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Late Quaternary palaeoenvironmental change in the Australian drylands

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ABSTRACT

In this paper we synthesise existing palaeoenvironmental data from the arid and semi-arid interior of the Australian continent for the period 40–0 ka. Moisture is the predominant variable controlling environmental change in the arid zone. Landscapes in this region respond more noticeably to changes in precipitation than to temperature. Depending on their location, arid zone records broadly respond to tropical monsoon-influenced climate regimes, the temperate latitude westerly systems, or a combination of both.

The timing and extent of relatively arid and humid phases vary across the continent, in particular between the westerly wind-controlled temperate latitudes, and the interior and north which are influenced by tropically sourced precipitation. Relatively humid phases in the Murray-Darling Basin on the semi-arid margins, which were characterised by large rivers most likely fed by snow melt, prevailed from 40 ka to the Last Glacial Maximum (LGM), and from the deglacial to the mid Holocene. By contrast, the Lake Eyre basin in central Australia remained relatively dry throughout the last 40 ka, with lake high stands at Lake Frome around 35–30 ka, and parts of the deglacial period and the mid-Holocene. The LGM was characterised by widespread relative aridity and colder conditions, as evidenced by extensive desert dune activity and dust transport, lake level fall, and reduced but episodic fluvial activity. The climate of the deglacial period was spatially divergent. The southern part of the continent experienced a brief humid phase around ~17–15 ka, followed by increased dune activity around ~14–10 ka. This contrasts with the post-LGM persistence of arid conditions in the north, associated with a lapsed monsoon and reflected in lake level lows and reduced fluvial activity, followed by intensification of the monsoon and increasingly effective precipitation from ~14 ka. Palaeoenvironmental change during the Holocene was also spatially variable. The early to mid-Holocene was, however, generally characterised by moderately humid conditions, demonstrated by lake level rise, source-bordering dune activity, and speleothem growth, persisting at different times across the continent. Increasingly arid conditions developed into the late Holocene, particularly in the central arid zone.

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1. Introduction

Australia is the world's driest inhabited continent. Approximately half of the land mass is either arid or semi-arid. The area experiencing such climates fluctuated considerably due to varying global climate cycles during the Quaternary, but the extent and intensity of these fluctuations, while receiving increasing attention, remain poorly defined.

In recent years substantial developments have been made in our understanding of environmental change in the arid interior, namely through: 1) a larger chronological dataset focussing on luminescence dating; 2) further consideration of the interpretation of proxy records; and 3) more systematic integration of techniques for palaeoenvironmental reconstruction. In this review we incorporate new data and methods not previously available in earlier reviews, enabling a more robust correlation with regional and global palaeoclimatic records. Due to the poor preservation potential of organic material such as pollen and charcoal, in most cases palaeoenvironmental reconstruction for the Australian continental interior must rely on geomorphic archives such as dunes, playas and fluvial systems which, while discontinuous, broadly preserve responses to climatic change.

This paper presents a review of arid and semi-arid zone palaeoenvironmental records for the Australian continental interior over the past 40 ka. This period is characterised globally, including within Australia, by substantial climatic changes, including the stadial and interstadial oscillations of marine isotope stage (MIS) 3, the Last Glacial Maximum (LGM), and the deglacial transition to Holocene interglacial climates (Walker et al., 1999; Turney et al., 2006). Earlier reviews demonstrated that the Australian continental interior was subject to variation in both the intensity and spatial extent of arid conditions during this period (Bowler, 1976; Bowler and Wasson, 1984; Wasson and Donnelly, 1991; Nanson et al., 1992b; Hesse et al., 2004). More recently published data provide additional information relating to landscape response to precipitation variability and, to some extent, changes in wind regime and intensity. These data come in the form of reconstructions of desert dunefield reactivation, expansion and contraction, varying lake levels, river hydrology, and speleothem growth. This review interprets arid zone environmental change through the convergence of this new information with earlier data.

2. The Australian continental interior

The majority of inland Australia experiences an arid to semi-arid climate (Fig. 1A). Since the continental interior lacks substantial topographic barriers to climatic systems, the region is primarily subject to the influence of seasonal zonal circulation, with a major effect exerted by continental heating and land-sea temperature contrast (Gimeno et al., 2010). Broadly, southern Australia experiences winter dominance in rainfall associated with westerly cold fronts. It is also evident from the orientation of longitudinal dunes in the south that westerly winds have been responsible for desert dunefield formation (e.g. Wasson et al., 1988; Fitzsimmons, 2007). Northern Australia is influenced by the summer monsoon and southeasterly trade winds in the winter, the latter being particularly influential in the northeast. In summer, precipitation in the central and northern drylands may also be derived from inland-migrating troughs and depressions formed by heating over the oceans. The arid core of the continent, centred on the large playa Lake Eyre, receives on average 125–150 mm annually, with high interannual variability. This precipitation is not dominated by any one climatic system over another (Fig. 1A). Compared with many deserts, precipitation in the Australian deserts is relatively high. Consequently inland Australia is relatively well vegetated compared with other deserts (Hesse and Simpson, 2006; Hesse, 2010). No parts of dryland Australia are classified as hyperarid.

The continental interior contains extensive longitudinal (linear) dunefields (Fig. 1B), which form broadly parallel to the resulting sand-shifting wind vectors (McKee, 1979; Rubin and Ikeda, 1990; Reffet et al., 2010). These occupy approximately one third of the continent, and extend beyond the presently arid regions (Wasson et al., 1988; Hesse, 2010), providing evidence of more extensive aridity in the past (Bowler, 1976; Hesse, 2010). Despite minor modern mobilisation of dune crests, particularly in the drier centre of the continent, the dunes are presently relatively stable and immobile (Hesse and Simpson, 2006). Exceptions to dune stability can be found in areas which have been disturbed by clearing for agriculture and grazing, for example in the vicinity of watering holes on pastoral leases, and farmed areas in southeastern South Australia in contrast to the conservation reserves in comparable landscapes in Victoria. A state of intermittent partial dune activity prevails under the present climatic conditions. The longitudinal dunes are distributed in a counter-clockwise whorl focused on the centre of the continent at 26 °S (Fig. 1B) (Jennings, 1968; Brookfield, 1970; Hesse, 2010), proposed to have been produced by the interaction of the westerlies in the south and easterlies in the north (Hesse, 2011). Dune distribution is complicated at the regional scale by the interplay between climate, topography, lithology and sediment supply (Jennings, 1968; Hesse, 2010), and the varying dominance of these factors through time. Consequently there is still controversy over the relative importance of supply, availability and transport limitation in dunefield formation. Supply limitation has long been recognised as allowing the growth of so-called "source-bordering" dunes in riparian and shoreline settings (Butler et al., 1973; Cohen et al., 2010).

The interior of the continent also contains large catchments and ephemeral playa lakes. The eastern portion of the arid zone is dominated by two large catchments: the Lake Eyre basin (LEB) that drains internally to Lake Eyre and the Frome-Callabonna lake system, and the Murray-Darling basin (MDB) that drains to the Southern Ocean. Together they comprise approximately one third of the continent (Fig. 1A). Both catchments have at least part of their headwaters located within the summer-dominated rainfall zones to the north (the MDB less so), and terminate in the westerly-influenced region. In the LEB, Cooper Creek and the Diamantina River system flow southwestward through the Strzelecki and Tirari dunefields. The Riverine Plain of the MDB, formed by the Murray, Murrumbidgee and Lachlan Rivers, comprises permanent watercourses characterized by low energy flow (Kemp, 2004). The now abandoned Willandra Creek diverges from the Lachlan River into the presently dry Willandra Lakes system (Bowler and Magee, 1978; Bowler et al., 2003). Transverse source-bordering dunes, including lunettes and palaeoshorelines, occur in association with playas and palaeochannels in both catchments.

3. Methods for palaeoenvironmental reconstruction in arid Australia

3.1. Geomorphology, sedimentology and stratigraphy

The landforms of the inland deserts are a product of increasing aridification which began prior to the onset of the Quaternary (Bowler, 1982). This trend initiated with the playa lakes (English et al., 2001) and stony desert pavements (Fujioka et al., 2005), and was followed by the development, and subsequent expansion and contraction, of desert dunefields (Fujioka et al., 2009). Successive arid and relatively humid phases are reflected in the response of these landforms (Bowler, 1976; Fujioka and Chappell, 2010). Enhanced aridity may correspond to landscape instability,

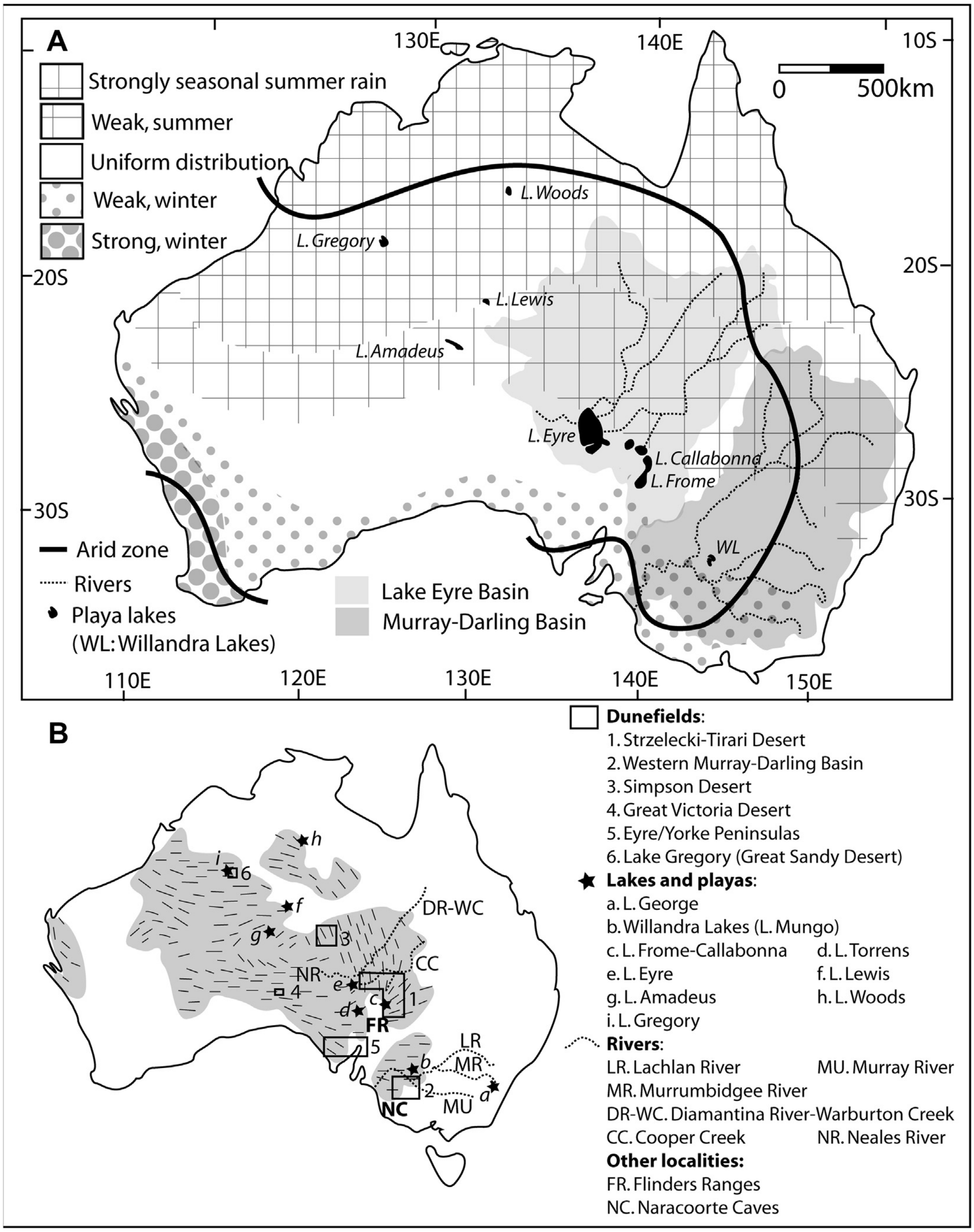

Fig. 1. A. Map of the Australian mainland illustrating the distribution of rainfall seasonality. The transition from semi-arid to arid climate is marked by a thick black line. The large catchments of the LEB and MDB are shown in grey, along with their major watercourses. Major playas and lakes described in the text are indicated in black. B. Distribution and orientation of desert longitudinal dunefields and major watercourses on the Australian mainland. The locations of study areas discussed in the text are shown. The Diamantina River flows into Warburton Creek downstream; given the scale of the map the two are shown as a single system, but can be distinguished in (A).

and is expressed as dune reactivation, lake basin deflation and deposition of eroded sediment downwind to form transverse dunes or lunettes (Bowler, 1973; Fitzsimmons et al., 2009), increased dust mobility (Hesse and McTainsh, 2003), and reduced river discharge and channel size (Nanson et al., 1992b, 2008). By contrast, relatively humid conditions may stabilise desert dunes through pedogenesis and increased vegetation (Fitzsimmons et al., 2009; Hesse, 2011), reduced long-distance dust transport (Hesse and McTainsh, 2003), and increase bankfull discharge in fluvial systems (Nanson and Tooth, 1999). Arid zone lakes under humid regimes may experience perennial high levels, resulting in waves depositing sandy lunettes downwind (Bowler, 1983). Consequently the deposition of clean sand reflects high water levels, compared with pelletal clays which are deposited in response to ephemeral lake conditions (Bowler, 1983, 1986; Magee, 2006). Responses to change can be recognised from landform morphology and stratigraphy associated with each environmental period. Generally, landscapes of the arid zone appear to preserve responses to variability in moisture availability rather than temperature.

However, records of landscape response are beset by limitations which must first be acknowledged before a palaeoenvironmental synthesis can be attempted. The reworking of arid zone landforms, particularly of dunes in sediment-poor regions such as the Australian interior (Wasson and Hyde, 1983), often prevents the preservation of continuous deposits (e.g. Munyikwa, 2005a; Fitzsimmons and Telfer, 2008). Landscape change in the arid zone is frequently a response to multiple contributing factors which must be decoupled to allow palaeoclimatic interpretation. Interpretation of landforms is also critically dependent on accurate and appropriate chronologies. As a consequence of these limitations, it is realistically only possible to undertake a broad brushstroke approach to reconstructing palaeoenvironments in the continental interior, based on the general convergence of proxy information.

Australian desert dune archives have the advantage over most other well-known dunefields in sometimes preserving multiple horizons separated by paleosols (Stone and Thomas, 2008; Fitzsimmons et al., 2009) (Fig. 2A, B), thereby recording both phases of mobilisation and stability. However, dune reworking, and the potential for paleosol removal, complicates attempts to correlate stratigraphy between sites (Fitzsimmons et al., 2007a, 2007b; Fitzsimmons and Telfer, 2008). Partial preservation bias at individual sites may be at least partly addressed by undertaking regional-scale chronostratigraphic surveys (e.g. Fitzsimmons et al., 2007b; Lomax et al., 2011). Furthermore, it is often difficult to determine the dominant cause of aeolian remobilisation. Longitudinal dune building may be governed by sand supply, availability (in part affected by vegetation cover) and wind transport capacity (e.g. Wasson and Hyde, 1983; Hesse, 2011). Sand may be supplied from nearby rivers or lakes, by climatic change to more arid conditions causing reduced vegetation and soil crust cover (Wasson and Nanninga, 1986; Rajot et al., 2003; Hesse and Simpson, 2006), or by increased transport capacity through stronger or more frequent strong winds (Rubin and Ikeda, 1990; Reffet et al., 2010). Given independent evidence of stable transport capacity (Hesse and McTainsh, 1999; Hesse et al., 2003a, 2004; Hesse and Simpson, 2006), where dunefields lie beyond the influence of major fluvio-lacustrine sediment sources, large scale dune activity is assumed to have most likely occurred in response to heightened aridity (Fitzsimmons et al., 2007b).

In rivers, greater fluvial discharges, as reflected in large palaeochannels or terraces by coarser-grained sediment than is presently deposited on floodplains, can derive from greater precipitation, although it is usually not possible to attribute this to changes in total annual or peak seasonal discharge. Increased alluviation in arid zone rivers corresponds broadly to increased precipitation and runoff (including sediment input) in the catchment headwaters and the construction of more extensive floodplains (e.g. Nanson et al., 1992b, 2008). Changes in sediment texture and palaeochannel dimensions in alluvial sequences may provide quantitative indices of flow-regime change (Schumm, 1968; Page et al., 1996). However, the variability in catchment vegetation (type and distribution) will influence runoff (e.g. Hope et al., 2004), probably reducing alluvial deposition during warm, wet interglacials (Hesse et al., 2004). Additionally, increased seasonal snow melt in highland catchment headwaters may increase flow during colder, though relatively arid, glacial periods (Kemp and Rhodes, 2010).

In shoreline dunes adjacent to lakes and playas, sedimentation is in some cases comparatively continuous, and sediment composition varies depending on hydrologic change (Bowler, 1986). However, the size of the catchment (and the lake size relative to catchment area) needs to be considered with respect to precipitation source, particularly considering the presence of very large catchments in the central arid zone (Bowler, 1981, 1986; Allen, 1985; Magee et al., 2004; Cohen et al., 2011). This is exemplified by the case of the Frome-Callabonna system within the LEB, where lake filling is influenced by Cooper Creek inflow from tropical moisture sources in the north, and at times by inflow from the adjacent Flinders Ranges which is predominantly reliant on westerly-derived precipitation (Cohen et al., 2011, 2012).

3.2. *Geochemical and palaeoecological proxies*

Geochemical and palaeoecological proxies, where available, can provide less ambiguous palaeoclimatic information than their geomorphic counterparts. Organic material, such as pollen and microbial lipids, and siliceous plant phytolith remains, while uncommon, are preserved at some sites, where they provide palaeoecological records (Luly, 2001; Pearson et al., 2001; Wallis, 2001; Pearson and Betancourt, 2002; Cupper, 2005; Bray et al., 2012). In many cases, however, this information is fragmentary or

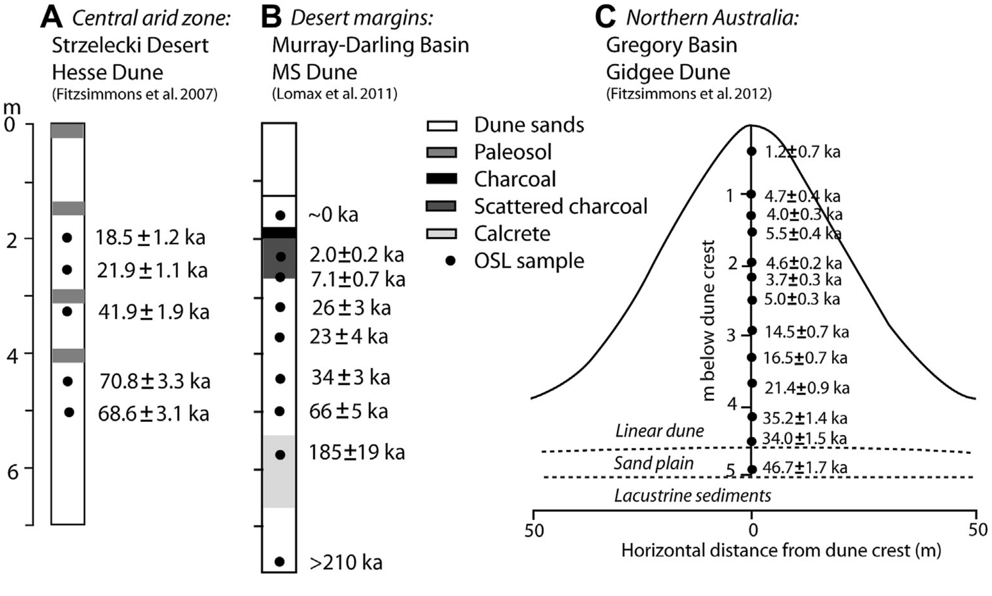

Fig. 2. Examples of longitudinal dune internal stratigraphy and age–depth relationships, for (A) the central arid zone (Fitzsimmons et al., 2007b); (B) MDB desert margins (Lomax et al., 2011); and (C) northern monsoon-influenced region (Fitzsimmons et al., 2012).

limited to the Holocene period due to poor preservation potential in arid environments. This is also the case for charcoal records which reflect the temporal and spatial variability of fire regimes. Charcoal fragments have been shown to reflect climatic change, with cooler conditions represented by less and warmer phases by more frequent fire (Mooney et al., 2011). Such records, however, are also both rare and poorly preserved in the arid interior.

The most common use of speleothems in palaeoenvironmental reconstruction is to assess past rainfall variation via their oxygen isotope ratios (e.g. Treble et al., 2005). However, with the exception of a ∼7–6 ka isotopic record (Quigley et al., 2010), there are no detailed or lengthy speleothem records for the last 40 ka period in arid zone Australia. Speleothem precipitation requires dripping water that is super-saturated with respect to calcite, and as such is a consequence of complex interactions between infiltrating rainwater, cave hydrology, temperature, and the concentration of carbon dioxide and calcium within the water, with the former controlled in part by plant productivity on the surface (Fairchild and Baker, 2012). Although speleothems are not a function of rainfall quantity alone, enhanced speleothem formation has been interpreted to indicate periods of higher effective precipitation in the past on the arid zone margins of Australia (e.g. Ayliffe et al., 1998; Cohen et al., 2011). Whilst these studies are more common on semi-arid desert margins (partly due to local geology but also availability of moisture), speleothem growth in these regions helps elucidate the expansion and contraction of the arid core (Ayliffe et al., 1998; St Pierre et al., 2009). As yet no reliable speleothem records have been located or analysed from the monsoon-affected northern arid zone.

The development of geochemical techniques has enabled palaeotemperature reconstruction by measuring rates of amino acid racemisation (AAR) (e.g. Miller et al., 1997), and palaeodiet records reflecting ecosystem change based on the variation of carbon isotopes within fossil eggshell (Johnson et al., 1999). Eggshell from large flightless ratite and dromornithid bird species is one of the most abundant fossil materials in the southern arid interior, and retains its proteinaceous and geochemical integrity over time (Miller et al., 1997). In addition, stable isotope analysis of carbon and nitrogen relating to palaeodiet, and by association to palaeovegetation and precipitation, may be applied to wombat teeth (Fraser et al., 2008), fish otoliths (inferring water salinity; Bowler et al., 2012), and eggshell (Johnson et al., 1998; Miller et al., 2005). Stable isotope analyses can similarly be applied to soil carbonates (Pack et al., 2003), and element ratios from lake precipitates and microfossils such as ostracods may yield palaeohydrological information (De Deckker et al., 2011). These approaches have the advantage of providing more precise palaeoclimatic data than geomorphic archives, but are restricted by preservation and availability.

3.3. *Geochronology*

Our understanding of palaeoenvironmental change in the Australian interior depends heavily on the reliability and suitability of geochronological techniques. Early hypotheses for the timing of aridification in Australia were made prior to the widespread availability of absolute dating. Gill (1955), for example, suggested that the major arid phase responsible for the formation of the present-day landscape took place during the mid-Holocene. Subsequent radiocarbon dating on various materials (Callen et al., 1983) across the arid zone extended the record back to the LGM (Bowler, 1976; Callen, 1984). These studies identified a widespread and intense cold, arid LGM in the continental interior (e.g. Bowler, 1976; Hesse et al., 2004). However, due to the lack of sufficiently well preserved organic material in desert dunes, and the unsuitable nature of pedogenic carbonate for dating (Callen et al., 1983), the timing of environmental change in the Australian arid zone remained poorly understood.

Substantial improvement in the reliability of determining the ages of Australian arid zone sediments occurred with the widespread application of luminescence techniques, initially using thermoluminescence (TL) (Wasson, 1983; Rust and Nanson, 1986; Gardner et al., 1987; Readhead, 1990; Nanson et al., 1992a, 1998), and later optically stimulated luminescence (OSL) (e.g. Bowler et al., 2003; Lomax et al., 2003). Luminescence dating directly determines the timing of sediment deposition based on the most recent exposure to sunlight (Aitken, 1998). It is an eminently suitable technique for determining the timing of landscape response to environmental change in the arid zone, particularly for desert dunes, given the high likelihood of exposure to sunlight prior to burial, and for the period of interest to this review (Lancaster, 2008; Singhvi and Porat, 2008). OSL has largely superseded TL as a dating method for quartz-rich sediments, although nevertheless a substantial TL dataset exists (e.g. Nanson et al., 2008). OSL has been shown to be particularly suitable for dating Australian quartz on the basis of sensitivity and reproducible response to measurement protocols (Pietsch et al., 2008; Fitzsimmons et al., 2010). Until recently, however, most studies in the Australian desert dunefields focussed on small areas (Lomax et al., 2003; Fitzsimmons et al., 2007a), leaving them at risk of localised sampling bias. This is beginning to be addressed by larger, regional scale datasets based on multiple sites (Hollands et al., 2006; Fitzsimmons et al., 2007b; Lomax et al., 2011).

OSL dating, however, is not without limitations, particularly when applied to discontinuous records. The technique dates only the most recent depositional event, and therefore reliable analysis of the duration of phases, such as aeolian reworking within dunes, is not feasible. The problem is less acute in arid zone floodplain contexts which are typically several to hundreds of kilometres wide and less easily reworked. However, these deposits face the problem of high clay content when sand-sized quartz is often sought for dating. Furthermore, the luminescence signal can be reset subsequent to deposition by exposure, and age populations may be mixed through bioturbation (Bateman et al., 2003). This is of particular concern in environments or intervals with low sedimentation rates, where such processes may overprint the depositional signal. To some degree this problem can be identified, if not always rectified, using single grain in preference to single aliquot measurements (Duller, 2008). Dose rate heterogeneity is also an issue for age estimate precision (Lomax et al., 2007; Darrénougué et al., 2009). Finally, at 5–10% uncertainty OSL is unlikely ever to reach the precision of radiocarbon, which reduces the resolution of palaeoenvironmental reconstruction.

Dating based on the accumulation of cosmogenic nuclides within sediments, as a result of interaction with cosmic rays, has successfully been applied in the arid zone both to surfaces in order to determine the timing of exposure of desert pavements (Fujioka et al., 2005) and the burial of quartz sand (Fujioka et al., 2009). However, complications with exposure histories prevent its utility during the period of interest to this review.

Alternative geochronologic techniques are applied to non-geomorphic proxies such as fossil eggshell and speleothems. U-series dating is the most suitable method for dating speleothems (Ayliffe et al., 1998). In the case of fossil eggshell, recent work yielded comparable age estimates using ^{14}C, U-series and AAR, with luminescence dating of sediment trapped within the same eggshell also lying within uncertainty limits, supporting an argument for the accuracy and suitability of each technique, and of eggshell as a suitable material for multiple dating techniques (Magee et al., 2009).

4. Geomorphic response to palaeoenvironmental change in the Australian arid zone

4.1. Desert dune records

The review by Hesse et al. (2004) of Australian arid zone records argued for a general trend of increasing aeolian activity in desert longitudinal dunefields from MIS 4 to the LGM, peaking around 20–10 ka and decreasing during the Holocene. The evidence available at the time was predominantly derived from TL and radiocarbon dating (Gardner et al., 1987; Nanson et al., 1988, 1990; Readhead, 1988, 1990; Chen, 1992; Nanson et al., 1992a, 1995; Croke et al., 1996; Spooner et al., 2001). Since that review, luminescence dating of both longitudinal dunefields and source-bordering dunes has been the focus of multiple studies across the continental interior (Hollands et al., 2006; Sheard et al., 2006; Maroulis et al., 2007; Twidale et al., 2007; Fitzsimmons et al., 2007a, 2007b; Cohen et al., 2010; Lomax et al., 2011; Fitzsimmons et al., 2012). These investigations not only attempt to eliminate the bias of sampling individual dunes by dating multiple sites throughout a region, but also interpret dune formation history in the context of the stratigraphy of individual landforms. The interior architecture of Australian longitudinal dunes is characterized by sand-paleosol packages corresponding to accretion and stabilisation respectively, in relatively thin conformable layers of increasing age (Fitzsimmons et al., 2009) (Fig. 2). This characteristic sits in contrast to the lack of stratigraphic markers for dune stabilisation in other dunefields such as the Kalahari (Stone and Thomas, 2008). Although the majority of these studies focus on the southeast (Fig. 1B), they nevertheless substantially increase the available database of dune ages within the time period of interest to this paper and provide a more comprehensive overview of aeolian activity.

In this paper we synthesise existing chronologies for longitudinal dune activity by assembling all available data for the past 40 ka. Source-bordering dunes, which more closely reflect sediment input from nearby fluvial activity, were excluded from these analyses for desert dunes. This dataset was divided into categories defined by climatic and geomorphologic similarities to look for groupings (statistical populations). These comprise the desert margins (southern MDB, Eyre and Yorke Peninsulas, and subhumid Blue Mountains: Hesse et al., 2003a; Twidale et al., 2007; Lomax et al., 2011; A. Hilgers, unpublished – see Supplementary Table S1), central arid zone (Strzelecki, Tirari, Simpson and Victoria Deserts: Nanson et al., 1995; English et al., 2001; Lomax et al., 2003; Hollands et al., 2006; Sheard et al., 2006; Fitzsimmons et al., 2007a, 2007b), and monsoon-influenced north (Fitzsimmons et al., 2012). Both the southeast desert margins and southern portion of the central arid regions are most strongly influenced by westerly systems, based on dune orientation, although summer rainfall regimes penetrate the central arid zone (Croke et al., 1999). Within the semi-arid desert margins of the MDB, Lomax et al. (2011) also identified spatially variable behaviour between the longitudinal, parabolic, and supply-limited source-bordering dunes, on the basis of sediment supply, and in the case of the latter, the influence of fluvial activity. There are insufficient data from the northern monsoon-influenced region (Hesse et al., 2004; Fitzsimmons et al., 2012) to undertake a comparable statistical analysis for this region.

Several approaches were taken to present and analyse the data, in order to identify peaks in dune activity. Visual representation of dune activity is shown in the relative probability plots, radial plots and age ranking of the desert dune datasets illustrated in Fig. 3. Relative probability plots represent the normalised sum of the probability distributions of individual ages (Galbraith, 2010). Clusters of similar ages form peaks, and the height of the peaks is a function both of the number of ages in the cluster and the fractional error of the ages. Therefore younger peaks appear higher than older peaks due to their smaller absolute error, combined with potential sampling bias towards younger sediments (Surovell et al., 2009; Galbraith, 2010). Despite these limitations, it is still possible to visually interpret peaks derived from the synthesised datasets as intervals of increased aeolian activity. By comparison, the radial plot compares age estimates against their precision. It represents an alternative means of identifying populations, with less visual emphasis on absolute errors (Galbraith, 1990).

Prominent groupings of ages, interpreted to correspond to aeolian events in each region, were tested to determine if they could be interpreted as individual populations using reduced χ^2 tests, and the finite mixture model (FMM) of Roberts et al. (2000) (Table 1). Analyses of datasets based on geochronologic method (TL and OSL), compared with all ages combined, yielded comparable results. Consequently the overall analyses incorporate all available ages for each region.

The tests for the complete dataset (Fig. 3A) identify five major preserved episodes of aeolian sedimentation using both methods (Table 1). Reduced χ^2 tests support the interpretation of groups at approximately 40–29 ka, 25–18 ka, 14–10.7 ka, 5.2–4.0 ka and 2.0–1.2 ka. The population means derived from FMM analysis lie at 25.3 ka, 11.9 ka, 4.8 ka, 1.6 ka and 0.1 ka. With the exception of the oldest and youngest groups, these results are consistent. The 0.1 ka group identified using the FMM approach is a minor component, and contains too few ages to be interpreted as a population, nor can activity at this time clearly be attributed to a dominance of climatic or land use influences. The 0.1 ka group is therefore disregarded from this study. The most significant difference between the approaches concerns the period ~40–18 ka. Reduced χ^2 tests identify two peaks during this period (late MIS 3 and the LGM), whereas the FMM identifies only one (early MIS 2), which lies in between those two.

It is also evident that there is some spatial difference in the dune chronologies, particularly during the ~40–18 ka period (Fig. 3C, D; Table 1). The late MIS 3 aeolian episode, while present on the desert margins, has few ages at this time (Fitzsimmons et al., 2007b; Lomax et al., 2011), although this may be an artifact of dating precision. Dune activity around ~35 ka is also preserved in the northern monsoon-influenced region, although this event may be a response to hydrologic conditions (Fitzsimmons et al., 2012).

Aeolian activity appears to have been widespread across the continent both before and during the LGM, although with spatial and temporal variability, as observed in the divergence between the reduced χ^2 and FMM analyses (Fig. 3). The records may represent the end of an extended arid period affecting the entire continental interior, including the north, and which culminated with the LGM. An extended arid phase may have involved reworking of relatively sediment-poor dunes in the central arid zone, resulting in preservation only of the terminal LGM phase. This interpretation is supported by earlier claims of widespread LGM dune activity and aridity (Bowler, 1976). However, it also suggests that this episode was longer lived, or more complex, in inland Australia than previously thought.

The arid peak of the LGM was followed by a phase of relatively few dune ages between ~18 and 14 ka across the continent, particularly on the desert margins. Stratigraphically this phase corresponds to pedogenesis and relative stability in the central arid zone (Fitzsimmons, 2010), and therefore to relatively humid conditions.

All regions record increased aeolian deposition between ~14 and 11 ka. Aeolian activity in the central arid zone is thought to be associated with relatively warm, dry conditions (Fitzsimmons et al., 2007b). Dune ages for this interval in the presently humid Blue Mountains near Sydney are interpreted to represent an imprint of

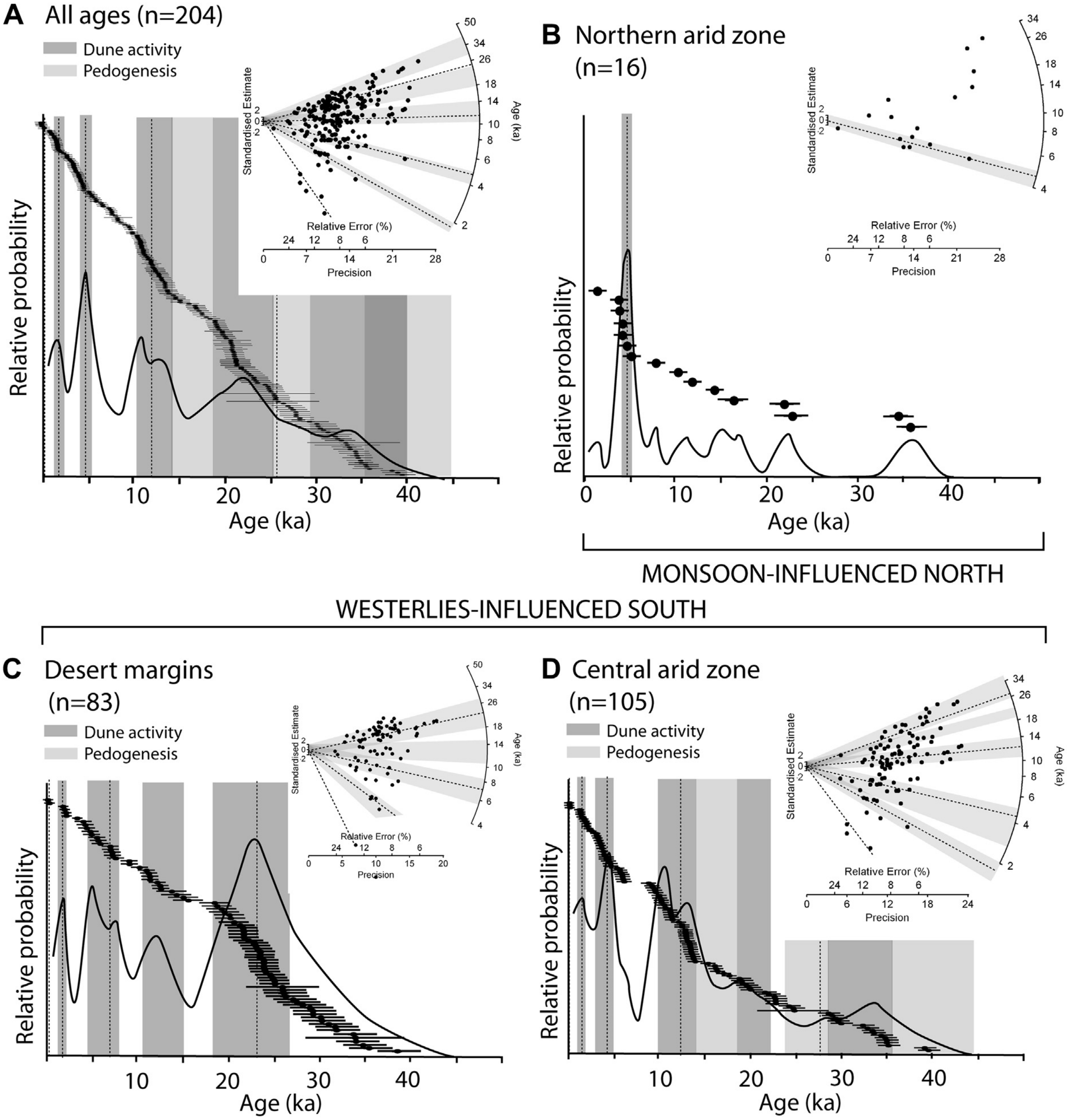

Fig. 3. Probability distribution plots and radial plots of desert dune ages, showing (A) all published ages for the Australian mainland ($n = 204$); (B) available ages for dunes in the monsoon-affected northern deserts ($n = 16$; Fitzsimmons et al., 2012); (C) all age estimates for dunes on the semi-arid desert margins within the zone affected by westerly circulation ($n = 83$; Hesse et al., 2003a, 2003b; Twidale et al., 2007; Lomax et al., 2011; A. Hilgers, unpublished – see Table S1); (D) all age estimates for dunes within the central arid zone ($n = 105$; Nanson et al., 1995; Lomax et al., 2003; Hollands et al., 2006; Fitzsimmons et al., 2007a, 2007b). On both the probability distribution plots and radial plots, statistically identified aeolian events identified using reduced χ^2 tests, are highlighted in dark grey. The population means identified using the FMM are shown with dotted lines. The approximate timing of pedogenesis in the central arid zone (Fitzsimmons, 2010), is highlighted in pale grey on the relevant probability distribution plots.

bioturbation on LGM dunes rather than continued aridity (Hesse et al., 2003a). Although dune building at this time is also preserved in linear dunes in the northwest of the continent (Fitzsimmons et al., 2012), reactivation of the monsoon from ~14 to 15 ka (Wyrwoll and Miller, 2001; Spooner et al., 2005) is proposed to have increased local sediment supply by increased bedload transport of sandy sediments onto river banks, and thence to the dunes nearby. This consequently increased the likelihood of aeolian deposition under subhumid rather than arid conditions in this region. This period, therefore, was probably not consistently arid across the interior.

Ages from desert dunes during the Holocene suggest periods of widespread dune activity (~2–1.2 ka), however at other times there appears to be a spatially variable response (e.g. mid-late Holocene). The desert margins, and particularly the western MDB (Lomax et al., 2011), preserve evidence for early to mid-Holocene remobilisation (~8.5–5.5 ka). This was a period of relatively high humidity and high lake levels in the Australian temperate zone (Petherick et al., 2013). Lomax et al. (2011) argue that this phase preceded the partial activity characteristic of present day conditions, although present day activity is also exacerbated by land use subsequent to human arrival. By contrast, relative aridity appears to have peaked during the mid- through to late-Holocene (~5–3 ka) in the central and northern arid regions.

Although desert dunes throughout Australia yield ages within the last millennium, including in the 200 years since European

Table 1
Results of reduced χ^2-tests, and identification of mean population values based on the finite mixture model (FMM) (Roberts et al., 2000), on available desert linear dune ages to determine discrete age populations corresponding to aeolian depositional events. The datasets are based on ages from the following references: All ($n = 204$; Fitzsimmons et al., 2007a, 2007b, 2012; Hesse et al., 2003a; Hollands et al., 2006; Lomax et al., 2003, 2011; Nanson et al., 1995; Twidale et al., 2007; A. Hilgers unpublished – see Table S1); Desert margins ($n = 83$; Hesse et al., 2003a, 2003b; Lomax et al., 2011; Twidale et al., 2007; A. Hilgers unpublished – see Table S1); Central arid zone ($n = 105$; Fitzsimmons et al., 2007a, 2007b; Hollands et al., 2006; Lomax et al., 2003; Nanson et al., 1995); Northern monsoon zone ($n = 16$; Fitzsimmons et al., 2012).

Dataset	χ^2-test results			Finite mixture model results	
	Time period (ka)	χ^2/ν	n	Population mean	%
All				0.1	2
	2.0–1.2	1.71	10	1.6	7
	5.2–4.0	1.16	20	4.8	19
	14–10.7	1.53	29	11.9	29
	25–18	1.46	44	25.3	42
	40–29	1.14	26		
Desert margins				0.1	2
	2.0–1.5	2.09	4	1.9	6
	8.3–5.5	1.97	11	7.2	27
	15.0–10.7	1.23	11		
	27–18	1.43	25	23.3	65
Central arid zone				0.1	3
	2.0–1.5	2.81	4	1.6	10
	4.9–3.0	1.45	13	4.5	19
	14.1–10.7	1.92	20	12.6	41
	22.0–18.0	1.27	13		
	35.7–28.0	1.75	14	27.6	27
Northern monsoon zone	5–4	2.36	4	4.8	50

arrival, no statistically significant population could be identified for this period. This period may instead reflect spatially variable and partial dune reactivation (e.g. Hesse and Simpson, 2006).

Aeolian landforms can preserve the orientation of past wind regimes. When dated, these ancient dune cores may provide a measure of changing wind direction. The alignment of successive newly constructed dunes in the northwest Simpson Desert suggest an anticlockwise rotation of longitudinal dune alignment from the LGM to the mid-Holocene, as the area became increasingly affected by easterly trade winds (Nanson et al., 1995; Hollands et al., 2006). This has been interpreted to represent the result of a southward shift of the overall circulation systems of around 1.5° latitude over this period. A transect from the Simpson Desert southward to the Mallee dunefield found a much larger divergence between dune orientation and modern sand drifts, and estimated a much greater latitudinal shift of up to 8° (Sprigg, 1982), although the timing of this shift is unknown. Continent-wide mapping shows that there is no simple translation of dune orientations north or south which matches the modern sand-shifting winds (Hesse, 2010). Instead, there is significant regional variation, with the greatest divergences along the centre of the dune whorl (26 °S) – where westerly and easterly winds converge – and in areas of onshore winds.

4.2. *Fluvial records*

Records from rivers in the interior reveal a pattern of declining fluvial activity over the last full glacial cycle (Nanson et al., 1992b, 2008). Evidence for this trend lies in increasingly smaller proportions of valley floors being reworked and deposited through time. In addition, fluvial records across much of central Australia and the Riverine Plain of the MDB show evidence for a transition from laterally active bedload-transporting channels during MIS 3, to Holocene-age suspended-load channels (e.g. Page et al., 1996; Nanson et al., 2008).

Luminescence dating of fluvial sediments has yielded useful palaeoenvironmental records in the central arid zone of the LEB (Fig. 4). This dataset comprises 45 ages from 35 sites, of which 17 are in the Cooper Creek catchment, 8 from the central arid zone uplands, and the remainder sourced from the Neales and Diamantina-Warburton Rivers. At each of these sites, the presence of significant bedload deposits is taken to be an indicator of high fluvial activity (Lewin et al., 2005). A summary of phases of enhanced fluvial activity, based on frequency analysis of dated bedload units (Fig. 4), builds on an earlier overview for the LEB covering a longer period of the Quaternary (Nanson et al., 2008). TL ages may overestimate the true depositional age, since the technique is more susceptible than OSL to partial bleaching during deposition, as well as to the averaging affect of multiple grain aliquots, which distort the true mean. However, a recent comparison between TL and OSL age estimates from the LEB rivers noted good agreement between them (Nanson et al., 2008). Overbank floodplain facies are excluded from this analysis, since although floodplain deposits may also build up during wetter phases, only bedload reliably reflects sustained higher energy flows associated

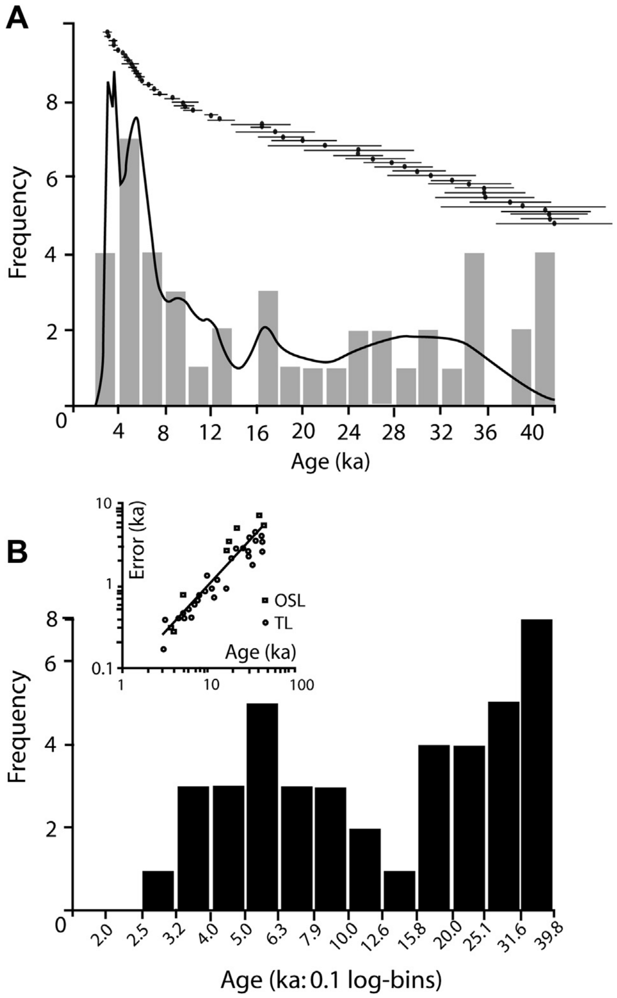

Fig. 4. Compilation of OSL and TL dated bedload units from rivers in the LEB plotted as frequency distributions of depositional ages since 42 ka ($n = 45$; Nanson et al., 1988, 1995; Croke et al., 1996; Tooth, 2007; Colman, 2002; Hollands et al., 2006; Maroulis et al., 2007; Cohen et al., 2010; Larsen, 2012). Ages <2 ka are excluded, and the weighted mean age is plotted for bedload units with multiple ages. (A) Ranked age plot with 1σ errors, histogram (linear 2 ka bins), and kernel density estimate (0.1 ka bandwidth), plotted as non-dimensional probability; (B) The same data separated into 0.1 logarithmic bins. Inset plot: 1σ errors versus age showing consistent error scaling among OSL and TL ages (error = 0.08 age$^{1.1}$, $r^2 = 0.89$).

with major channel reworking. The majority of the present fluvial systems in both the LEB and MDB are dominated by suspended overbank deposits and no longer actively transport or sequester much bedload. These characteristics may reflect a reduction in precipitation or discharge, and subsequent rates of channel activity.

By 40 ka, the LEB rivers had undergone a protracted decline in bedload activity following the strong peak in MIS 5 (Maroulis et al., 2007; Nanson et al., 2008). The LEB rivers continued to carry bedload from 40 ka until just after the LGM (Fig. 4). The LGM was characterised by a brief hiatus in fluvial activity, although there may have been a period of enhanced fluvial activity along Cooper Creek downstream of the Innamincka Dome (Nanson et al., 2008; Cohen et al., 2010), which supplied sand for source-bordering dune development (Cohen et al., 2010). Fluvial activity increased from the deglacial period to a modest peak in the mid Holocene throughout the LEB (Pickup et al., 1988; Pickup, 1991; Patton et al., 1993; Hollands et al., 2006; Nanson et al., 2008), and in the Barrier Ranges on the south-eastern LEB margins (Jansen and Brierley, 2004). However, in comparison with the very powerful rivers earlier in the Quaternary (Nanson et al., 2008), the last 40 ka saw only a modest period of enhanced river activity in the LEB during MIS 3, and a still more modest enhanced flow during the mid-Holocene.

The rivers of the MDB reflect a strong contribution from orographic precipitation, and at times snow melt, from the Great Dividing Range (GDR) (Petherick et al., 2013). Therefore, the hydrology of these fluvial systems is more closely tied to the climatic changes within the more temperate climate zones from which they originate (Page et al., 1996, 2009; Kemp and Rhodes, 2010). In addition, they feed several systems of shallow lakes along the length of the rivers, such as the Willandra Lakes, which also reflect the history of these headwater-driven catchments.

4.3. Alluvial records from the Flinders Ranges

Alluvial fans – fluvial landforms often found in arid and semi-arid environments – also record pulses of activity responding to variations in effective precipitation and runoff intensity, in particular large flood events (Williams, 1973). Alluvial fans are common landforms in the Flinders Ranges piedmonts, and drain to the east and west into playas Frome-Callabonna and Torrens respectively (Fig. 5A). Infrequent and high magnitude flood events, typical of the semi-arid precipitation regimes in this region, transport sediment to the alluvial fans on the proximal piedmont. Fan aggradation and dissection is controlled by variations in effective precipitation and runoff, as well as sediment supply (Williams, 1973). The present day morphology comprises channels which have incised into both alluvium and bedrock, with floodplain and/or floodout deposition on the distal piedmont. Only occasionally is sediment delivered to the terminal splays as far as the playas. Within the ranges themselves, thick fine-grained valley fills preserve additional records of alluvial activity extending to MIS 5 (Williams et al., 2001; Haberlah et al., 2010a, 2010b).

Intermittent fan aggradation, including debris flows, in the western Flinders Ranges has been dated using OSL and conventional radiocarbon from ~120 to 30 ka (Williams, 1973; Quigley and Sandiford, 2006; Quigley et al., 2007) (Fig. 5B). This period has been

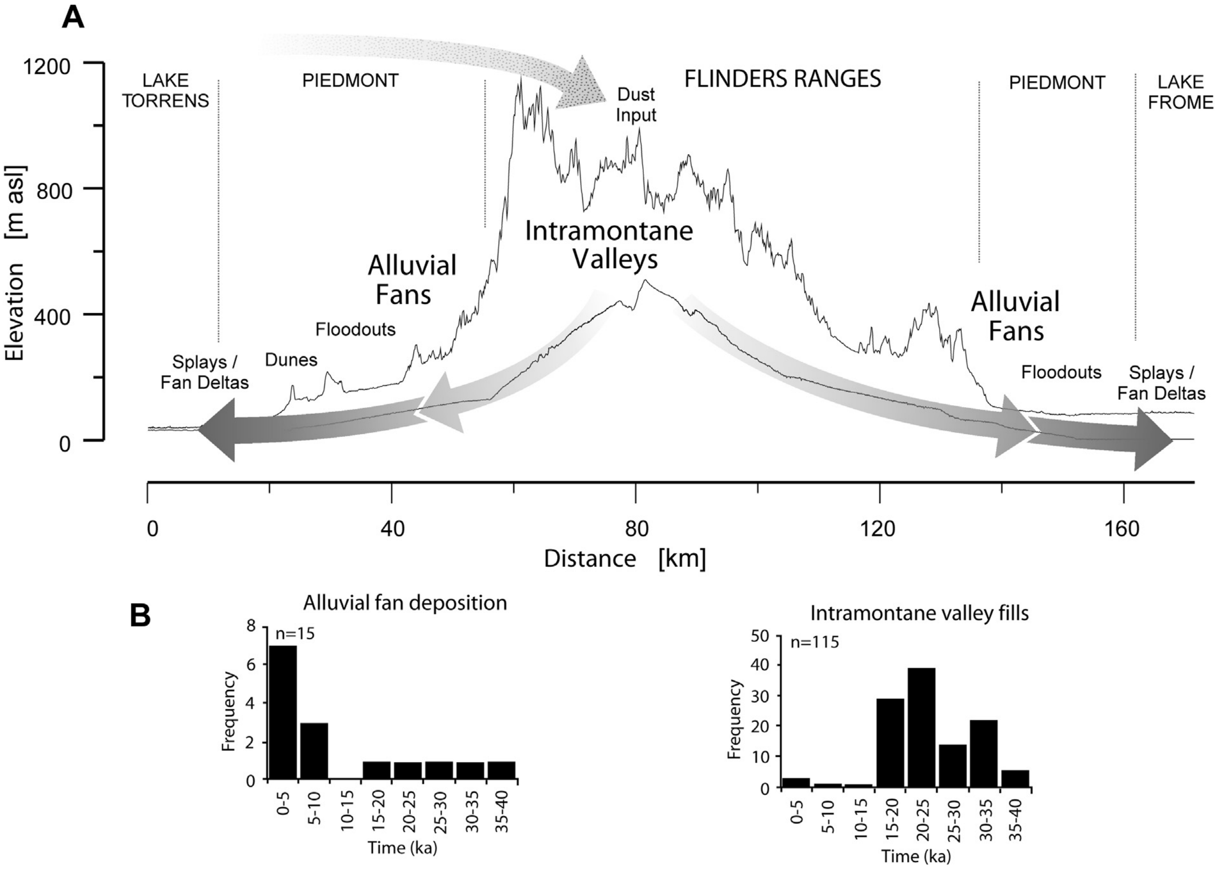

Fig. 5. Overview of the geomorphic setting and age estimates from alluvial records in the Flinders Ranges. (A) Major geomorphic elements and average topography along a W–E transect across the Flinders Ranges (based on swath profile between 30°51′25″ and 31°34′00″S measured from 90 m SRTM digital elevation data; upper curve = max. elevations, lower curve = min. elevations); (B) Summary of the available chronologies for alluvial fan deposition and intramontane valley fills (Quigley and Sandiford, 2006; Quigley et al., 2007; Haberlah et al., 2010a).

linked to comparable activity in the Flinders and Mount Lofty Ranges further south (Bourman et al., 1997; Sheard, 2009). Fan activity was followed by pedogenesis reflecting increased stability and precipitation around ~40–30 ka (Williams, 1973; Callen et al., 1983). However it should be noted that conventional radiocarbon methods and bulk sampling are no longer considered the most suitable dating technique for these environments. Subsequent low energy sediment deposition on the distal fans, coincident with rapid fine-grained valley fill aggradation, took place before, during and after the LGM (Williams, 1973; Quigley et al., 2007; Haberlah et al., 2010b). Conventional radiocarbon dating suggests that calcareous paleosol formation took place within alluvial fan sediments following the LGM, around ~18–14 ka (Williams, 1973; Callen et al., 1983).

Aggradation of fine-grained valley fill sediments increased from ~47 ka, followed by an interval of stable conditions characterized by pedogenesis between ~36 and 30 ka (Haberlah et al., 2010b). During the LGM, in particular between ~24 and 18 ka, Haberlah et al. (2010b) propose that dust was transported to the Flinders Ranges from playa lake deflation and dune activity upwind, which was subsequently eroded and deposited downstream as fine-grained valley fills. Such deposits therefore suggest variable and unstable LGM climatic conditions. These valley fills are interpreted as fluvially reworked loess, and accumulated most thickly in reaches characterised by backflooding and slackwater deposition (Haberlah et al., 2010a, 2010b). It has also been suggested that aeolian material and low energy fluvial sediments were deposited onto alluvial fans on the eastern flanks of the Flinders Ranges during the LGM as a distal expression of the fine-grained loessic valley fills within the ranges (Quigley et al., 2007). Post-LGM soil formation coincides with the termination of fine-grained aggradation and initiation of incision (Haberlah et al., 2010a).

Erosion of valley fills post-LGM reflects either decreased sediment supply and/or increased precipitation in the catchments (Haberlah et al., 2010b). It is coeval with increased sediment delivery to Lake Frome during its post-LGM highstand (Cohen et al., 2011, 2012). This may imply that aggradation on the Flinders Ranges alluvial fans is not always coincident with high lake levels at Lake Frome. Instead, alluvial fan aggradation along the proximal piedmont may reflect catchment-wide decline in transport capacity, either linked to decreasing flood frequency and magnitude, or increasing sediment supplies. A mismatch between fan deposition and lake records, however, may be attributed to the additional influence on Lake Frome palaeohydrology of the tropical monsoon in its headwaters, whereas alluvial fan activity could be driven by local precipitation regimes from westerly moisture sources, or to limitations of the dating techniques.

4.4. *Palaeohydrology recorded within lakes and their shorelines*

Palaeohydrologic change within the ephemeral lakes of the Australian arid zone is preserved within both basin sediments (e.g. De Deckker et al., 2011), and especially in the case of deflationary regimes, their shorelines (Bowler, 1983). Shore marginal depositional systems such as lunettes, accumulating downwind, provide useful hydrologic information where deflation has removed lake sediments. Arid zone lake shorelines and lunettes may be preserved either as features forming at multiple levels representing lake stands of quantifiable volume (e.g. Lakes Frome-Callabonna and Eyre: DeVogel et al., 2004; Magee et al., 2004; Cohen et al., 2011), or as multiple occupations of the same shoreline through time (e.g. Willandra Lakes: Bowler, 1998; Bowler et al., 2003, 2012). Arid zone lakes of the LEB and MDB are dominated by runoff from large catchments, and have different hydrological thresholds determined by the effectiveness of local and catchment precipitation, and lake geometry (lake area: catchment area ratio) (Bowler, 1981; Bowler and Teller, 1986). Previous surveys (Wasson and Donnelly, 1991; Harrison, 1993) have demonstrated that not all lakes behave synchronously, even in the same region, because of these constraints. Nevertheless, with the addition of recent studies there are recognisable temporal trends of lake filling and drying in these lake records.

Existing lake records for the Australian arid and semi-arid zones show a broadly drying trend over at least the last full glacial cycle, irrespective of whether the catchments are under the influence of monsoon or westerly-dominated climates (Hesse et al., 2004). This has entailed a shift from large perennial lake phases during MIS 5 and 3, through to diminishing playa systems by the mid-Holocene. Early records of lake palaeohydrology during the last ~40 ka were limited to small numbers of TL and OSL age estimates from isolated shorelines (Lake Mungo: Bowler, 1998; Lake Woods: Bowler et al., 1998; Lake Lewis: Chen et al., 1995; English et al., 2001; Lake Tyrrell: Stone, 2006) (Fig. 1B). More recently, systematic lake-margin studies have produced larger datasets, with a greater emphasis on OSL (Lake Mungo: Bowler et al., 2003, 2012; Lake Eyre: Magee et al., 2004; Lake Frome-Callabonna: Cohen et al., 2011).

A summary of lake filling and drying is illustrated in Fig. 6. The distinction is made between records from playa lakes connected to the MDB system, and those of the LEB terminal playas in the central arid zone. The former are presently influenced by the westerly weather systems, and from the Tasman Sea which supply precipitation to the MDB tributaries. The northern lakes (Mulan, Woods and Lewis) are directly influenced by the monsoon. Lake Eyre is dominantly filled by monsoonal catchments to its north (Magee et al., 2004), whereas Lake Frome-Callabonna is affected both by the northern and southern climatic systems, given its connection to the Cooper Creek via Strzelecki Creek and the Flinders Ranges fans (Cohen et al., 2011). Records from the Willandra Lakes suggest oscillating lake levels between ~40 and 28 ka, following a period of higher lake levels (Bowler, 1998; Bowler et al., 2003, 2012) (Fig. 6C), and correspond to cooler, wetter conditions in the eastern highlands as recorded in the Lachlan River fluvial deposits (Barrows et al., 2001; Kemp and Rhodes, 2010). By contrast, TL dating of the lunettes at Lakes Urana and Cullivel on the Riverine Plain indicate ephemeral lake conditions until ~35 ka, with more permanent conditions from 30 to 10 ka (Page et al., 1994) (Fig. 6C). This earlier part of the Lake Urana record does not agree with the Willandra Lakes chronology, but may be attributed either to differences in sub-catchment sources or inaccuracies in the dating techniques. Short-lived lake-full conditions in the Willandra, based on lunette chronologies and radiocarbon dating of fish otoliths corresponding to permanent lake conditions, are constrained around the LGM at ~20–17 ka (Bowler et al., 2012), and may reflect spring snow-melt brought to the Willandra Lakes via the Lachlan River headwaters during and after the LGM. This period was followed by lake deflation after flow ceased in Willandra Creek and was diverted into other branches of the Lachlan River (Bowler, 1998; Bowler et al., 2012). Lake Urana-Cullivel indicate high lake levels extending from ~30 to 10 ka as a result of their connection to the Murrumbidgee River during the MIS 2 Gum Creek and MIS 3 Kerarbury phases of fluvial activity (Page et al., 1996). MDB playa lakes west of the Darling River and Willandra system also record lacustrine sedimentation throughout the Holocene (Cupper, 2006).

Lake records from the central arid and monsoon-influenced zones do not always form a consistent picture of wetter and drier phases (Fig. 6A, B). During the MIS 5 interglacial, the region appears to have been substantially wetter than any conditions experienced since then, with larger rivers and higher lake levels (Bowler et al., 1998, 2001; Magee et al., 2004; Maroulis et al., 2007). Early MIS 3 may also have been relatively humid (Veth et al., 2009). There is evidence for lake filling around ~40–33 ka at Lakes Eyre (but only to modern playa levels), Frome, Mulan and Woods (Bowler et al., 1998;

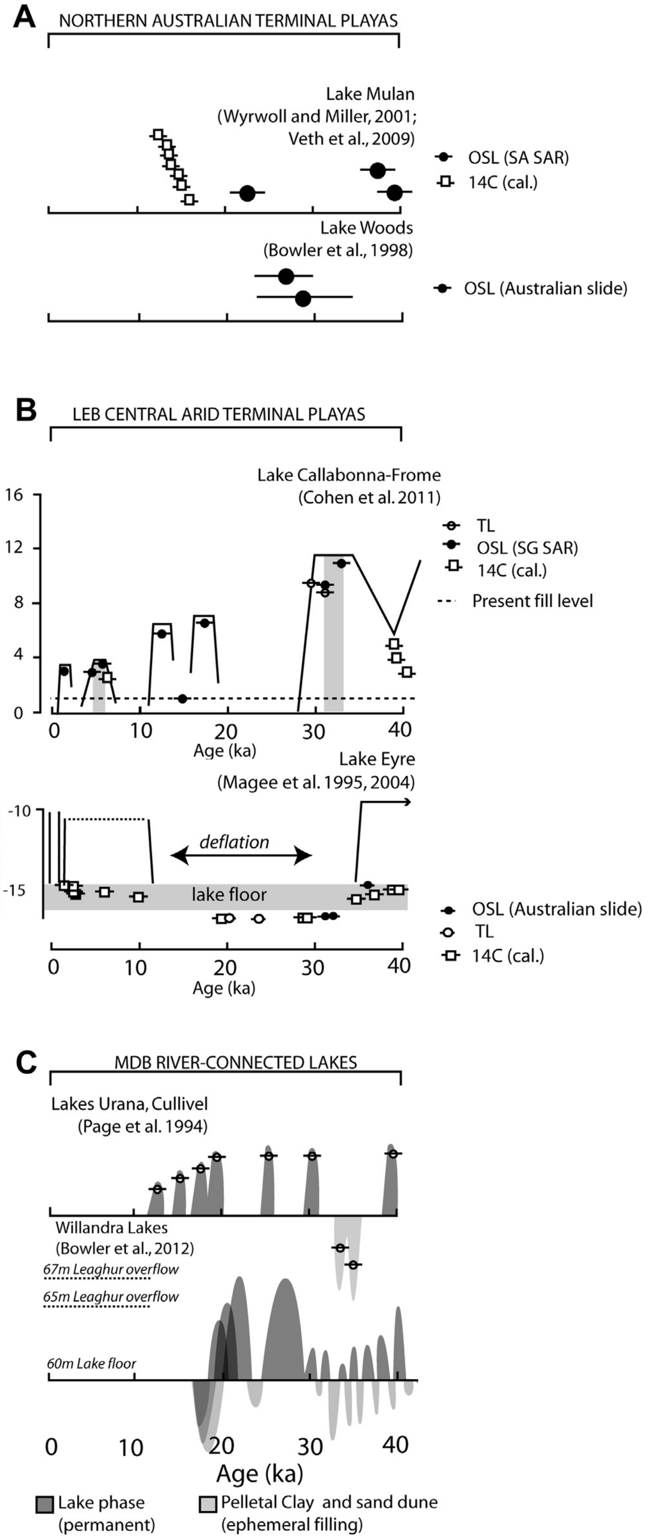

Fig. 6. Summary of lake filling and drying in (A) the monsoon-affected northern playas (Bowler et al., 1998; Wyrwoll and Miller, 2001; Veth et al., 2009), compared with (B) changing lake hydrology in the central Australian terminal playa Lakes Frome and Eyre (Magee et al., 1995, 2004; Cohen et al., 2011) and (C) the westerly-affected southern MDB catchment (Page et al., 1994; Bowler et al., 2012).

Veth et al., 2009; De Deckker et al., 2011; Cohen et al., 2012), all of which are sourced by headwaters within the zone of monsoon penetration. Lake Frome-Callabonna also filled around 33–31 ka (Cohen et al., 2011, 2012). This evidence is consistent with a wetter late MIS 3. However, the climatic drivers cannot be identified. Evidence for lake levels in central Australia post-LGM also exhibit spatial variability. The largest discrepancy lies with the records for Lakes Eyre and Frome-Callabonna between 35 and 14 ka (Fig. 6A, B), with deflation persisting to ~14 ka at Lake Eyre (Magee and Miller, 1998; Magee et al., 2004), compared with refilling at Lake Frome-Callabonna around ~18–16 ka (Cohen et al., 2011, 2012). This suggests that Lake Frome-Callabonna contained substantial water post-LGM, at a time when adjacent Lake Eyre preserves no evidence of perennial lake conditions. It prompts the question as to the potential source of water to both lakes (Cohen et al., 2012).

Subsequent high lake stands at Lakes Mulan, Eyre and Frome around the period ~14–12 ka have been interpreted to represent an intensified monsoon (Wyrwoll and Miller, 2001; Magee et al., 2004; Cohen et al., 2012).

Holocene records from the central arid zone and monsoon-influenced region are few. Magee et al. (2004) report late Holocene (~3–2 ka) oscillating lake levels at Lake Eyre, comparable with the present hydrological regime. The Lake Frome-Callabonna and Lake Lewis Holocene records both indicate moderate filling around ~5 ka (English et al., 2001; Cohen et al., 2012), but never to the same extent as prior to the Holocene (De Deckker et al., 2011). Furthermore, Lake Frome-Callabonna records a significant filling event around ~1 ka (Cohen et al., 2011, 2012).

4.5. *Palaeoprecipitation recorded in speleothems*

Several sites within the arid Flinders Ranges provide discontinuous archives of speleothem growth during the last ~40 ka (Fig. 7). Two stalagmites extracted from Mairs Cave in the northern Flinders Ranges, south of Lakes Frome and Torrens, preserve evidence for speleothem growth from ~20 to 15 ka, with a peak in growth rate interpreted to correspond to increased effective precipitation, and coincident with a lake highstand at Lake Frome, around ~17–15 ka (Cohen et al., 2011) (Fig. 7A). A younger speleothem from a rock shelter at Yudnamutana Gorge further north presents evidence for a relatively short-lived growth phase at ~11.5 ka, before growth ceased until ~8–6 ka. Relatively higher growth rates between ~7 and 6 ka were interpreted as higher effective precipitation to this region during this interval (Quigley et al., 2010) (Fig. 7B).

The Naracoorte Cave system, on the semi-arid desert margins of the southern MDB, provides several longer speleothem records, with growth intervals extending well beyond the last ~40 ka (Ayliffe et al., 1998). Ages for speleothem growth within the Blanche (St Pierre et al., 2009), Fox and Victoria Fossil Caves (Ayliffe et al., 1998) at Naracoorte suggest that more effective precipitation prevailed during ~50–40 ka and ~35 ka (Ayliffe et al., 1998) (Fig. 7C). U-series ages from straw speleothems within Blanche Cave utilise more recent mass spectrometry techniques, and suggest that the growth intervals at Naracoorte may be more precisely constrained to ~42–38 ka, ~32 ka, over the LGM and deglacial periods (~20–14 ka), and during the mid-Holocene (~5–3 ka) (St Pierre et al., 2009, 2012) (Fig. 7D). The ~20–14 ka phase of speleothem growth from Blanche Cave correlates with, although is somewhat longer lived than, the post-LGM humid period recorded at the (presently) more arid Mairs Cave.

The presence of MIS 3 and early MIS 2 speleothem growth within the Naracoorte Cave system coincides with sediment accumulation within the Blanche Cave between ~40 and 20 ka (Darrénougué et al., 2009). Geochemical and sedimentological analyses from these sediments suggest an association of increased effective precipitation with increased woody vegetation cover, and were interpreted as a more northerly shift in northerly wind regime (Darrénougué et al., 2009).

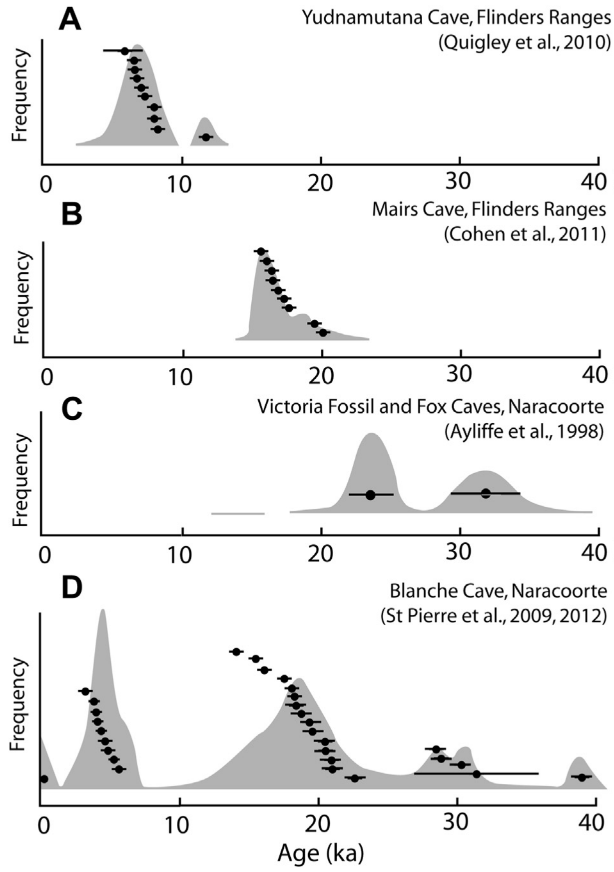

Fig. 7. Stacked ages and probability density functions for speleothem records from the westerly-influenced arid and semi-arid zones: (A) Yudnamutana Cave, Flinders Ranges, in the central arid zone (Quigley et al., 2010); (B) Mairs Cave, Flinders Ranges, in the central arid zone (Cohen et al., 2011); (C) Naracoorte Caves (Victoria Fossil and Fox Caves) (Ayliffe et al., 1998) and (D) Blanche Cave in the Naracoorte Cave system (St Pierre et al., 2009, 2012), on the semi-arid margins.

Caves in both the central arid zone and on the desert margins record evidence of increased effective precipitation during the mid-Holocene. However, the ~5–3 ka phase of speleothem growth at Blanche Cave post-dates that preserved at Yudnamutana Cave in the arid zone (~8–5 ka). The cause of this temporal difference is not clear, nor can it unequivocally be asserted that relatively humid conditions persisted on the desert margins for later than in the arid zone.

4.6. *Beyond the arid interior: long-travelled dust records*

Peaks in aeolian dust flux may in one sense more reliably indicate intensified aridity than do desert dunes, since drier conditions over the source areas are required to entrain fine-grained sediments for long-distance transport (Hesse and McTainsh, 2003). Suspended dust is then deposited over the landscape, into coastal lagoons or the sea floor, predominantly by rainfall scavenging. Two major long-travelled dust pathways were postulated by Bowler (1976). The best understood of these is the plume moving eastwards with the westerlies from the southern half of the continent, and extending from the latitude of southeastern Queensland to Tasmania (McGowan and Clark, 2008). This pathway has contributed dust to sites in North Stradbroke Island (Petherick et al., 2009), the southeastern highlands (Hesse et al., 2003b; Marx et al., 2011), the Tasman Sea (Hesse, 1994; Kawahata, 2002), and the South Island of New Zealand (Marx et al., 2005; McGowan et al., 2005). The other major pathway travels westward into the Indian Ocean from northwestern Australia (Hesse and McTainsh, 2003). Although it can be difficult to determine the exact provenance of dust sources, owing to the variety of potential source landforms over vast regions, each of which may dominate the long-travelled dust component over different periods of time, substantial recent advances have been made using geochemical (Marx et al., 2005; McGowan et al., 2005; Gingele et al., 2007; Petherick et al., 2009) and remote sensing techniques (Baddock et al., 2009).

Long-term records of long-travelled dust from the Australian continent, however, are sparse (Fig. 8). In the monsoon-influenced zone, two cores provide records of dust transport to the Indian Ocean (Hesse and McTainsh, 2003). The northernmost core (SO-14-08-05, 16°21′S 118°23′E) (Fig. 8c) has the higher dust flux, although it is much lower than the fluxes to the southeastern dust path. Dust flux calculated using an AMS radiocarbon chronology (Hesse, unpublished data; see Tables S2 and S3) was sustained at moderate

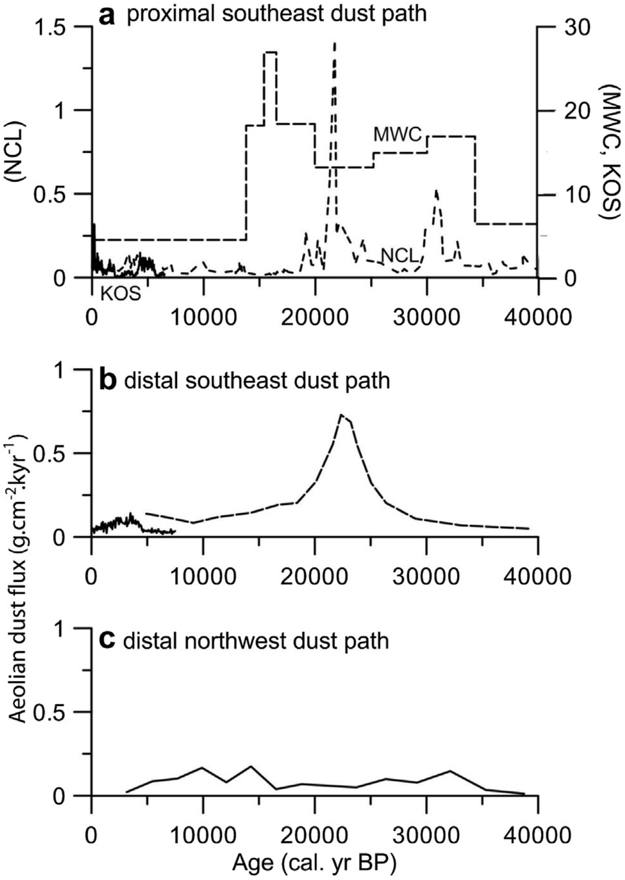

Fig. 8. Records of far-travelled dust: (a) in the proximal southeastern dust path (eastern Australian seaboard), showing flux of far-travelled dust to Native Companion Lagoon (NCL) in southeast Queensland (double dashed line) (Petherick et al., 2008; and Petherick unpublished revised age model), mass accumulation rate of loess at Mackenzies Waterholes Creek (MWC) in the Central Tablelands of New South Wales (single dashed line) (Hesse et al., 2003b; and J Campbell unpublished single-grain OSL ages – Table S6), and flux of dust in Upper Snowy River peat core, Kosciuszko National Park (KOS), New South Wales (Marx et al., 2011); (b) distal southeastern dust path (Tasman Sea and New Zealand), showing mass accumulation rates for dust flux to core E26.1 in the eastern Tasman Sea (dashed line) (Hesse, 1994; revised calibrated ^{14}C timescale – Tables S4 and S5), and flux of Australian dust in Old Man Range peat core, South Island, New Zealand (solid line) (Marx et al., 2009); (c) distal northwestern dust path, showing mass accumulation rates for dust flux to core SO-14-08-05 in the east Indian Ocean, off the northwest Australian coast (Hesse and McTainsh, 2003; revised calibrated timescale, Hesse –Tables S2 and S3). All timescales except MWC are dated using radiocarbon, and calibrated using IntCal09.

levels from at least 32 ka to 5 ka, with no distinct LGM peak. The highest values occur after ~14 ka, around the same time as reactivation of the tropical monsoon (Wyrwoll and Miller, 2001). The more southerly core (offshore Exmouth) has lower dust fluxes overall, with a weak late LGM peak and slightly higher fluxes during the Holocene (Hesse et al., 2004). These data point to a weaker and smaller (or at least more northerly) dust pathway westward than envisaged by Bowler (1976).

An LGM peak in dust flux is observed in records from sites within the southeastern Australian dust plume (Hesse, 1994; Hesse et al., 2003b; Petherick et al., 2008) (Fig. 8a, b; Tables S4 and S5). An additional, smaller, peak in long-distance aeolian transport took place around ~31 ka at the northern margin of the pathway (Petherick et al., 2008). Higher resolution studies exist for the Holocene, based on sites in the southeastern Australian highlands and New Zealand (Marx et al., 2009, 2011). These records suggest an increase in dust flux from the mid-Holocene, with indications of increased climatic variability and possible aridity around ~5.5–4 ka, and again from 2 to 0 ka (Marx et al., 2011). Provenance studies based on the geochemistry of aeolian sediments deposited on North Stradbroke Island suggest that the dominant source of sediment prior to the LGM was the MDB (Petherick et al., 2009). At other times, dust was primarily transported from arid central Australia (Marx et al., 2009; Petherick et al., 2009). There are as yet no available data for provenance of dust for the peak of the LGM, although dust transported to the Tasman Sea was carried further north in glacial intervals, retreating to the south in interglacials around 3° latitude (Hesse, 1994) in agreement with palaeoceanogreaphic studies (e.g. Bostock et al., 2006). These northward advances may be responsible for bringing more dust to southern Queensland during the LGM (Petherick et al., 2008). A loess deposit in the Central Highlands of New South Wales, at Mackenzies Waterholes Creek (Hesse et al., 2003b), has a low resolution single grain OSL chronology (J. Campbell unpublished data, pers. comm., see Table S6 – superseding fine-grain OSL ages published in Hesse et al., 2003b), which also supports high rates of dust deposition through the period 34 ka–14 ka.

There are several studies which discuss past wind strength in the Australian arid zone. Dust transported to the Tasman Sea shows no evidence of changed wind strength from the LGM to the Holocene (Hesse and McTainsh, 1999). Dust deposited in the eastern highlands during the LGM has the same particle size distribution as dust deposited in the Holocene (Hesse et al., 2003b). This may suggest unchanged wind strength, although direct comparisons between studies using different methodologies may be unreliable. The combined sand dune ages (Fig. 3) also point to winds sufficiently strong to form dunes at all times during the last 40 ka, where sand was available. However, the Holocene dust record from Blue Lake in the Snowy Mountains (Stanley and De Deckker, 2002) shows coarser dust after ~6 ka, compared with the period 12–6 ka, suggesting a stronger mid-late Holocene westerly circulation, or changes in sediment source.

5. Discussion

5.1. ~40–30 ka: a late MIS 3 humid phase, and initiation of cooler conditions

The late MIS 3 period from ~40 to 30 ka appears to have been broadly characterised by humid conditions across the continent, although the timing of this phase may have varied between south and north (Fig. 9). However, while this period appears to have been wetter than the present, there is evidence to suggest that still wetter conditions prevailed prior to 40 ka across the arid zone (e.g. Ayliffe et al., 1998; Bowler et al., 2003; Magee et al., 2004; Veth et al., 2009). It is therefore possible that the late MIS 3 humid phase described here represents the end of a more substantial humid period. Lake systems at all scales maintained perennial conditions through to or intermittently up to ~30 ka, coeval with peaks in river activity. Rivers flowing into and through the western MDB carried high bankfull discharges around this time, probably until ~25 ka (Page et al., 1996, 2001, 2009). Enhanced hydrologic activity was combined with a higher likelihood of dune pedogenesis prior to ~35 ka in the central arid zone (Fitzsimmons, 2010). Palaeoecological data relating to the northern arid regions suggest wetter vegetation assemblages during late MIS 3 (Wallis, 2001; van der Kaars and De Deckker, 2002).

Evidence for late MIS 3 interstadial conditions is poorly understood in the southern hemisphere (Munyikwa, 2005b; Williams et al., 2009). The most viable explanation is a combination of moisture supply to the atmosphere from both the tropical and temperate oceanic source regions, despite sea surface temperatures remaining relatively stable throughout this period (Lea et al., 2000).

Amino acid racemisation analyses undertaken on emu eggshell suggest that both the central arid zone and MDB were up to 8–9 °C cooler than present. Terrestrial cooling initiated around ~45 ka (Miller et al., 1997). Cohen et al. (2011) argued for increased effective precipitation and cooler temperatures in the westerly-influenced zone due to a northward displaced winter westerly circulation. However it has also been argued, although based on limited chronological evidence, that an intensified monsoon was responsible for lake level rise and increased river discharge at this time in the Lakes Mulan and Woods catchments in the north (Bowler et al., 2001; Veth et al., 2009). Regardless of the drivers, lake level fall appears to have taken place earlier in the north than in the south.

5.2. ~30–18 ka: LGM aridity and a complex glacial response

The period after ~30 ka appears to have been characterised across the continent by the onset of drying conditions which lasted until the end of the LGM. Dune activity and dust transport appear to have become more widespread following a period of pedogenesis and stability, with aeolian deposition peaking around ~22–20 ka. The area affected by desert dune activity expanded beyond the present-day arid core and desert margins, to the presently temperate zones of eastern and southern Australia (Hesse et al., 2003a; Duller and Augustinus, 2006; Gardner et al., 2006). The LGM peak in dune ages is interpreted to reflect the culmination of a widespread phase of dune activity. The peak in desert dune ages in the central arid zone is corroborated by the hydrologic evidence. The LEB lakes appear to have dried out from ~30 ka, remaining that way until ~17 ka (Lake Frome) and the Pleistocene–Holocene transition (Lake Eyre).

Large catchments in the monsoon-affected north also experienced lake level fall, and reduced river flow, coincident with a hypothesised reduced effectiveness of the monsoon during the LGM. A possible exception to this evidence is Lake Lewis in central Australia, which experienced enhanced fluvial input around 18–17 ka (English et al., 2001). Evidence for higher frequency flood events in plunge pools in the northern savannah, argued to be due to increased monsoon intensity during the LGM (Nott and Price, 1994), and contrasting channel and bedload deposition on the Cooper Creek fan (Cohen et al., 2010), highlight the conundrum of interpreting hydrologic records during the LGM and the reliance on accurate dating techniques. The nature and extent of episodic fluvial activity during the LGM remains to be resolved, particularly with respect to potential spatial variations in northern moisture sources associated with low sea levels, and interruptions in heat transfer in the seas north of Australia.

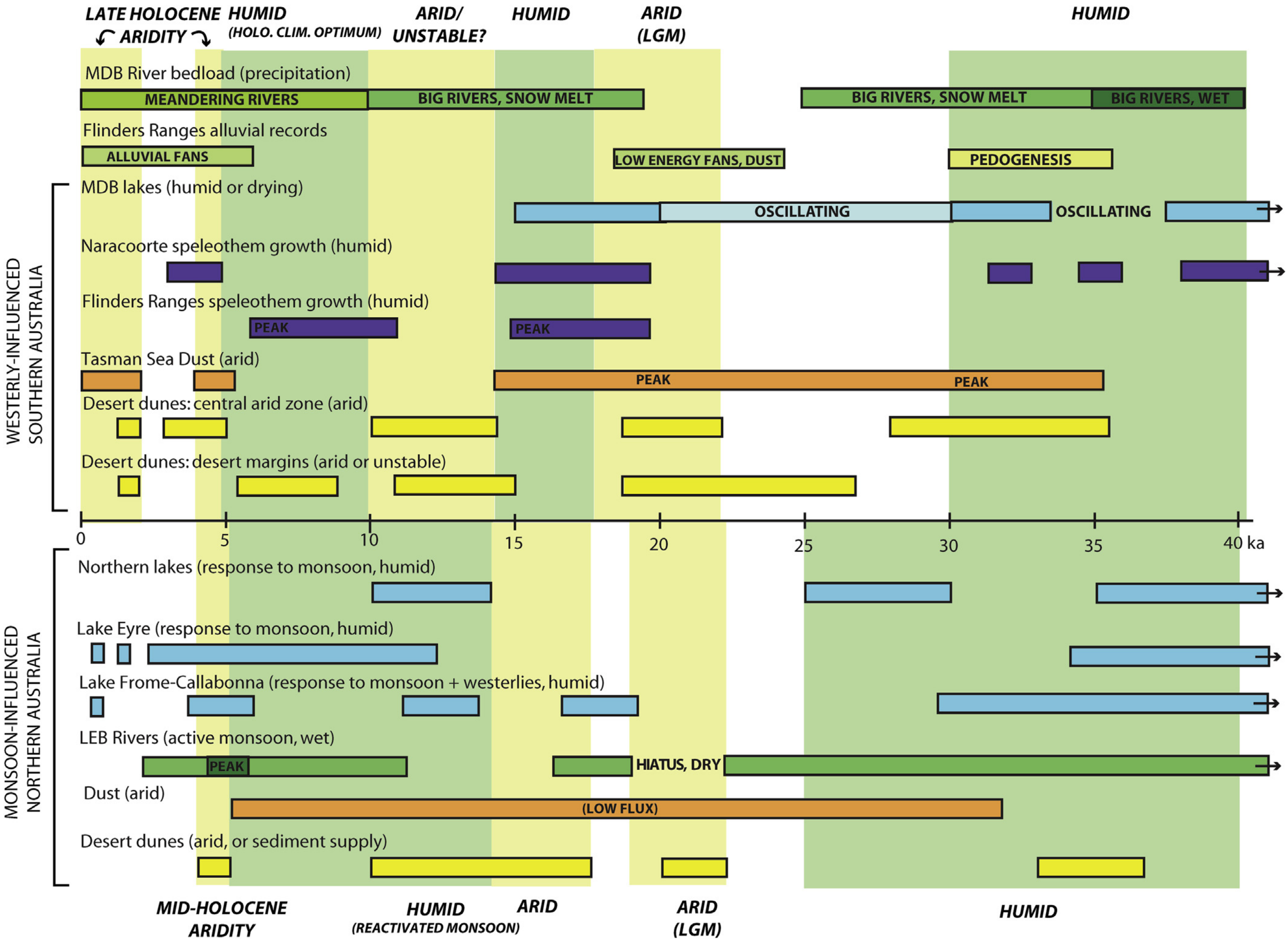

Fig. 9. Synthesis of palaeoenvironmental change in the Australian arid zone, interpreted from geomorphic response to climatic variability. Conditions prior to 40 ka are indicated by arrows.

Palaeoecological data from the north support proposed dry conditions during the LGM, with the disappearance of palm trees (indicators of wetter climates) from the phytolith record (Wallis, 2001) and evidence for a drier vegetation assemblage from marine core pollen (van der Kaars and De Deckker, 2002). The post-LGM arid phase appears to have prevailed in the north until ~14 ka, at which time the monsoon resumed (Wyrwoll and Miller, 2001; Spooner et al., 2005).

By contrast, MDB hydrologic archives show increasing activity throughout the period ~30–18 ka, and particularly during the LGM. Oscillating lake levels in the Willandra Lakes persisted throughout this period (Bowler et al., 2012). These conditions were most likely connected with increased flows in the Murrumbidgee and Lachlan Rivers, thought to be attributed to seasonal snow melt combined with increased runoff in the highlands (e.g. Kemp and Rhodes, 2010), which were subject to periglacial conditions during MIS 2 (Barrows et al., 2002, 2004). The formation of source-bordering dunes along the Murrumbidgee River (Page et al., 2001) is consistent with seasonal flows and sediment supply from increased bedload around this time, but would have required a substantial volume of water to be transported down the low gradient of the MDB rivers from their highland headwaters. Lateral migration in the Darling River west of the Willandra Lakes also increased during the LGM (Bowler et al., 1978). However, since the Darling River headwaters lie in the subtropical region to the northeast, a meltwater scenario for increased runoff cannot be invoked as for the other MDB rivers. The Darling River record could suggest the importance of precipitation derived from the Coral Sea contributing to its discharge, which agrees with fluvial records in the adjacent Fitzroy River catchment (Croke et al., 2011). By contrast, the speleothem records of the Naracoorte and Flinders Ranges regions record a growth hiatus consistent with decreased effective local precipitation. At present it is difficult to decouple local and distal climatic influences on the MDB landforms without more systematic, higher precision chronologies for fluvial activity in this region.

The LGM is defined as the global peak in glacial conditions, as measured by terrestrial ice cover, sea level lowering, polar and sea surface temperature minima, and reduced atmospheric CO_2 concentration. Although sea surface temperatures were lower during this time (Barrows et al., 2000; Barrows and Juggins, 2005), the relationship between the global drivers and moisture availability, particularly in the southern hemisphere, is less clear. The temperate climate areas of Australia, including the highland headwaters of the MDB catchment, experienced landscape instability (Petherick et al., 2013) but were never as intensely arid as the dryland core. It is possible that lower temperatures, combined with reduced atmospheric carbon dioxide, acted to reduce vegetation cover, thereby increasing effective runoff and the availability of sediment for aeolian transport. Residence time of suspended sediments in the Murrumbidgee palaeochannels was an order of magnitude lower in the Lateglacial than for either the late MIS 5 or Holocene channels (Dosseto et al., 2010). These average ages represent more efficient transport of sediment from the headwaters and comparatively less reworking of older floodplain sediment during the LGM.

5.3. ~18–12 ka: deglacial variability

The period following the LGM was characterised by spatial variability in landscape response between the south and north of the continent, and may reflect an increased divergence between the monsoon and westerly influences. Furthermore, an increasing distinction in degree of landscape instability between the central arid region and desert margins of the westerly zone appears to have developed.

In the westerly-influenced zone, increased speleothem growth rates and lake filling suggest higher effective precipitation immediately following the peak of the LGM, around ~18–14 ka (Fig. 9). The onset of speleothem growth is recorded both in the arid Flinders Ranges and on the desert margins at Naracoorte (Fig. 7), suggesting that this more humid phase was widespread. Although lake levels do not reach those of shorelines from late MIS 3, a lake level highstand at Lake Frome occurred around ~18–16 ka (Cohen et al., 2011), and a brine pool was located below the lake, suggesting altered hydrological conditions (De Deckker et al., 2011). From about 20 ka until the onset of the Holocene, the rivers of the MDB were particularly active, filling the associated systems of lakes such as Lake Urana (Page et al., 1996, 2009). This more humid phase appears to have been followed by one of increasing aridity, especially in the arid core. A peak in dune deposition in both the arid interior and on the desert margins (Lomax et al., 2011) between ~14 and 10 ka was coincident with decreased fluvial activity and reduced speleothem growth. Correlation with palaeoclimatic proxies from beyond the arid zone suggests that this period was comparatively warmer than the LGM (Fitzsimmons et al., 2007b). However, short-lived lake high stands took place at Lakes Frome-Callabonna and Eyre from ~12 ka, indicating increased availability of water to these systems. It is hypothesised that these lakes were filled by increased precipitation associated with the reactivated monsoon in the catchment headwaters to the north (Magee et al., 2004; Cohen et al., 2011), which took place from ~14 ka (Wyrwoll and Miller, 2001). Decoupling regional climate from distant moisture sources appears to be one of the major challenges for this time interval.

By comparison, the early deglacial period in the monsoon-influenced arid zone was characterised by a period of continued aeolian activity which continued until ~15 ka. Dust fluxes in this region show no significant changes (Fig. 8). Since more securely dated palaeohydrologic records do not exist for this region, it is unclear what conditions drove dune building, although increased sediment supply from nearby lake and river systems may have been responsible (Fitzsimmons et al., 2012). From ~14 to 15 ka, the monsoon shifted southwards (Wyrwoll and Miller, 2001; Spooner et al., 2005), possibly in two stages initiating as early as ~17 ka (Williams et al., 2009). This resulted in wetter conditions, as demonstrated by lake level rises in both the northern lakes and the LEB. This wetter phase, coincident with increased aridity in the southern half of the arid zone, suggests divergence between climatic influences and corresponding landscape response across the continent.

5.4. ~12–0 ka: variability during the Holocene

The Holocene appears to have been characterised by spatially divergent and abrupt responses to palaeoenvironmental change across the continent. In the MDB, the vigorous flows following the LGM declined sharply at the start of the Holocene. The rivers of the LEB appear to have been largely inactive following the LGM and at the start of the Holocene. Earlier reviews argued for climatic warming and stabilisation across the interior during the Holocene, and particularly for relative humidity during the mid-Holocene, followed by gradually intensifying aridity over the last ~5 ka (e.g. Hesse et al., 2004). The new evidence reviewed in this paper supports these arguments, with the rivers showing a degree of enhanced activity in the mid-Holocene.

In southern central Australia, the early to mid-Holocene appears to have experienced increasingly humid and stable climatic conditions, culminating around ~7–5 ka. These conditions are evidenced by speleothem growth and fluvial activity, stability and pedogenesis on the Flinders Ranges alluvial fans, and a short-lived lake level rise at Lake Frome. However, this relatively more humid period in the LEB was less intense than earlier interglacial phases of the late Pleistocene (Magee et al., 2004; Nanson et al., 2008; Cohen et al., 2011, 2012), with much debate as to its cause. Generally wetter conditions in temperate southern Australia during the ~7–5 ka period are evidenced by lake level highs from western Victoria and at Lake George near Canberra (Bowler and Hamada, 1971; Jones et al., 1998; Fitzsimmons and Barrows, 2010). Interestingly, the early to mid-Holocene also saw increased dune activity on the desert margins in the MDB, and a peak in dust output from this region. This activity has been attributed to localised instability which is not reflected in comparable records from the arid core (Lomax et al., 2011), but lacks a satisfactory explanation without additional proxy data.

After ~5 ka, the late Holocene saw intermittent peaks in aeolian activity in the central arid zone around ~5–3 ka and ~2–1.2 ka, coupled with peaks in dust flux east and south of the continent. Dune activity was coeval with lower discharge from the MDB rivers (Gingele et al., 2004, 2007), suggesting a trend towards aridification. The dune records in particular appear to preserve intermittent phases of activity over the late Holocene. This may reflect sampling and preservation bias, or increased geochronological precision.

Records of environmental change during the Holocene in arid northern Australia are relatively few. Fluvial records indicate enhanced early Holocene discharge, peaking between ~10 and 6 ka. A substantial mid-Holocene peak in desert dune ages following lake level rise in the Gregory Lakes (Mulan) basin (Fitzsimmons et al., 2012) suggests a brief period of aridity from ~5 ka similar to that experienced in the arid core. The balance of evidence indicates a general trend of aridification in the northern part of the continent from ~5 ka. This is consistent with arguments for a weakened monsoon after this time (Lees, 1992; Wyrwoll and Miller, 2001), and has been attributed to late Holocene weakening of the Walker circulation over the tropics (Shulmeister, 1999).

The Holocene, despite corresponding to a global interglacial phase, appears not to have regained the relative wetness of full interglacial conditions in the Australian arid zone, and may not even have been as wet as the MIS 3 humid phase described in this review. The relative aridity of the Holocene still lacks a satisfactory explanation. In particular, the monsoon-affected northern zone is substantially less humid during the Holocene compared with the MIS 5 interglacial. It is unclear whether the distinction between the two interglacials reflects a long term drying trend and trend of decreasing monsoon strength, as has been proposed in other reviews (Magee, 2006; Fujioka and Chappell, 2010). A change in boundary conditions, for example due to ecological and hydrological changes wrought by varied fire regimes due to human agency, has also been proposed (Miller et al., 2005; Notaro et al., 2011). The best way to address this problem is through the investigation of longer term records in understudied regions, and increased geochronological datasets of landscape change, in order to support climate models which may elucidate the driving mechanisms for change.

6. Conclusions

Although it is not possible to specify the precise magnitude, intensity, or duration of climatic change using the proxy records available for the arid zone, the data compilation presented here provides us with the most comprehensive possible assessment of the broad changes in moisture availability across the Australian dryland regions over the past ~40 ka.

This review builds on those undertaken in the past for the Australian arid zone (Bowler, 1976; Chappell, 1991; Hesse et al., 2004; Turney et al., 2006). It does so primarily through a substantially larger chronological dataset using more suitable dating techniques than previously available, particularly in the dunefields; the analysis of proxies using recent developments in geochemical and other analyses; and the application of statistical techniques to the chronological datasets not previously feasible with smaller numbers of ages. The resulting synthesis, based on the convergence of proxy indicators, reinforces earlier palaeoenvironmental interpretations, such as the arguments for an arid and climatically unstable LGM. However, it also highlights the complexity of landscape response to palaeoclimatic variability, such as: 1) evidence for dune instability during ~14–10 ka; 2) a complex, spatially variable and longer-lived MIS 2 arid phase than previously thought; 3) the out of phase response of rivers and dunes to moisture availability through time; 4) the apparent discrepancy between northern and southern drylands, linked to changes in monsoon intensity; and 5) a spatially diverse response to Holocene climatic variability across dryland Australia. Holocene conditions may reflect the end of a longer term drying trend between interglacials, however at present there are insufficient data to confirm this hypothesis.

A number of key questions remain unanswered for palaeoenvironmental research in the Australian arid interior, and pave the way for future research. In particular, this review highlights the need for quantifiable terrestrial proxies reflecting precipitation, temperature, wind direction and strength. At present, however, the means to quantify these parameters is largely lacking for the arid zone. The change through time of ratios between evaporation and precipitation, and their relationship with runoff regimes and palaeovegetation, also remain poorly understood. These parameters are critical for interpreting the response of landscape processes to climatic change, in terms of thresholds, sensitivity to change, and magnitude. Furthermore, increased geochronological precision, and most importantly, expanded geochronological datasets, are required in order to more reliably define rates of change and the duration of events.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2012.09.007.

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