in italics in brackets.

5.5. Location B2; Wills Grave

On the left bank, opposite the above section on Tilcha Waterhole, is a well-defined meander loop, an historic site known as Wills Grave (Fig. 3a), with a sequence of floodplain scrolls visible from the air but not on the ground. Here Cooper Creek has been progressively eroding into its right bank to expose the Tilcha section, and in the process has left an alluvial record of its migration.

A sequence of four holes were augered to depths of 22 m with a truck-mounted drilling rig in a transect orthogonal to the scroll pattern near the apex of the end(Fig.9).Auger Hole1on the floodplain,at49m AHD and about 9 m above typical low water level, consists of coarse and large pebbles at the base (43 m AHD) overlain by unconsolidated coarse very pale brown sand that TL dated at26.2±2.7ka(W2574), fining up to fine sand at the surface. Auger Hole 2, a further 50 m south, arrested in the clay of the Namba Formation at 38 m AHD but from 10.2 m up to 8.0 m depth consists of unconsolidated very pale brown coarse alluvial sand that gave a TL age of 45.5±5.9 ka (W2575) at 39 m AHD. This unit was overlain by5 m of a coarse to medium very pale brown to yellowish sand and pebble unit, fining in the uppermost 3.5 m to very pale brown medium fluvial sand. Auger Hole 3, south again by another 50 m, penetrated the Oligo-Miocene Namba Formation to 26 m AHD. Above this were two alluvial units fining upwards from basal unconsolidated coarse very pale brown sand and pebbles to very pale brown medium sand, the lowermost providing a TL age of 250± 60 ka (W2578) at 37 m AHD. Above this a third very pale brown medium sand and pebble unit 4 m thick gave a TL age of 55.3 ± 7.6 ka (W2577) at 43 m AHD, and was overlain by unit of very pale brown medium sand with no pebbles that gave an age of 35.9±3.5 ka (W2576) at 46 m AHD or 3 m depth overtopped with 2 m of fine sand. A further 55 m south, this last age is closely replicated (35.9 ±4.3 ka; W2579) at a similar depth in an 8 m deep sand body in Auger Hole 4.

5.6. *Interpretation of Tilcha Waterhole and Wills Grave*

These two adjacent sites on the ‘Cooper Creek Fan’ (Fig. 1) appear to represent a number of fluvially active periods with the transport and deposition of coarse to medium sand and fine gravel during episodes in the Middle and Late Pleistocene. There is evidence of an active channel that migrated across this general location, truncating the Oligo-Miocene Namba Formation at about 250 ka. Subsequent lateral activity by Cooper Creek truncated this ~250 ka alluvium, replacing it with OIS 6 alluvium (~150 to ~145 ka) that is visible at the base of the Tilcha section. It may be the same unit as that dated in OIS 6 at Shire Road (185-165 ka) and at Chookoo (~160 ka). This is superimposed with OIS Stage 5 alluvium (~120 to ~100 ka) visible in the lower part of the Tilcha section, overlapping in age although somewhat older than the OIS 5 fluvial unit at Chookoo (~105 to ~80 ka). During OIS 3, a precursor to the present channel migrated northwards through the OIS 6 and OIS 5 deposits, laying down the scroll-patterned floodplain at Wills Grave that dates from ~55 to 45 ka. The ~35 ka ages from Holes 3 and 4 appear to represent a chute channel across the meander loop at about this time and correspond to deposits of similar age in the cross section immediately below the bedrock choke of the Innimincka Dome (Fig. 6). The ~26 ka date from Hole 1 appears to coincide with a period of somewhat enhanced alluvial reworking characterised by flow confinement and a resulting amplification of the alluvial record within the Innamincka Dome and consequently not widely recognised outside it (Cohen et al., in prep). During at least a part of OIS 3, on the floodplain immediately north of this very slowly migrating bend, southerly winds were forming source-bordering dunes of OIS 3 age at Tilcha (~60 to ~55 ka) that became capped with a well-defined calcrete palaeosol. Relatively thin aeolian deposits appear to have been laid down between ~35 and ~30 ka, either with sand from the ~35 ka chute channel or with that reworked from adjacent older OIS 3 dunes. About 3.5 m of aeolian sand was added to the upper part of the Tilcha section at ~22 to ~20 ka during the LGM. This raises the question of whether the river was seasonally active to supply sand at this time, or if this too is largely reworked sand from older dunes? Since about 25 ka, the river appears to have remained in roughly its present location and, unlike sections within the Innamincka Dome, provides no evidence of a period of enhanced early to mid Holocene flow. However, the bankfull channel here is over 200 mwide with an extensive sandy gravel point bar that may at depth represent the infill of an early–mid Holocene channel.

5.7. Tirari Desert

In the Tirari Desert (Fig. 1) Cooper Creek is incised some 0–20 m into the relatively unconsolidated Tertiary and Quaternary formations exposed in river bluffs, the depth of incision increasing as the river approaches Lake Eyre. Away from the river, exposures also occur in wave-cut margins of now dry lakes. In this most arid part of the Lake Eyre basin, fluctuating lake levels, expanding and shrinking rivers and periodic dune development have provided conditions suitable for episodes of intense gypsum and carbonate formation providing material suitable for U series dating. Callen and Nanson (1992) briefly reviewed these exposures in response to other suggestions of the age of the alluvium and dunes in this region.

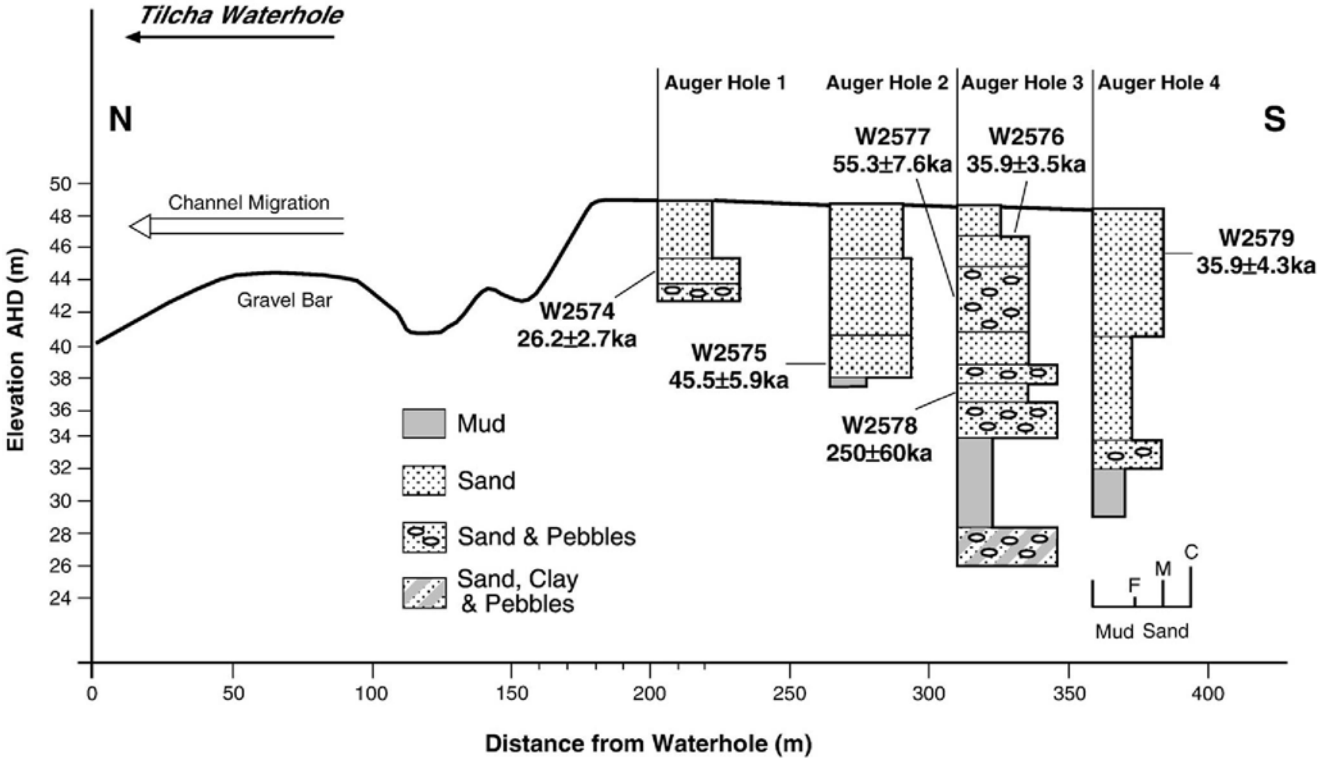


Fig. 9. The auger hole stratigraphy of Wills Grave on the southern bank of Tilcha Waterhole (Fig. 3a).

The oldest stream patterns, faintly visible in the Tirari Desert from aerial photographs and remotely sensed imagery, are low sinuosity distributaries indicative of fan-deltas that Tedford et al. (1986) referred to as ‘prior streams’. They are aligned west to northwest and are only apparent after flooding fills and aligns the clay-pans in the interdune corridors. These systems deposited the Tirari and Kutjitara Formations in the Late Tertiary and Early Pleistocene. Here we describe in detail an outcrop of the Kutjitara Formation at Lake Hydra (Figs. 1 and 10) representing one of these fan-deltas.

Along lower Cooper Creek, abundant outcrops of the Katipiri Formation reflect the shift in sedimentology and sedimentary architecture from the low sinuosity relatively wide and shallow Kutjitara distributary system to the narrower more sinuous inset channels of the Katipiri Formation. The two meander belts of the Katipiri Formation (southern and northern, Fig. 10) are more extensive than the present floodplains and are partly overlain by encroaching linear dunes. The very different planform of Lake Eyre associated with each formation, the different marsupial fossil types and abundances and the strong disconformity separating these two fluvial sequences suggests a substantial time difference between the deposition of the Kutjitara and Katipiri Formations (Tedford et al., 1986; Tedford and Wells, 1990).

5.8. Lake Hydra

This dry lake pan appears to have incised by deflation into basal lacustrine dark grey clays of the Wipajiri Formation deposited by an earlier Late Tertiary eastward extension of Lake Eyre. It is a late Quaternary feature constrained by formation of the present regional dunefield (Callen and Nanson, 1992). Pollen from the Wipajiri Formation suggests moister conditions in the Late Tertiary than today, with patches of Casuarina-dominated forest or open woodland and no significant grass understory but varying fresh to brackish rivers (Tedford et al., 1986;

Luly, pers. comm., 1990; Alley, 1998). Wave erosion on this now dry lake has exposed a 6 m high cliff in the Kutjitara Formation on a small island at the western side of the lake (Fig. 10). The exposure reveals shallow units of muds and horizontally bedded unconsolidated white-grey and orange stained fluvial sands with multiple small cross-beds mainly less than 2 cm thick making up ~20 cm thick cosets (Fig. 11) which here is overlain by dune sand that contains fragments of emu egg shell and human-crafted stone flakes. The northern end of the exposure has been entrenched by a 3–4 m deep (width unknown) channel infilled with fine sand (only the upper part is shown in Fig. 11). The depth of the channel contrasts with the shallow flow structures it is cut into. A 2.3 m long 0.7 m deep trench was excavated into the lake floor near the base of the vertical section to reveal that here the Kutjitara Formation is inset into an earlier lake clay and has itself been partially eroded by a subsequent lake depositing highly organic inclined beds (Fig. 11). There is evidence of disturbance by animals having walked over this soft shoreline.

The Lake Hydra section is reasonably typical of the Kutjitara Formation and suggests wide shallow fluctuating flows spread over a wide area and entering a lake larger than present. The climate must have been variable for the relatively narrow deep channel suggests a base level fluctuation with associated incision and subsequent infilling. In general, fluvial activity appears to have been low energy, probably shallow deltaic. There is no evidence of great channel sinuosity and nothing in the deposits to indicate significant channel migration. Two saturated TL ages gave values N320±71 ka (W810) and N440±90 ka (W809), the latter from the more recent sandy channel-fill and, although not definitive, they support an Early Pleistocene to possibly Late Tertiary interpretation. It is into the Kutjitara and the older Tirari Formations that the Katipiri Formation along Cooper Creek is inset.

5.9. Lower Cooper Creek

Here (Location C, Fig. 1) Cooper Creek is incised into a shallow alluvial trough encroached upon by some minor northward extension of the linear dunefield. It consists of a series of shallow disjunct salty waterholes with low source-bordering dunes adjacent to the channel, but the trough every decade or so fills with floodwaters that spread into the linear swales of the adjacent dunefield. A series of alluvial exposures up to 6 m in thickness, in places topped with aeolian dunes, occur along lower Cooper Creek between South Tilla Tilla Waterhole and Katipiri Waterhole (1 km upstream of Eli Hartigs Soak — the type section for the Katipiri Formation; Fig. 3b). Several of these stratigraphic sections are described here and two were surveyed to within ±1.5 m of AHD using an Omnistar-based DGPS correction.

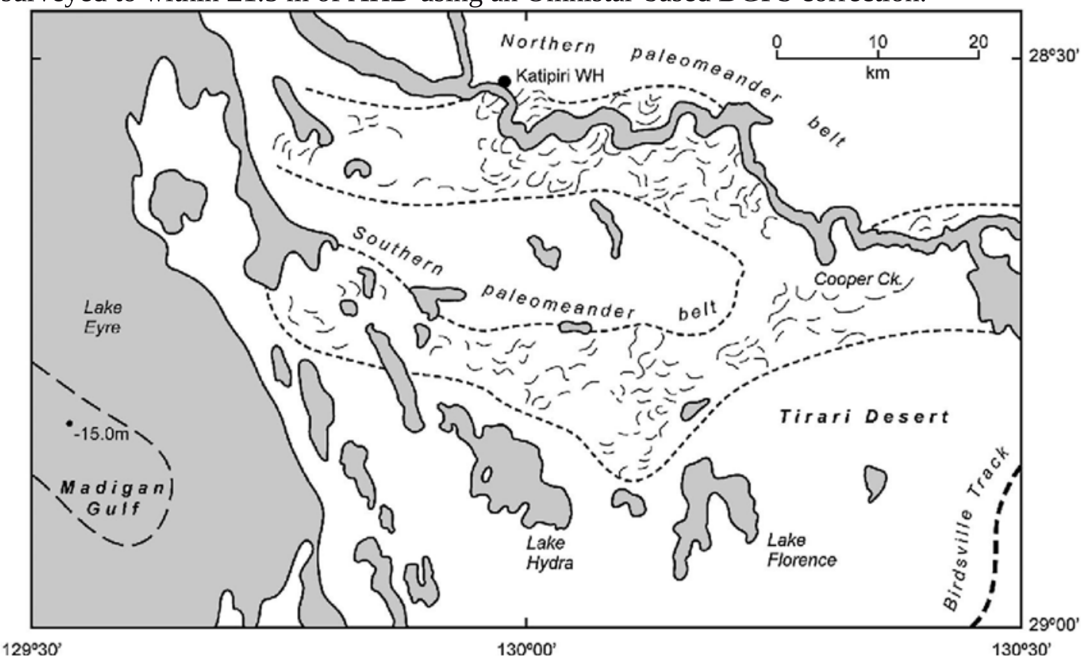


Fig. 10. The Tirari Desert adjacent to Lake Eyre, showing the northern and southern palaeomeander belts and the

path of the lower reach of Cooper Creek along the northern belt (after Wells and Callen, 1986).

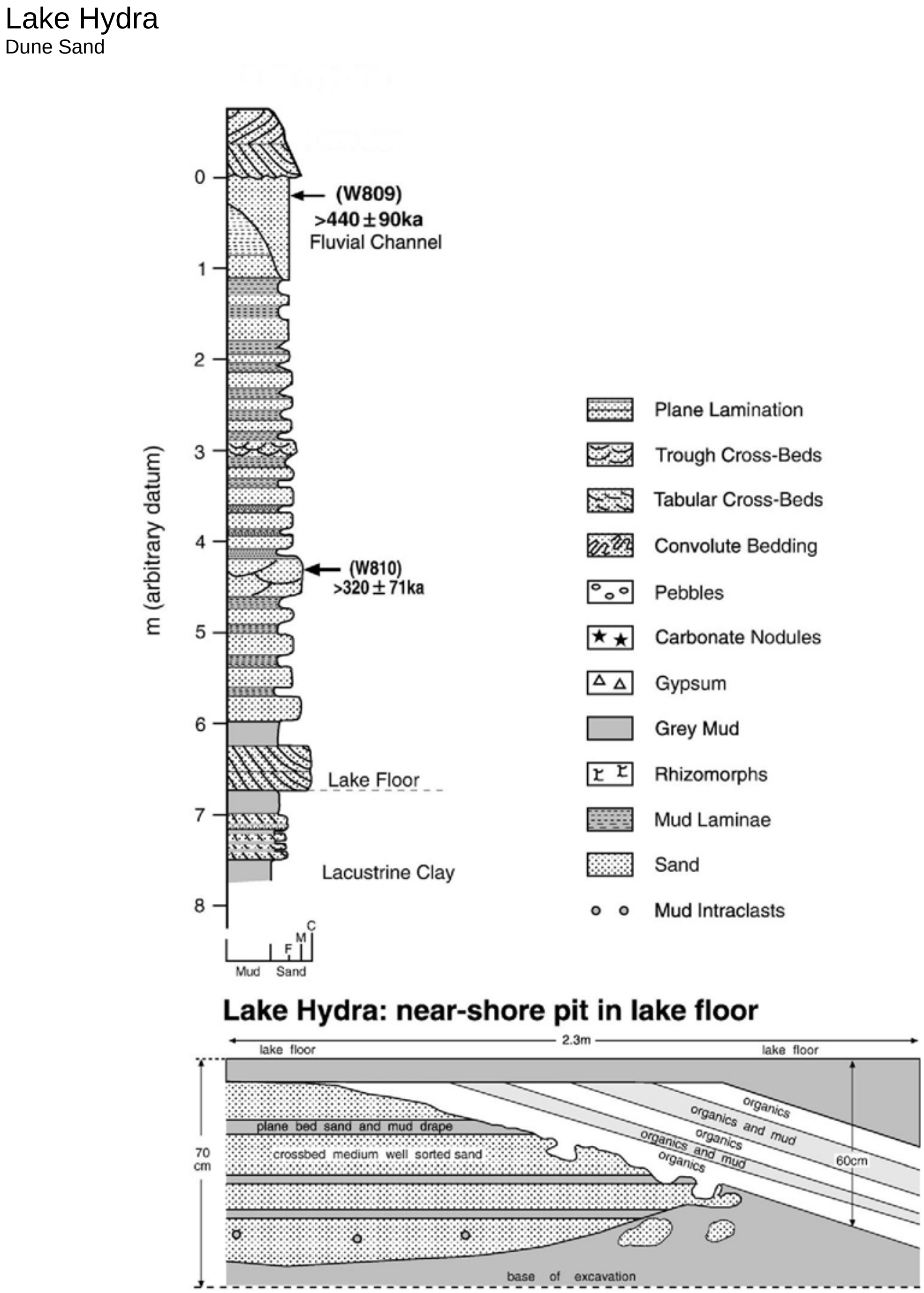


Fig. 11. A near vertical exposure of the Kutjitara Formation on the island on the western side of Lake Hydra in the Tirari Desert (Fig.10). A pit excavated in the lake floor, several metres away from the base of the section, exposes a continuation of the vertical section below 6.8 m relative datum. The upper part of a 3–4 m deep trench is exposed near the top of the section. Possible animal foot prints have disturbed one of the lower organic boundaries in the pit on the lake floor. As this location has not been surveyed to AHD, heights are given only to a relative datum.

The oldest unit investigated on lower Cooper Creek is the Tirari Formation at Eli Hartigs Soak near Katipiri Waterhole (Fig. 3b). Here an 8 m high bluff of dark orange fluvial sand on the north bank overlies a basal unit of grey lacustrine clay, probably Etadunna Formation. The overlying alluvium is Tirari Formation and consists of interbedded strata each 30–50 cm thick of gritty coarse to medium trough-bedded sand and uniform muds. This yielded a saturated TL age of N290±48 (W811). From about 5 m to 2 m there is a fining upward fluvial coset of very shallow trough sets of muddy fine to very fine sand, heavily indurated with gypseous rhizomorphs and massive gypsum. One hundred metres upstream the same coset can be viewed showing well-defined large cross-beds accreting over trough sets and inter-bedded mud sets. The upper alluvial contact is overlain by 1 m of the eroded remnant of an old dune formed of medium sand with interbedded mud (aeolian dust?). To the north, relatively modern aeolian dunes overlie the eroded relatively-flat upper surface of the exposure. This substantial exposure of the Tirari Formation with gritty coarse sands at the base suggests a more powerful river than later laid down the Katipiri Formation in this area.

Also on the north bank of Cooper Creek but at Katipiri Waterhole (Fig. 3b) a 30 m long and ~6 m high section of Katipiri Formation yielded a TL date of 108±10 ka (W812) from well-defined trough sets of medium to fine mostly white quartz sand (Fig. 12). These sands fine upwards to about 3.2 m of interbedded grey mud and fine sand strata forming a west-dipping lateral accretion succession below a truncated uppermost surface. Sand deposition appears to have been rapid with loading deformation structures in some of the lower trough sets. The site provides clear evidence of migration and lateral accretion of a scrolled meandering channel system.

Another substantial exposure of Katipiri Formation on the northern bank occurs at Cuttupirra Waterhole (Fig. 3b). The lowest barely exposed unit in this section below 5.7 m depth is dark orange stained fine sand, probably Tirari Formation (Fig. 13). The basal unit of the Katipiri Formation here consists of a few centimetres of clay, probably deposited in pools, overlain by 20 cm sets of trough cross-bedded medium to fine sands yielding a TL date of 115±15 ka (W808). This is overlain by plane-bedded medium to fine sand and some tabular cross-bedded planar sand sets each 3 cm thick. At 4.8 m convoluted trough sets of medium to fine sand grade up into less distorted sets of the same lithology. This coset TL dated at 115±18 ka (W807) at 3.8 m. From 3.1 m to 0.6 m the section consists of 10–20 cm trough cross-sets of clean white fine sand with an intervening 30 cm coset of 1–2 cm thick ripple sets between 1.5 m and 1.2 m. A 3 cm thick gypcrete layer occurs at the top of the ripple beds. The uppermost 60 cm consists of muddy fine sand, probably an overbank deposit, plane-bedded with few structures but some small carbonate nodules at the top. The base of an overlying aeolian dune dates at 32.5±3.0 ka (W806).

A further 14 km upstream at Pirranna Waterhole (Fig. 3b), the north bank of Cooper Creek reveals an 8 m wide, 3 m high transverse section through a point bar with incipient scrolls (Fig.14). The base of the section at ~1.0 m AHD consists of white horizontally laminated medium fine sand, partly orange stained with scour features and fine mud drapes, The core of the point bar is medium sand TL dating at 101±13 ka (W814; Fig. 14) and is overlain by medium to fine sandy tabular dune cosets (weakly orange stained) migrating downstream towards the northeast. These structures have been scoured into linear ridges and form incipient scrolls over which interbedded fine sand and mud units lie, the entire sequence being covered by a fine sandy mud overbank deposit. A gully on the landward side of this bar provided a section perpendicular to the transverse face. Here basal orange sand beneath an erosional contact dated at 132±23 ka (W813) whereas at the overbank contact, U series analysis of a gypcrete and calcrete rhizomorph gave an age of 112 + 8–7 ka (LH0696), these uncertainties overlapping the TL age stratigraphically below.

The Pirranna Waterhole location represents a point bar formed in a tightly curved bend in a relatively small channel. The steeper face is towards the channel and the gently sloping surface towards the bank. The secondary flow is directed obliquely towards this bank (Fig. 14).

The incipient scroll bar is formed from three adjacent downstream oriented linear sand-ridges which form a topographic high along the mid point of the bar platform. The abundant mud drapes and tight curvature of the bend indicate the probability of muddy cohesive banks, as does the substantial unit of muddy overbank sediment. Scrolled features such as this one and that at Katipiri Waterhole were probably widespread at the time, as shown by the scroll-patterned Cooper Creek palaeochannel surfaces visible in Fig. 10.

The final site on lower Cooper Creek to be described is South Tilla Tilla Waterhole (Fig. 3b) where a nearly 6 m high section exposes three alluvial units of distinctly different age (Fig. 15). The base consists of indurated fluvial cross-bedded medium sand that is dark orange stained and, based on the degree of weathering, is probably Tirari Formation. TL gives a minimum age of N400±98 ka (W805). Overlying this at an elevation of ~0.0 m AHD, but separated by a distinct mud unit, well-defined medium dark orange stained trough cross-stratified medium to coarse sand that gave a TL age at 1.3 m of 220±27 ka (W804), with 5–10 cm thick sets containing mud intraclasts and carbonate nodules. Mud drapes line the base of the troughs but decline in dominance upwards. A few centimetres of mud separates this unit from the overlying 15 cm thick trough cross-beds of clean grey fine sand with less orange staining. There is evidence that, at the time, large animals walked on and disturbed one of the muddy bounding surfaces.

At 2.2 m AHD a 4–5 cm thick mud unit is overlain by inclined fine clean sand with sets of smaller trough cross-beds migrating up-slope, an indication of lateral accretion. Along with the cross-beds below, this could have been an upward fining sequence with darker orange staining due to groundwater at the base. TL yielded an age of at 2.5 m AHD of 117±14 ka (W803) indicating a phase of the Katipiri Formation, some 100 ka younger than that just 1.3 m below (Fig.15). This disconformity could not have been recognised without dating, indicating that the Katipiri Formation is made up of often indistinguishable multiple depositional episodes from the Middle to Late Pleistocene.

From about 3.0 to 4.5 m AHD plane- and cross-bedded tabular sets of clean fine sand are interbedded with silty mud units, all weakly indurated with carbonate. These are primarilyfluvial but some aeolian reworking is possible. To the surface is a massive unit of overbank fine sand and silt with abundant carbonate and gypsum nodules and rhizomorphs. A section of the latter yielded a U/Th age of 97.0+7–6 ka (LH697) (Fig. 15), with uncertainties overlapping those of the TL age below.

In summary, the exposures along lower Cooper Creek and at Lake Hydra reveal a corridor of meandering stream activity represented by Katipiri Formation dating from OIS 7 and 5, overlying and partly incised into less confined Late Tertiary and probably Early Pleistocene deposits of the Tirari and Kutjitara Formations, respectively. The latter two are probably representative of a larger Lake Eyre and more widespread alluvial activity (Tedford et al., 1986).

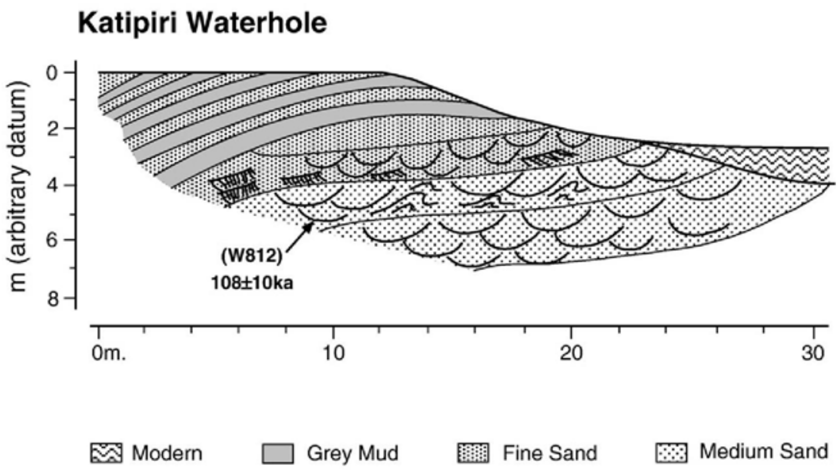


Fig. 12. Bank section at Katipiri Waterhole (Fig. 3 b) showing an exposure of scroll-pattern floodplain formed of

sandy trough sets at the base and grading upwards to interbedded muddy and silty fine sands and mud. This location has not been accurately surveyed to AHD and therefore heights are given only to a relative datum.

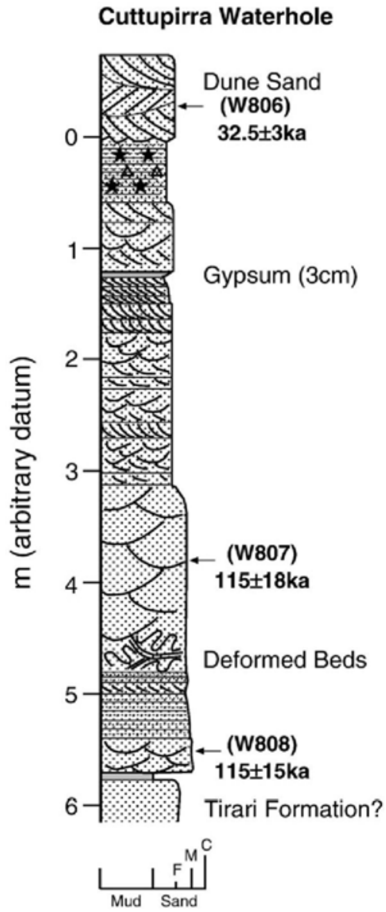


Fig.13. Stratigraphic section at Cuttapirra Waterhole (Fig. 3b). This location has not been accurately surveyed to AHD and therefore heights are given only to a relative datum. For key see Fig. 11.

Interestingly, no Pleistocene deposits dating in the range between ~750 and ~300 ka as occur at depth beneath the Shire Road transect were found along lower Cooper Creek. Such deposits may exist elsewhere in the region, as for example along the southern meander branch which has so far not been investigated. Unfortunately, the luminescence dates from Kutjitara deposits at Lake Hydra, some 30 km south of the present course of Cooper Creek, were saturated at N400 ka, but they could conceivably be as young as Middle Pleistocene which would indicate that the extensive fan-delta and expanded lake system they represent is more recent than proposed by Tedford et al. (1986).

6. Ages of alluvium in the Lake Eyre basin and northern Australia

In order to assess the relative abundance of alluvium in different age classes in central and northern Australia, a sequence of histograms are presented in Fig. 16. They represent a total of 221 TL samples collected from outcrops and auger holes over the past ~25 years. Mostly sandy alluvium representative of relatively high-energy bed-load transport (i.e., uncharacteristic of today's muddy rivers) has been sampled, hence the distributions represent an approximate index for the intensity and spatial extent over time of flows capable of moving bedload. In Fig. 16b for northern Australia, 22 plunge-pool beachridge samples (Nott and Price, 1994; Nott et al., 1996) have been included as representative of enhanced waterfall activity, as have 33 colluvial-sand samples indicative of the active formation sand aprons adjacent to escarpments in Arnhem Land (Roberts, 1991). No duplicate dates are included although where individual strata are especially thick or laterally extensive, the same strata may have been sampled more than once. In Fig. 16a the TL dates described in this study are combined with those from earlier work and presented as a distribution of 112 dates from the northeast quadrant of the Lake Eyre basin. They show pronounced fluvial conditions extending back to OIS 7 and 8 and a marked peak of activity in OIS 5 between about 120 and 75 ka. There is a smaller peak in late OIS 4 (65–60 ka) and another in mid OIS 3 (45– 40 ka). Throughout much of the Quaternary, the Lake Eyre Basin has been affected to varying degrees by tropical airmasses from seas north and northeast of Australia. A plot of 109 TL published (Nott and Price, 1994; Nott et al.,1996; Nanson et al., 2005) and previously unpublished dates for rivers in northern Australia, north of the Lake Eyre Basin (Fig. 16b), also show pronounced fluvial conditions extending back to at least OIS 7.

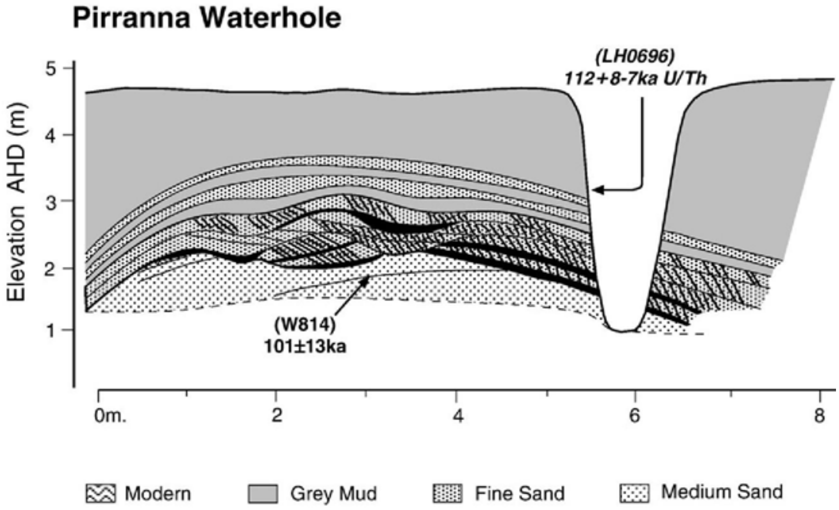


Fig. 14. Pirranna Waterhole (Fig. 3 b), showing an exposure of scroll-pattern floodplain formed of sandy trough sets at the base and grading upwards to interbedded muddy and silty fine sands and an upper unit of massive muds. A Useries date was obtained from a carbonate and gypsum rhizomorphinthe gully perpendicular to the exposure and stratigraphically at the contact between the overbank unit of massive mud overlying the interbedded sands and muds. This location has not been accurately surveyed, however, the top of the section was measured with an Omnistar-based DGPS to be 4.5±1.5 m AHD and an approximate vertical scale is given.

However, compared to the Lake Eyre basin, there appears to be limited fluvial activity in the north in OIS 5 and a marked increase in OIS 3. Interestingly, there appears to have been a sharp increase in runoff after the LGM, rising to a maximum in the early to mid Holocene and declining in the late Holocene.
Combining both histograms provides an index of the average runoff characteristics for the northeastern quadrant of Australia (Fig. 16c). Despite the decreased probability of locating and dating alluvium from the older parts of this record, there appears to have been marked fluvial activity to from least OIS 8 and 7 (a glacial and interglacial, respectively). There is also evidence for fluvial activity in OIS 6 (a glacial) but increasing markedly in OIS 5 (an interglacial), followed by a drop and then a sharp rise in OIS 4 (a stadial) that continues into OIS 3 (an interstadial). There were declining flows towards the LGM. The sharp rise after the LGM and into the Holocene appears to have been restricted largely to northern Australia although is recognisable on Cooper Creek within the confinement of the Innamicka Dome (Fig. 6).

While this record will only represent an approximation of flow regime changes, the magnitude of the changes appear to be substantial over a widespread area of the continent and reinforces the interpretation by Nanson et al. (1992) that Australia has experienced a marked oscillatory climate alternating between prolonged wet and dry episodes during the mid and late Quaternary.

South Tilla Tilla Waterhole

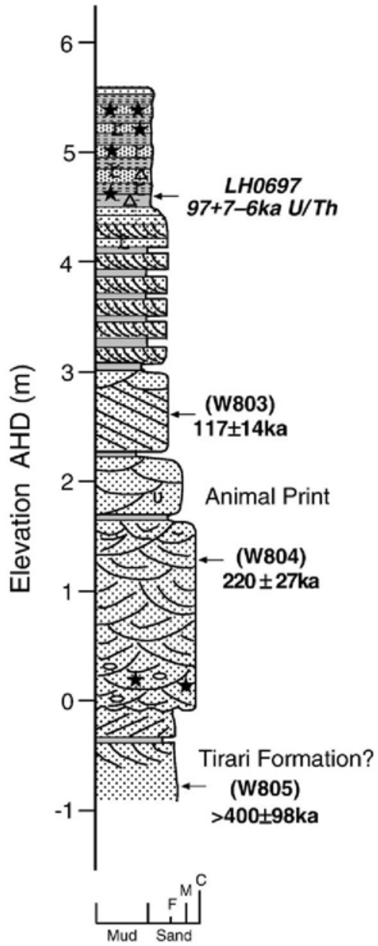


Fig. 15. Stratigraphic section South Tilla Tilla Waterhole (Fig. 3b). This location has not been accurately surveyed, however, the top of the section was measured with an Omnistar-based DGPS to be 5.5±1.5 m AHD and an approximate vertical scale is given. For key see Fig. 11.

7. Summary and discussion

Cooper Creek drains a large part of the eastern Lake Eyre basin and alluvium from the Late Tertiary to the Holocene has been deposited in a sequence of shallow neotectonic structures along the lower 500 km of its length. The older Quaternary and Tertiary deposits are beyond the range of absolute dating, however, luminescence has yielded a chronostratigraphy from ~750 ka to late Holocene. Some of the region's neotectonic structures clearly remain active with Cooper Creek's dated alluvial record indicating that the Innamincka Dome is rising at a rate of ~36 m Ma^{-1}, plus the rate of channel incision that is yet to be determined.

Alluvial evidence suggests much higher precipitation and runoff in the eastern Lake Eyre basin during Late Tertiary and Early to Middle Pleistocene than later. These climate conditions must have fluctuated considerably during the Quaternary, with one of the oldest Pleistocene units described here, the Kutjitara Formation, showing signs of base level incision and accretion near Lake Eyre before 400 ka. During times of pronounced wetness and increased runoff, Cooper Creek has been able to laterally migrate and rework a vast store of sandy bedload now sealed in extensive floodplains capped by 2–6 m of alluvial mud (Nanson et al., 1988, 1992). However, superimposed on these intense variations appears to have been an overall drying trend from OIS 7 or possibly earlier. For example, during OIS 6 and earlier the entire Cooper Creek floodplain at the Shire Road was reworked, but in OIS 5 only about one third of it was replaced. Even less has happened since then. On lower Cooper Creek, the Tirari and Kutjitara Formations in the Tirari Desert reveal widespread fan-delta alluviation towards an expanded Lake Eyre in the Late Tertiary and Early Pleistocene. During or perhaps before OIS 7 to 5, Cooper Creek incised to a lower lake level (or series of lower lake levels) leaving deposits only along two relatively narrow meander tracts (Fig. 10). A progressive increase in aridity during the middle to late Quaternary has been noted in Australia from a variety of proxy climatic data (e.g. An et al., 1986; Chen and Barton, 1991; Chen et al., 1991; Nanson et al., 1992), and is especially recognisable over the past ~350 ka (e.g. Hesse, 1994; Kershaw et al., 2003).

Bankfull discharges on Cooper Creek in OIS 7–6 are estimated at one location tohave been about 5to 7 times larger than those of today. A discharge estimate could not be obtained for OIS 5 but the stratigraphy from the Shire Road indicates that during that stage Cooper Creek was only able to rework about one third of a floodplain that it had entirely reworked in OIS 6 and earlier. Furthermore, source-bordering dunes were supplied from what must have been strongly seasonal flows along Cooper Creek in mid to late OIS 5, and again in OIS 3. Clearly, increasing aridity had greatly diminished this major Australian inland river by about 40–35 ka.

Only proximal to the Innamincka Dome, where local flow confinement and steepening amplified declining stream powers, has an alluvial signature of enhanced flows along Cooper Creek been preserved after ~35 ka. This location indicates larger discharges than today during or near the LGM, and again in the early to middle Holocene. Nanson et al. (1998) have evidence for possible short-lived high-stands in Lakes Frome and Eyre during or near the LGM, and Nanson et al. (1995) have shown that the Finke River on the western side of the Lake Eyre basin was fluvially active and able to rework its confined floodplain in the early to middle Holocene. Computations from palaeochannel dimensions in the Innamincka Dome indicate that bankfull flows on Cooper Creek at this time could have been a remarkable 8–9 times greater than present. If this is the case, then a lack of reworking elsewhere on Cooper Creek floodplain at that time (e.g. Shire Road and Chookoo, and Nanson et al., 1988; 1992) suggests such Holocene flows were powerful but short lived, perhaps catastrophic rather than systematic in character.

Confirmation of greatly enhanced runoff into waterfall plunge pools in northern Australia at about the time of the LGM, and again in the early to middle Holocene, has been obtained by Nott and Price (1994) and Nott et al. (1996). Such features could indicate relatively short-lived tropical cyclones or cluster of cyclones in northern and central Australia, rather than an overall upward shift in the flow regime. This suggests more erratic climate and flooding conditions during the temperature maxima and minima of the glacial-cycles compared to the more sustained periods of systematic perennial or seasonal runoff that reworked the extensive floodplains of Cooper Creek during the intervening periods.

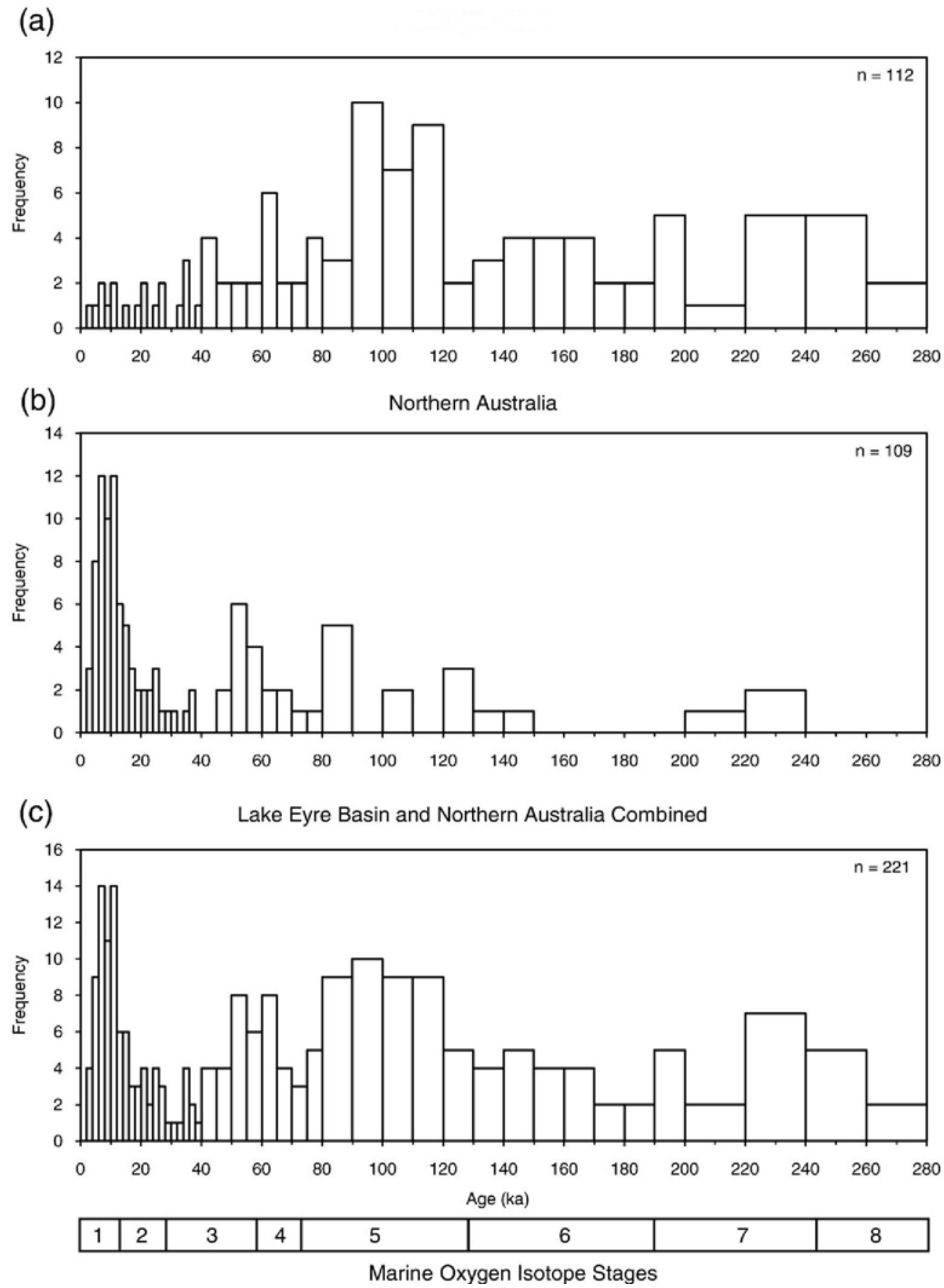


Fig. 16. Age histograms illustrating the frequency of TL samples dated in various age classes for: (a) the Lake Eyre basin; (b) Northern Australia; (c) the Lake Eyre basin and northern Australia, combined. Because age uncertainties increase with age, and the preservation of material and hence the probability of sampling material declines with age, class sizes have been adjusted as follows: 2 ka class size from 0 to 40 ka; 5 ka class size from 40 to 80 ka; 10 ka class size from 80 to 200 ka; 20 ka class size from 200 to 300 ka. Marine oxygen isotope stages after Martinson et al. (1987).

Evidence for episodes characterised by huge river discharges on what is now the globe's largest arid ice-free continent begs two important questions; where did all the water come from and why has this supply varied so dramatically? Nanson et al. (1992) found that fluvial activity in the Channel Country during OIS 5 probably peaked at ~110 ka, with subsequent fluvial evidence, including that provided here, generally supporting the argument that the rivers in the Lake Eyre basin and northern Australia were most active in middle to late OIS 5 (Fig. 16c). It has subsequently been assumed that the climate driver must have been an enhanced monsoon, not just at the interglacial maximum (OIS 5e) but also later in OIS 5 when temperatures were cooler and sea levels lower (e.g. Magee et al., 1995, 2004; Croke et al., 1998). The problem with such a scenario is that it requires development of several complex models to explain firstly, the abundance of moisture reaching the arid central regions of the continent at times of both high and reduced global temperature and sea levels, and secondly, the perceived failure of the present interglacial (the Holocene) to return high levels of precipitation and runoff to the now-arid centre (Johnson et al., 1999; Miller et al., 1999, 2005a and b; Magee et al., 2004).

It is beyond the scope of the present paper to evaluate the complex sequence of events these models require, however, data presented here may offer a simple alternative explanation. Evidence by Magee et al. (2004) for an OIS 5e maximum at ~10 m AHD is based essentially on a limited number of beach ridge OSL dates for that elevation at that time from Lake Eyre. However, the uncertainties around these dates suggests they may all lie outside the range of OIS 5e where most of their other beach ridge dates in fact lie. Evidence for high water levels at Lakes Woods and Gregory in northern central and northern western Australia (Bowler et al., 1998, 2001), and the compendium of fluvial chronology from Fig. 16 supports an interpretation that prolonged precipitation maxima may not have occurred during but rather after OIS 5e. Very significantly, there is no evidence thus far for a substantial deposit of the Katipiri Formation commensurate with a 10 m AHD Lake Eyre on lower Cooper Creek; the extensive alluvial sequences here appear to be graded to a lake level well below this (e.g. Figs. 14 and 15). It may be that the higher beach ridges are the result of shortlived and therefore exceptional lake level excursions above the elevation rivers entering the lake were graded to while they were building floodplains to lower lake levels over prolonged periods of time.

The evidence from Australia's northern lakes by Bowler and co-workers, and the alluvial dates revealed in Fig. 16, suggest global conditions in OIS 5e more in keeping with those at times during OIS 4 and 3 when temperatures and sea levels were neither particularly high nor low. This removes the need for climatic conditions that led to increased moisture in Australia at various times when conditions were both warmer and cooler than the present. It also removes the need to speculate why the Holocene has failed to supply greatly enhanced precipitation (Magee et al., 2004); such conditions could follow the Holocene when, as in the past, temperatures and sea-levels achieve more intermediate levels.

If maximum precipitation and runoff were achieved under conditions cooler than present, then Australia's northern monsoon is unlikely to have been a major source of the moisture. Alternatively, a western Pacific warm pool trapped close to eastern Australia by reduced sea levels and the abandonment or confinement of passage ways through Torres Straight and the Indonesian archipelago, may well have been sufficient. Such conditions could have created a semipermanent ‘La Nina’ with trade winds crossing the Coral Sea and Queensland and irrigating the Lake Eyre basin. Furthermore, increased warm water would have travelled down the east Australian current under conditions of greater ocean to atmosphere temperature gradients, providing greater atmospheric instability and an enhanced supply of moisture to the rivers of southeastern Australia. Indeed, thoroughly documented evidence shows southeastern Australia experienced greatly enhanced discharges at much the same time as the eastern Lake Eyre basin (Nanson et al., 1992; Page et al., 1996; Nanson et al., 2003), something that would be difficult to achieve with an enhancement of the monsoon alone. Nevertheless, resolution of the exact timing and cause of major changes in precipitation and runoff in Australia during the Quaternary will require additional data from diverse sources and improved chronological resolution. All three are gradually being achieved.

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