Loess and floods: late Pleistocene fine-grained valley-fill deposits in the Flinders Ranges, South Australia

(excerpt from Hans Heysen 1929: “Foothill of the Flinders”, Morgan Thomas Bequest Fund 1939)

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This thesis is submitted in fulfilment of the
requirements for the degree of Doctor of Philosophy
in the Faculty of Science, University of Adelaide

August 2009

1. Introduction

'It is true that we are made of dust. And the world is also made of dust. But the dust has motes rising.' – Muhammed Iqbal

This study is presented as a PhD thesis by publication and consists largely of material submitted for publication in the form of journal papers and book chapters. At the same time, it attempts to comply with the basic structure of a conventional thesis by including a chapter each on introduction, methods, results and discussion, and conclusions and outlook. The original papers have been to some extent adapted and are put into the larger context at the beginning of each chapter, to improve the coherence and flow of reading of the thesis. Detailed methodological reviews not suitable for publication complement the journal papers in the methodology chapter. The final chapter briefly summarises overall conclusions and outlines potential future research. Background information, laboratory protocols, detailed data tables and published conference abstracts referred to in the text are listed at the end as appendices. References are kept with the original manuscripts, or are otherwise listed at the end of individual chapters.

In the introduction, the fine-grained valley-fill remnants of the Flinders Ranges, hereafter referred to as the "Flinders Silts", are placed in a regional, continental and global context in the form of three separate literature reviews. The palaeo-environmental literature on the late Pleistocene of the Flinders Ranges and surrounding areas is reviewed and discussed within the chronostratigraphic framework of the Brachina valley-fills as known at the outset of this study in 2006 (Cock et al. 1999; Williams et al. 2001). This manuscript (section 1.1) did not get published and in light of the present data would need to be fully revised. However, it presents a useful literature review for future studies attempting to establish the link between rapid aggradation of the lacustrine sediments of flanking terminal playa lakes and the erosion of the Flinders Silts. In the second paper (section 1.2), depositional models inferred elsewhere for similar late Pleistocene valley-fill formations are reviewed and discussed as potential scenarios. This manuscript is written from the vantage point of a chronostratigraphic study and was consequently used to apply for funding for the regional dating campaign. The third paper (sections 1.3 and 1.4) investigates our present understanding of loess-derived sediments in Australia.

While the impact of Quaternary dust on Australian alluvium has been the subject of ongoing research since the Canberra INQUA-commissioned workshop in 1980 (Wasson 1982), proximal dust has only recently been inferred as a significant source for the Flinders Silts (Williams et al. 2001; Williams and Nitschke 2005). The same applies to other well-published global occurrences of similar fine-grained valley-fill formations (e.g. Rögner et al. 2004).

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A review of the last deglacial response in South Australia

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Abstract

Late Pleistocene fine-grained sediments in lake cores collected from Lake Frome, a playa lake in presently arid South Australia, had been interpreted as indicative of high lake levels. Evidence from well-dated valley-fill deposits in the nearby Flinders Ranges and from less well dated piedmont sediments and associated palaeosols, suggests an alternative interpretation. According to our model, barren loess mantles blanketing the ranges during the Last Glacial Maximum (LGM) were eroded by Late Pleistocene frontal winter rainfall as early as ~20.2 ka. The suspended load rapidly filled and levelled out pre-existing rock-cut relief and accumulated in the flanking terminal depocentres. Closely spaced gypsum bands point to a shallow lake, prone to rapid evaporation. Deposition of loess-derived fluviatile and lacustrine sediments ceased by ~16 ka, when rising temperatures and monsoonal incursions from the north promoted colonisation of the landscape by grassland communities. Subsequent sandy deposition in Lake Frome is interrupted just before ~5 ka by a 'clayey band' linked to the arid transition from dominant summer to winter precipitation. Terminal LGM frontal rainfall may explain other enigmatic 'pluvial' observations in southern Australia and be a global phenomenon, as similar occurrences of loess-derived alluvium in Namibia and Egypt suggest.

Keywords:

Australia, Flinders Ranges, Lake Frome, Last Glacial Maximum, Loess

Introduction

Fine-grained sediments associated with the time following LGM peak aridity are widespread across southern Australia. These are typically associated with aeolian deposition but also fluvial and lacustrine sedimentary systems, and provide important records of the environmental conditions at this time. Ironically, the precise palaeo-environmental significance of these deposits is poorly understood. For instance, within the sedimentary records of Lake Frome, the onset of fine-grained sedimentation has been interpreted as expressing a deepening of the lake associated with higher water levels (Bowler et al., 1986; Ullman and Collerson, 1994). However, this interpretation is not well supported by preservation of elevated shorelines or other proxy records expressed in the range of landscape components across the region. This manuscript collates and combines a wide array of palaeo-environmental data to assess the last deglacial landscape response to widespread LGM deposition of these fine-grained sedimentary mantles in South Australia. Changes in sediment provenance within the catchment, in particular the fluviatile reworking of widespread aeolian accessions of silts and fine sands referred to as loess mantles, are demonstrated to account for the rapid deposition of fine-grained valley-fill formations in the Flinders Ranges and the lacustrine facies within Lake Frome.

The Flinders Ranges and its flanking terminal depocentres provide an ideal setting for a critical synthesis of wide-ranging palaeo-environmental data sets. Inter-related fluvial, aeolian, lacustrine and pedologic records, many of which have been the focus of previous climate research, form well-preserved, significant occurrences within the study region (Fig. 1). The Flinders Ranges is an approximately 400km long, near-meridional trending mountain belt, running from the Southern Ocean to the arid interior of the continent. Frequently rising to heights above 900m ASL, the central ranges receive around twice the amount of orographically enhanced precipitation than the surrounding low-lying plains. The climate of the region is at present arid to semi-arid. Flanking salinas Lake Torrens and Lake Frome receive a spatially variable annual precipitation amounting to ~200 mm, with frontal winter rainfall associated with westerly anticyclonic air masses decreasing to the north, which is increasingly dominated by sporadic but intense summer thunderstorms associated with tropical monsoon incursions (Schwerdtfeger and Curran, 1996). Potential evaporation is twenty times that of the actual annual evaporation rate of ~160 mm, estimated at the lacustrine core sites from depth profiles of deuterium delta values (Allison and Barnes, 1985).

NOTE:
This figure is included on page 5
of the print copy of the thesis held in
the University of Adelaide Library.

Fig. 1) *ETM+ mosaic (modified data from http://glcf.umiacs.umd.edu/ [1 November 2006]) displaying the location of the Flinders Ranges between Lake Torrens and Lake Frome. Sites of sedimentary sequences discussed in the text are indicated in black; 1) Lacustrine cores LF82/1-3, 2) Suite of formations on the Lake Torrens piedmont plain, 3) Balcoracana Creek, 4) Hookina Silts 4) Brachina Silts. Other Australian sites mentioned in the text are indicated in red on the outline map; 1) Lake Gairdner, 2) Lake Eyre Basin, 3) Yanco Palaeochannel on the Riverine Plain, 4) Naracoorte Caves, 5) Kosciuszko Massif in the Snowy Mountains, 6) Lake George.*

Lake Frome physiography

Lake Frome derives its water primarily from intermittent surface runoff and direct precipitation. Most of the runoff is from ephemeral streams from the eastern Flinders Ranges and occasionally from the Olary Ranges to the south (Ker, 1966), (Fig. 1). Inflow of Great Artesian Basin ground water from isolated mound springs on the eastern side of the lake amounts to less than several litres per hour (Draper and Jensen, 1976). The western lake margin consists of coalescing delta fans from larger streams. There is shallow subsurface flow through the coarse talus and alluvium that extends from the range front towards the playa lake (Ker, 1966). East of Lake Frome the landscape is made up of dunefields interspersed saltpans of the southern Strzelecki Desert. Historical observations describe the playa lake surface as dry (Frome, 1899; Madigan, 1929). However, years of abnormally high precipitation, last recorded for 1972-1974, result in rapid inundation of large areas of the lake floor (Draper and Jensen, 1976; Callen, 1984). At present, the floor of Lake Frome is flooded episodically for short intervals (Bowler et al., 1986) during which surface water are concentrated around small islands in the southeast and at the mouths of some creeks (ETM+ imagery).

Islands of Lake Frome

An archipelago of ~15 groups of islands rises out of the deepest part of Lake Frome. These represent former dunes aligned roughly NE-SW. At present, they are cliffed, terraced and in some cases segmented by wave erosion. Their sedimentary sequences consist of aeolian clay pellets and gypsiferous quartz sands resting on the former laminated lacustrine bed. Horizontal bedding planes with low-angle cross-bedded structure are indicative of the former dunes (Callen, 1984).

The islands present the best-preserved sedimentary section recording the terminal desiccation and subsequent deflation of the playa lake floor during LGM peak aridity. The gradually desiccating playa floor supplied sediments that were blown downwind into longitudinal dunes which now overly and preserve remnants of the final pre-LGM lacustrine phase. The dune remnants consist of a sequence of beds composed of pelletal clays and gypsum fragments, with the fore-set dips indicating westerly winds. The aeolian clays at the base pass into relatively pure sand-sized gypsum crystals. Prolonged sediment supply requires repeated cycles of inundation and desiccation to allow for salt shattering and clays to dry and crack (Bowler, 1976; Pye, 1995). Hence, the higher strata of the dunes (Callen, 1984, Fig.5) are likely to represent later stages of lake-floor deflation. On the other hand, the basal unit should coincide broadly with the initial dune-building phase during the LGM. The closest age estimate is based on one conventional ^{14}C-date, derived from inorganic carbonate partly precipitated around *Clara* oogonids blown in from the lake floor and sampled from the centre of the 3m high basal aeolian clay pellet bed. Its age of ~23.33 $\pm$ 0.46 ka[1] (Bowler, 1976; Callen et al., 1983; Callen, 1984) gives a minimum age for the onset of deflation of the lowest part of the playa lake floor and the consequent inception of gypsum dune formation. The formation of dunes on the wettest part of the lake-bed could be coeval with the formation of the clastic sediment mound

[1] All presented ^{14}C-dates are calibrated using the calibration software 'CalPal May 2006' (www.calpal.de/ [1 November 2006]) and the calibration curve of Fairbanks et al. (2005)

springs, trapping aeolian sediment from the lake floor (Draper and Jensen, 1976) and with the gypsum mounds that flank the eastern side of Lake Frome (Callen et al., 1983).

The lacustrine chronostratigraphy

The sediments of the playa lake have issued from surface runoff entering the lake on all but the eastern margins, mainly in the form of delta fans of streams flowing from the Flinders Ranges. The three stratigraphic lacustrine units recognised by Draper and Jensen (1976) were analysed in greater detail by Bowler et al. (1986), Singh and Luly (1991) and Ullman and Collerson (1994), (Fig. 2). The Lower Sands (Units C and D, Bowler et al., 1986) are found at progressively greater depth towards the centre of the playa lake, where they unconformably overlie pedogenic horizons of the fluviatile Willawortina Formation (Fig. 3). This basal unit is composed of mostly well-sorted unconsolidated sand to sandy mud with subangular to rounded grains of quartz, feldspar and mica. The Lower Sands contain abundant freshwater ostracods and oogonia of freshwater algae. The Upper Sands (Unit A, Bowler et al., 1986) are distributed over much of the present surface of the embayment proper. In lithology and fossil assemblages they resemble the Lower Sands, apart from the relative abundance of detrital carbonate (Draper and Jensen, 1976). The unit is still forming today, but is restricted to the margins of the lake and immediate areas around the islands. The present playa floor is covered by a veneer of evaporite minerals, mainly halite, which forms a solid crust up to 30cm thickness towards the centre, and reddish-brown gypseous sandy clays rising a couple of decimetres from the water table.

Both sandy units encompass a distinct fine-grained lithofacies, (Unit B, Draper and Jensen, 1976; Bowler et al., 1986), consisting of silty clays laminated towards the base (Singh and Luly, 1991) with a high content of post-depositional displacive gypsum (Bowler et al., 1986; Ullman and McLeod, 1986). The fine-grained unit is exposed at the surface in the central lake area, wedging out laterally and becoming covered by the Upper Sands towards the margins. The clays are composed of kaolinite, montmorillonite and illite forming thin discontinuous laminae along bedding planes, which in places are disrupted by diagenetic gypsum crystals. Fossils are rare and restricted to ostracods and oogonia, partly reworked and concentrated along the planes. Propagation of the fine-grained lithofacies over the Lower Sands is interpreted to indicate a westerly movement of the shoreline as a result of rising lake levels (Draper and Jensen, 1986; Bowler et al., 1986).

A group of three nearby cores (LF82/1-3) were recovered by hollow-flight auger coring (Chivas and Bowler, 1986) from a site ~6km east of the western shore just beyond the line where fan sediments merge with deeper lake sediments (Draper and Jensen, 1976; ETM+ imagery), (Fig. 1). The cores reveal ~580cm of lacustrine sediment unconformably overlying the fluviatile Willawortina Formation. The chronostratigraphy of this lacustrine sequence is now based on ten ^{14}C-dates from organic carbon samples. Eight ages were determined by conventional dating of very fine disseminated organic carbon, requiring the treatment of up to 30cm core length as single samples (Bowler et al., 1986). Two subsequent ^{14}C-dates where obtained by accelerator mass spectrometry (AMS), confirming the general validity of the conventional radiocarbon ages (Luly and Jacobsen, 2000).

The fine-grained lithofacies (Unit B) accumulated on top of a sedimentary discontinuity at 346cm, interpreted to indicate the LGM-interval of lake-floor deflation. The inference of a substantial time break at this depth, "identified by sharp lithological changes" (Bowler et al., 1986, 256), was not questioned by subsequent studies. However, similar fine-grained sediments grade down to a sandy facies at a depth of ~460cm (Bowler et al., 1986, Fig.7), possibly representing the Lower Sands of Draper and Jensen (1976). A potential lower onset of initial post-LGM sedimentation would be supported by the ^{14}C-date of 19.92 $\pm$ 0.63 ka from 377-360cm (Fig. 2). However, very low organic-carbon contents (<0.5%) make sediments below 346cm "very unreliable for age determination" (Bowler et al., 1986, 256). Conventional ^{14}C-dates suggest that the initial post-LGM flooding of the lake floor took place shortly before ~20.23 $\pm$ 0.36 ka (325-310cm). The first 6cm above the unconformity are slightly reddened, implying an oxidising, relatively dry environment. Between 340-120cm, the fine-grained unit consists of grey gypseous silty clays. While the lower part of the lithofacies is laminated, a marked reduction in those laminae is evident between 185-120cm (Singh and Luly, 1991). The fine-grained lithofacies terminates at this depth, with sandy clays and sand setting in, likely representing the Upper Sands of Draper and Jensen (1976). The timing of the termination of the fine-grained sedimentation regime can be estimated by taking the two ^{14}C-dates 16.11 $\pm$ 0.32 ka (140-125cm) and 12.69 $\pm$ 0.4 ka (90-80cm) as maximum and minimum ages, respectively. The entire fine-grained unit is marked by sedimentation rates far in excess of those of the coarser facies above and below (Bowler et al., 1986), (Fig. 2). The sedimentation regime of the upper sandy facies was interrupted by the deposition of a conspicuous thin grey 'clayey band' associated with secondary gypsum precipitation between 45cm and 34cm (Singh and Luly, 1991). The age of the fine-grained band is best estimated by an AMS sample from 38-35cm, dated to 5.06 $\pm$ 0.15 ka (Luly and Jacobsen, 2000). The top 34cm of the sequence consist of reddened sandy clays (Singh and Luly, 1991).

An earlier independent radiocarbon chronology for the fine-grained lithofacies (Unit B) is in good agreement with the ages presented above (Draper and Jensen, 1976). According to it the ages between the two sandy units range from 20 ± 0.7 ka near the base to 15.8 ± 0.5 ka near the top of the fine-grained unit.

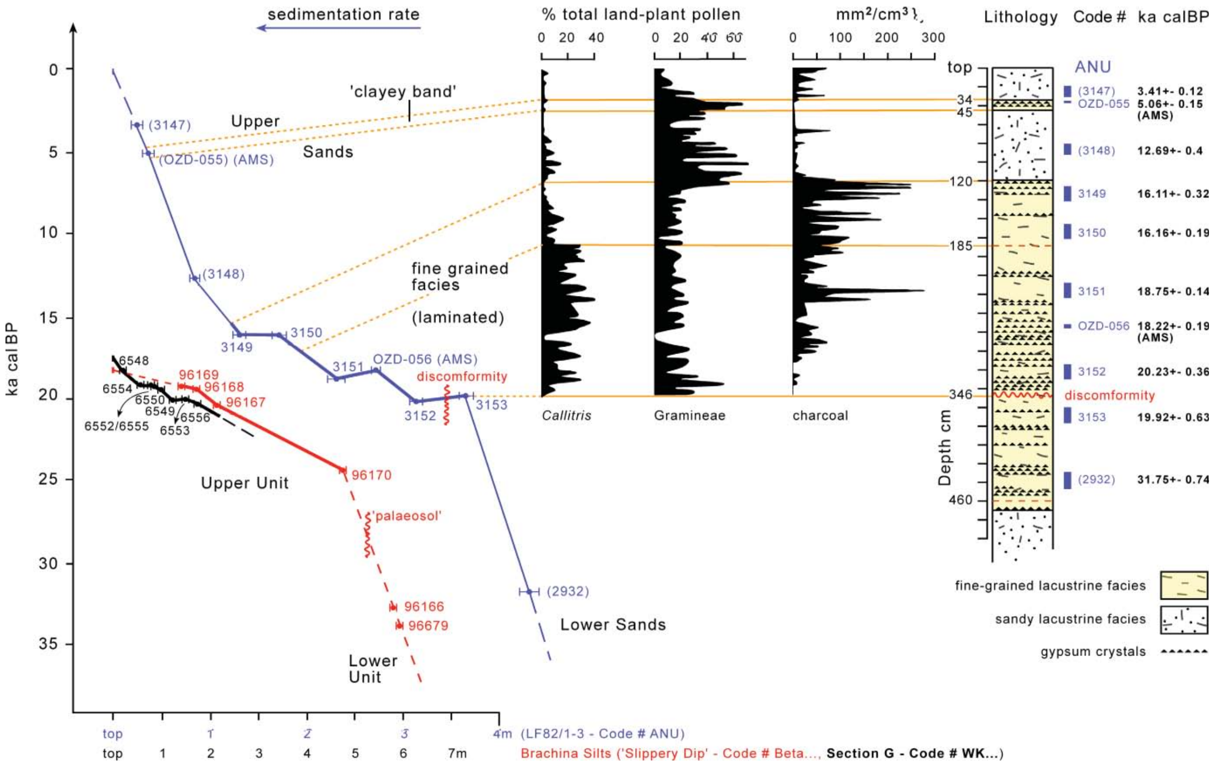

Fig. 2) *Calibrated depth-age plots of Lake Frome core LF82/2 (blue, thick line for fine-grained lacustrine facies, dates from Bowler et al. 1986; Luly and Jacobsen 2000) and the Brachina Silts (red for the 'Slippery Dip' type section, black for 'Section G', dates from Cock et al. 1999; Williams et al. 2001). Correlated lithology, location of gypsum bands, radiocarbon date sample intervals (modified from Bowler et al., 1986; Luly 2001) and Callitris and Gramineae pollen and carbonised particle concentrations (Singh and Luly, 1991; Luly, 2001) are indicated.*

Geochemical record from Lake Frome

Chlorine/Bromine ratios of salts of the brine and halite crust suggest that they are derived either from second cycle brines or weathering of saline rocks exposed in the Flinders Ranges. Similar bromide deficiencies in the brines of Lake Torrens and Lake Gairdner to the west (Johns, 1968), (Fig. 1), and the lack of substantial evaporite deposits in the catchment suggest an allochthonous aeolian provenance.

Indirect evidence of lake-level fluctuations and desiccation events may be derived from the interpretation of evaporite minerals. Well-formed gypsum crystals, up to several centimetres in diameter, have formed diagenetically within the lacustrine sequence disrupting laminations of organic-rich clays. Due to the presence of unoxidised pyrite and lack of evidence for solution of detrital carbonate, gypsum precipitation is interpreted to result from saturation reached by evaporation (Draper and Jensen, 1976; Ullman and McLeod, 1986). By modern analogue, it can be assumed that the gypsum crystals formed within the top 20cm of the sediment surface (Ullman and Collerson, 1994). Gypsum bands of variable thickness occur primarily in the lower section of the fine-grained lithofacies and in the 'clayey band' between 45-34 (Bowler et al., 1986, Fig.7), (Fig. 2). Small crystal sizes and multiple phases of crystal growth in larger crystals as indicated by inclusions, suggest rapid evaporation rates (Draper and Jensen, 1976).

Changes in strontium isotope ratios, recorded in authigenic gypsum precipitating from the brines, are assumed to reflect local hydrological changes related to climate variations (Ullman and Collerson, 1994). Drier intervals are expected to result in higher $^{87}Sr/^{86}Sr$ ratios, due to a greater flux of radiogenic continental dust and an increased residence time of surface groundwater allowing for a greater degree of reaction with more radiogenic sedimentary particles. Accordingly, above a depth of 330cm, a sharp drop in the strontium isotope ratios indicates an abrupt transition from arid to humid conditions which is reversed at ~140cm. Thereafter, a drying trend culminating in the present set in, reversed only by possibly deeper lake levels recorded by two gypsum crystals at 39-38cm and 36cm, within the 'clayey band'.

Minor element concentrations were analysed in 38 gypsum samples from cores LF82/1-3 with the aim of establishing a palaeosalinity record for Lake Frome (Ullman and McLeod, 1986). Displacive gypsum crystals are formed post-depositionally and their analytical ratio of Na^{+}/Ca^{2+} averages gypsum-precipitating intervals of unknown length. Therefore, the interpolated absolute ^{14}C-ages can only be taken as approximations of minimum ages. However, the relative stratigraphy remains intact and reequilibration and recrystallisation were dismissed due to large variations in adjacent samples (Ullman and McLeod, 1986). The Na^{+}/Ca^{2+} ratio was measured to estimate the chemistry and salinity of the brines since the LGM. From the dataset, a sudden initial drop and steep subsequent rise from hypersalinity to lower salinity and back, followed by a similar event of lower magnitude, is evident (Ullman and McLeod, 1986, Table 1). The first event is recorded by six gypsum crystals between 337-317cm. Salinity concentrations rapidly dropped after the initial onset of post-LGM sedimentation with low-salinity conditions lasting until 20.58 $\pm$ 0.37 ka (325-310cm, for carbonate). The second low-salinity interval is recorded by three gypsum crystals between 196cm and 160cm, corresponding with the two ^{14}C-ages 16.17 $\pm$ 0.42 ka (199-169cm, for carbonate) and 16.16 $\pm$ 0.19 ka (180-165cm). Higher salinity values are recorded for the overlying ~30cm by another four crystals, prior to a return to two lower salinity values and a long hiatus until 39cm that is interrupted by two crystals recording low-salinity concentrations at 93cm and 87cm. From these results, Ullman and McLeod (1986) suggest a freshwater phase with salinity levels below that of gypsum precipitation that can be bracketed by the two ages 16.16 ± 0.19 ka (180-165cm) and 7.14 ± 0.14 ka (64-44cm, for carbonate).

Pollen record

A pollen sequence, derived from the dated cores, presents an important and independent line of palaeo-environmental evidence, establishing a vegetation history since the 346cm unconformity associated with LGM deflation (Singh and Luly, 1991). Lake Frome is uniquely positioned within the shifting ecological boundary dividing winter and summer rainfall zones. Hence, the palynological record registers both the influence of monsoonal incursions from the north and frontal precipitation associated with the westerlies from the south. Distinctive although overlapping plant communities reflect the differing seasonal rainfall regimes. Chenopods register winter rainfalls, and hummock and tussock grassland communities are indicative of dominantly monsoonal summer precipitation.

Most probably due to oxidation, no workable amounts of pollen were preserved below the disconformity at 346cm (Luly 2001). Above 346cm, the pollen from tree populations rapidly attained high values during initial post-LGM sedimentation (Fig. 2). *Callitris* dominates over *Eucalyptus*, with a total pollen count many times above the present. High rainfall events are important in encouraging mass recruitment of *Callitris glaucophylla* (Lacey, 1972), the currently dominant species in the Flinders Ranges (Gell and Bickford, 1996). The palynological evidence implies that precipitation associated with the lower laminated unit between 346-185cm must have been largely derived from westerly anticyclonic air-masses. A sharp decrease of Cupressaceae pollen is offset by an increase in *Eucalyptus* pollen at 185cm. This is interpreted to indicate a reduction in winter rainfall while summer rainfall was still low (Singh and Luly, 1991). At present, *Callitris*-dominated woodlands are best developed in semi-arid eastern Australia with annual rainfall averaging between 300-650mm (Luly, 2001). The closest ages for this transitional period are 16.17 ± 0.42 ka (199-169cm, for carbonate) and 16.16 ± 0.19 ka (180-165cm, Bowler et al., 1986, Table 2). Winter rainfall must have been plentiful enough to allow for a more abundant growth of trees than today or after ~16 ka. The decline in Cupressaceae pollen is closely followed by a dramatic increase in carbonised particles (Luly, 2001, Fig.6), (Fig. 2). Extremely low pollen counts of fern spores below a depth of 120cm suggest that during sedimentation of the fine-grained lithofacies humidity was low and summer months have been as dry as or even drier than at present (Singh and Luly, 1991). The sporadic presence of pollen from taxa typical of temperate areas further to the south indicates that temperatures were lower, an interpretation later supported by independent studies further north (Miller et al., 1997).

A substantial rise in Gramineae, accompanied by the first appearance of subtropical to tropical taxa from the summer rainfall zone, sets in at 120cm, just 20-5cm below an organic carbon sample dated to 16.11 ± 0.32 ka (Bowler et al., 1986), (Fig. 2). This suggests that the onset of summer monsoon incursions to latitudes of ~31°S took place ~16 ka. Although relative vegetation stability is recorded until a depth of 34cm, grass values constantly decline until ~45cm, where they suddenly recover. From 34cm to the top of the sequence, a rapid decline of Gramineae coincides with a rise in pollen from halophytes and ephemerals and the onset of present playa conditions, suggesting a reduction in the frequency of tropical rainfall incursions. The transition at 34cm postdates 5.06 ± 0.15 ka, as indicated by an AMS sample from 38-35cm (Luly and Jacobsen, 2000). The palynological evidence from Lake Frome therefore suggests that the Flinders Ranges have been within the winter rainfall zone, except for the interval between ~16-5 ka.

The piedmont plain and palaeosol record

The Lake Frome record may be compared with the record of alluvial and aeolian deposition on the piedmont plains and within the ranges. The widespread occurrences of distinct pedogenic carbonate segregations separate the depositional records into genetic sequences that are ideal for comparison. The carbonate segregations occur as a series of morphologically distinct horizons at or just below sedimentary discontinuities. A subhumid climate with annual rainfall between 200-600 mm (Goudie, 1983), high rates of evaporation or evapotranspiration (Wright and Tucker, 1991), and slow sedimentation rates relative to rates of pedogenesis (Wright, 1990; Kraus, 1999) are conducive to pedogenic carbonate precipitation. Hence, these fossil soils register intervals of landscape stability between erosional and depositional episodes. In contrast to the depositional records from playa lakes, alluvial fans and valley-fill formations, the record from pedogenic carbonates provides information about moist intervals of minimal deposition.

The piedmont plains around the Flinders Ranges constitute a link between valley-fill formations within the ranges and the flanking terminal depocentres of the salinas Lake Torrens and Lake Frome (Fig. 1). The Lake Torrens piedmont plain is mantled by some of the best-developed alluvial fans and pediments in Australia (Williams, 1973; Bourne and Twidale, 1998). General stratigraphic observations suggest that a prolonged interval of fan aggradation was succeeded by aeolian accession and shorter intervals of fan dissection, all separated by periods of calcareous soil-formation. Fan dissection prevails today and is indicative of overall aridity and low stream-discharge (Williams, 1973).

Three morphologically distinct pedogenetic phases are recorded within the alluvial and aeolian deposits (Williams and Polach, 1971; Williams 1973). Their common diagnostic attributes consist of nodules of authigenic carbonate, concentrated within distinct horizons. On the Lake Torrens piedmont plain, the chronology is mostly based on conventional radiocarbon dating of these carbonate concretions (Williams and Polach, 1971; Williams, 1973). In a similar study, the ages of longitudinal dunes and alluvium along the eastern side of Lake Frome were estimated (Callen et al., 1983).

Pedogenic carbonates are often unreliable in terms of ages of the calcrete segregation processes. However, by excluding whole-soil samples and samples from truncated buried soils, and by sampling only fine-grained carbonate (<20µm) of the lower Bc-horizons from locations above present flood levels, chronological sequences can be obtained that correlate remarkably well with the other palaeo-environmental evidence. Whenever possible, pedogenic age estimations are paired with ^{14}C-dates from organic carbon samples (Williams, 1973; Lampert and Hughes, 1988; Cock et al., 1999) and thermoluminescence (TL) dating (Gardner et al., 1987; Williams et al., 2001).

A major period of alluviation and fan building in the piedmont plains is dated by two radiocarbon ages for detrital wood to 39.33 ± 2.51 and >42.54 ka, extending back beyond the range of radiocarbon dating. The alluvial fan deposits, with a maximum exposed thickness of ~15m, consist of mudstones with lenticular pebble- to boulder-conglomerates in a red matrix of clayey silts and sands. Towards the range-front, the so-called Pooraka Formation passes without a break in surface slope into talus breccias with a similar matrix and into mottled grey and yellow fine-grained valley-fills within the gorges (Twidale, 1966; GE Williams, 1973; DLG Williams, 1982; MAJ Williams et al., 2001). Along the eastern side of Lake Frome, apparently coeval fluviatile sands of the Eurinilla Formation were deposited in channel, overbank and deltaic environments (Callen et al., 1983).

Within the fluviatile parent material of the Pooraka Formation, a distinct 1-2m thick pedogenic carbonate horizon is developed impregnating the fine-grained matrix and coating the larger clasts. Locally, the calcareous bands grade laterally into massive laminated groundwater calcrete. Excluding whole-soil carbonate samples, eight ^{14}C-dates from the so-called Wilkatana Palaeosol were obtained from various stratigraphic settings. The radiocarbon dates range from ~39.81 ± 2.11 to 24.39 ± 0.46 ka, grouping around a median of 33.75 ± 1.08 ka (Williams, 1973, Table 2). East of Lake Frome, coeval calcareous segregations form several individual layers of hard calcareous nodules and cement the fluviatile sediments of the Eurinilla Formation. Collectively referred to as the Pinpa Palaeosol, they were dated by more than 17 samples. The ^{14}C-dates span an interval between 44.26 ± 2.52 and 26.2 ± 0.28 ka. The considerable spread of the dates may reflect an extended period of pedogenesis consisting of multiple calcrete forming events which resulted in composite profiles (Candy et al., 2003). It is likely that pedogenesis coincided with ongoing and laterally shifting fan building episodes of the Pooraka Formation. As with the overall fan aggradation, the pedogenetic processes could have been initiated earlier than indicated by the ^{14}C-dates dates. Taken at face value, the radiocarbon ages for carbonates nodules within the fluviatile Pooraka and Eurinilla Formations suggest three major intervals of soil formation towards ~39, ~31 and ~27 ka.

Subsequent to a decline in pedogenetic processes ~27 ka, an undated interval of dune building and fan dissection is stratigraphically recorded in the Lake Torrens piedmont plain. A "red clayey horizon as much as 1m thick" (Williams and Polach, 1971, 3073) mantles the upper reaches of the fans. Towards the base, the aeolian deposits develop into 2-5m thick longitudinal dunes of the Lake Torrens Formation, erosively overlying the Wilkatana Palaeosol. On the eastern side of Lake Frome, aeolian deposits form partly consolidated cores of longitudinal and lunette dunes. The aeolian unit, which unconformably overlies the Pinpa Palaeosol and is locally covered by a veil of modern loose drift sands, is referred to as the Coonarbine Formation (Callen et al., 1983). Within these fine-grained aeolian formations, horizons of carbonate concretions occur, with ^{14}C-dates for the so-called Motpena Palaeosol from the Lake Torrens piedmont plain ranging from 19.3 ± 0.24 to 14.01 ± 0.16 ka (Williams, 1973, Table 2). Within the Coonarbine Formation, two episodes of carbonate segregation are distinguished. Based on their close morphological resemblance and similar scope of ^{14}C-ages, the stratigraphically lower and therefore older calcareous horizons of the Moko Palaeosol can tentatively be linked with the Motpena Palaeosol from the western piedmont plain. Excluding two spurious samples, all remaining five ^{14}C-dates fall within the range from 19.36 ± 0.18 to 17.32 ± 0.51 ka, with two distinct probability peaks at ~19.4 and ~18.2 ka.

Holocene alluviation is recorded by several conglomeratic terraces, deposited within the main channels of the alluvial fans, and by abandoned fan segments on the western piedmont plain. Collectively termed the Eyre Gravel Formation (Williams and Polach, 1971; Williams, 1973), their lithology of the pebble- to boulder-gravels with an overall light reddish brown colour has provided a ^{14}C-date of 5.88 ± 0.12 ka for a charcoal sample collected 40cm below the top of the oldest and highest terrace of the complex. Laterally equivalent sandy deposits, flooring the distal interdune corridors of the Lake Torrens Formation and truncating the Wilkatana and Motpena palaeosols, are collectively called the Thompson Creek Formation. The latter consists of two up to 2m thick members which are separated by a vesicular layer of a desert loam and the pedogenetic horizon of the so-called Nacoona Palaeosol consisting of soft calcareous tubules and patches of "earthy carbonate" (Williams and Polach, 1971, 3075). Charcoal from the parent material is dated to 6.86 ± 0.13 ka. At present, the youngest pedogenic formation is capped by unweathered gravels and sands which are the product of ongoing fan dissection. Further to the N, the Motpena Palaeosol is buried by red, moderately consolidated aeolian quartz-sands. The youngest interval of pedogenic carbonate segregation in the aeolian Coonarbine Formation remains unnamed. While two dates obtained at the northern tip of the Lake Frome are close to ~12.35 ka, samples from morphologically similar soft small calcareous rhizomorphs, crust and patches close to the southern tip present ages of 9.09 ± 0.19 and 8.00 ± 0.13 ka.

Stratigraphic accounts from the eastern piedmont plain of the Flinders Ranges are rare. A channel bank section of the Balcoracana Creek discharging into the south-western end of Lake Frome has been logged and dated (Gardner et al., 1987; Lampert and Hughes, 1980, 1988), (Fig. 1). Shell samples from a pedogenic horizon described as a "probably sheetwash layer of blocky fine to medium sand rich in land snail shells" (Gardner et al., 1987, 350) ~210cm below top were radiocarbon dated to 16.34 ± 0.9 ka and 14.78 ± 0.15 ka. The former date corresponds well with a carbonate sample from the underlying palaeosol dated to 16.36 ± 0.36 ka (Gardner et al., 1987). These ages lie in-between those inferred for the Moko Palaeosol to the east and the Motpena Palaeosol to the W. Below modern loose drift sands, soft carbonate nodules were concentrated in the youngest pedogenic horizon which, based on the TL-age of 5.5 ± 1.6 ka from similar depth (Gardner et al., 1987), is likely to correlate closely with the unnamed youngest soil-forming interval with the dunefields east of Lake Frome (Callen et al., 1983).

Fine-grained valley-fill formations of the Flinders Ranges

In many cases, coalescing fan deposits from the piedmont plains extend upstream, breaching the scarp of the ranges where they form a distinctive and recurring sequence of valley-fill deposits.

Hookina Creek

Laminated fine-grained valley-fill formations in the Flinders Ranges were first described from Hookina Creek (Twidale, 1966), (Fig. 1), and later correlated with fan deposits of the Pooraka Formation from the adjacent piedmont plain further downstream (Williams, 1973) on the basis of a single radiocarbon date. The charcoal sample, dated to 38.36 ± 2.18 ka, was derived from 9-8m below the top of the valley-fill formation, further referred to as the Hookina Silts. The modern creek meanders within deeply incised bedrock channels, eroding the unconsolidated fine-grained sediments and exposing their near-horizontal bedding planes.

Three main facies were differentiated from a sedimentary sequence exposed in a ~15m vertical river bank section (Williams, 1982). Basal conglomerates rest unconformably upon bedrock. Two overlying units of fine-grained, unconsolidated valley-fill alluvium form the bulk of the Hookina Silts. The lower unit consists of clayey to sandy laminae of variable colour that can be traced for tens of metres laterally. The sediments are poorly sorted and display localised current-bedded structures. The upper unit consists of uniform red-brown silt and sand with occasionally inset sandy or gravelly channel-fill deposits. It is characterised by calcareous laminations. Aquatic mollusca described from the lower unit become increasingly rare in the upper unit and are replaced by fossil shells of land snails. Within the entrenched modern creek channel, low gravel terraces abut alternate sides. A single charcoal sample, radiocarbon dated to 2.16 ± 0.14 ka (Williams, 1982), suggests that the terraces are late Holocene phenomena, possibly deposited coevally with the upper members of the Eyre Gravel and Thompson Creek Formations in the adjacent foreland (Williams, 1973).

Based on the observation of fresh-water mollusca (*Corbiculina angasi*, *Pettancylus* sp. and *Physastra* sp.), the Hookina Silts were initially interpreted as "accretion-gley deposited in a marshy area of local high, fluctuating water table" (Williams, 1973). In a subsequent study, an assemblage of 2270 individuals of aquatic and terrestrial species was described from a sandy channel-fill deposit ~5m below top (Williams, 1982). The most common aquatic mollusc is the Hydrobiidae *Potomopyrgus* sp (85%), followed by the Planorbidae *Gyraulus* sp. (9%), both living in a habitat of still to flowing water and tolerant of low to moderate salinity levels. The former still occurs within the modern creek bed, where it is found clinging to the walls of seasonally flooded rock pools.

Brachina Creek

Comparable sequences occur throughout the Flinders Ranges, forming extensive gently sloping valley-fills upstream of resistant ridges and within narrow rock-cut gorges. The best dated sequence is that of the Brachina Creek ~45km north of Hookina Creek, here termed the Brachina Silts (Fig. 1). At the 'Slippery Dip' type section, a sedimentary sequence consisting of three distinct units is exposed in a ~9m high near-vertical cliff face (Williams et al., 2001, Fig.7). The basal Lower Unit consists of largely uniform silty clay with discrete lenses of gravel. Shells of the aquatic freshwater species *Glyptophysa* sp. are abundant but decrease towards the distinctively brown top of the unit that is interpreted to represent a palaeosol (Cock et al., 1999). Current microfossil studies describe an assemblage of free-swimming and benthic freshwater mollusca and ostracoda, testifying a diversity of habitats. This is followed by ~5m of alternating light- and dark-coloured bands that form the Upper Unit, grading towards a more sandy, coarsely bedded 'red layer' forming the top of the sequence and the modern near-level valley floor While the total number of ostracods and mollusca rapidly increases and then fluctuates towards the top of the sequence, the Upper Unit is characterised by a marked decline in diversity of the assemblage and by a prevalence of broken shell fragments indicative of high-energy transport. The lithology of the Lower and Upper Units consists of similar silty clay, with occasional thin discontinuous lenses of local scree structuring the more massive bedding planes. While several depositional models are possible (Haberlah, 2006), the pattern of laminations consisting of massive layers alternating with calcareous bands and veneers of organic mud is indicative of slackwater couplets. They could be explained by back-flooding of the tributary mouth just upstream of the confining gorge (Zawada, 1997).

Initially, the Brachina Silts were believed to represent a Pleistocene lake (Callen and Reid, 1994; Cock et al., 1999). A later theodolite survey established that the surface of the Silts has a sloping gradient parallel to the modern bedrock channel and higher terraces, and therefore was re-interpreted as a former wetland (Williams et al., 2001). The possibility that the upper sequence represents a terminal Pleistocene palaeoflood record is currently under study. While aggradation of the Lower Unit terminates ~33 ka, as inferred from AMS ^{14}C-dates 33.94 $\pm$ 0.54 ka for charcoal and 32.61 $\pm$ 1.6 ka for shell, supported by the minimum OSL age 32.8 $\pm$ 2.8 (Williams et al., 2001), the deposition of the bulk of fine-grained sediments above the 'palaeosol' seems to reflect from two or three groups of episodes of rapid deposition (Fig. 3). The calibrated dates for thirteen AMS shell and charcoal samples for the Silts of the Upper Unit from 'Slippery Dip' and 'Sections G' group tightly around probability peaks ~20.2 ka, 19.4 ka and 18.2 ka (Williams et al., 2001, Table 1), (Fig. 3). The chronostratigraphy is supported by three OSL ages ranging from 20.3 $\pm$ 1.0 ka to 18.0 $\pm$ 1.2 ka (Williams et al., 2001, Table 3). Rapid sedimentation of the Brachina Silts is analogous and contemporaneous with the deposition of the fine-grained lacustrine facies in Lake Frome (Fig. 2). Williams and Nitschke (2005) demonstrated that loess mantles accumulating within the catchment in the period between the alluviation of the Lower and Upper Units contributed the bulk of the fine-grained sediments (Fig. 3), thereby explaining the marked difference to the contemporary fluvial regime characterised by coarse bedload transported during erratic floods.

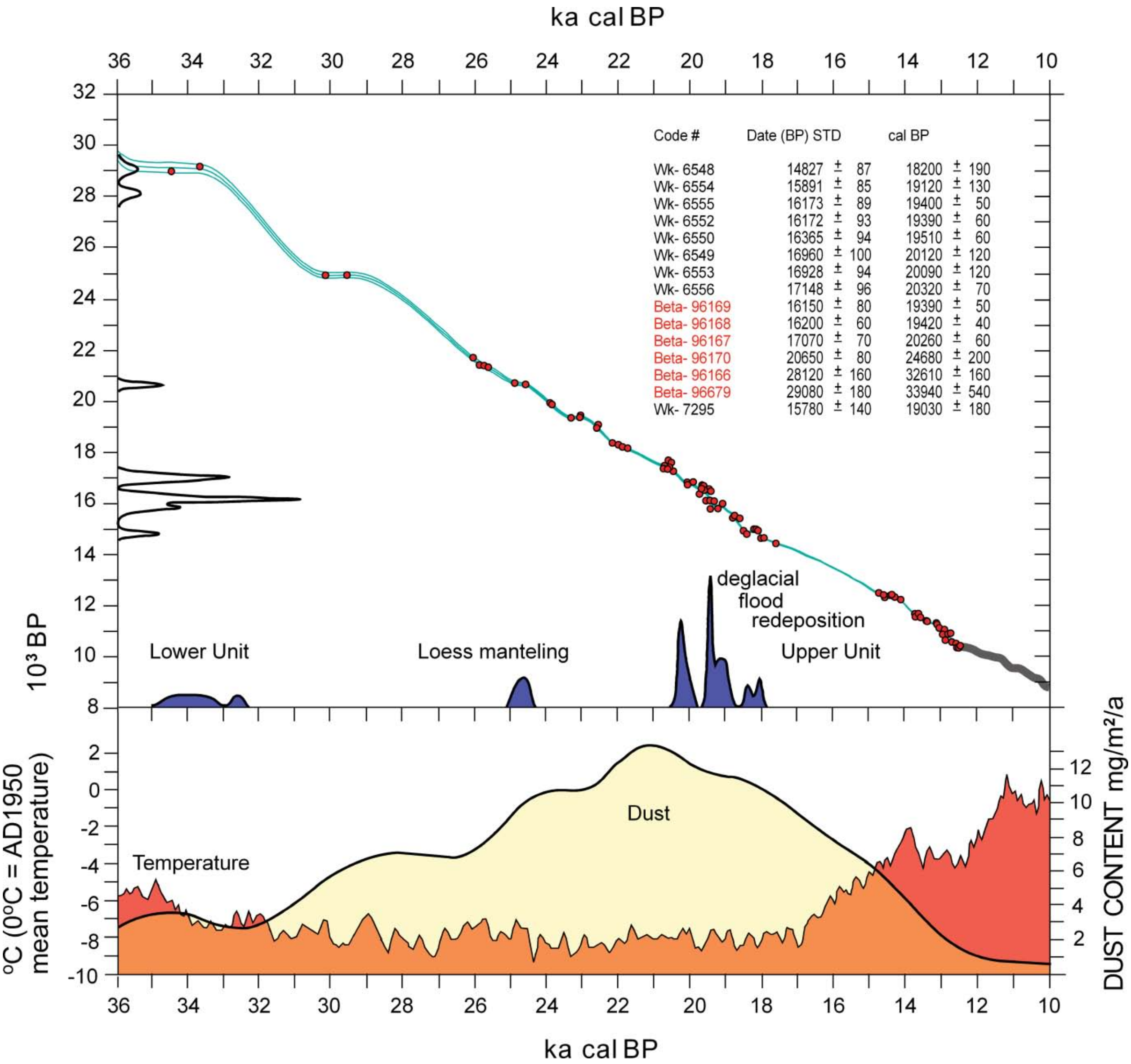

Fig. 3) *2-D dispersion of calibrated ^{14}C-dates for the Brachina Silts (modified diagram of ^{14}C-calibration program 'CalPal May 2006', www.calpal.de/ [1 November 2006]) using the calibration curve 'Fairbanks Aug 2005' (Fairbanks et al., 2005). Indicated depositional units are collated with 'Vostok ice core 1999' temperature and dust content records (Petit et al., 1999). Samples of the 'Slippery Dip' type section are listed in black and those of 'Section G' in red (dates from Williams et al., 2001).*

Discussion

Deglacial environmental responses in southern Australia are complex. In order to develop a sound understanding of palaeoclimatic changes following LGM peak aridity, the range of widely occurring terminal Pleistocene and Holocene aeolian, fluviatile and lacustrine fine-grained sediments needs to be explained. The Lake Frome data are based on a limited number of cores largely from one location, with a low-resolution conventional radiocarbon chronology. However, clearer patterns emerge when the Lake Frome data are compared with the records from the dunes, piedmont deposits and valley-fills in and around the Flinders Ranges

Interpretation of silty lacustrine sequence of Lake Frome

The Lake Frome cores shows a change from generally sandy to fine-grained sedimentation between ~20 ka and ~16 ka and possibly around ~7 ka. Previous workers interpreted these changes in terms of fluctuating lake-levels, with the intervals of fine-grained sedimentation considered to reflect deep-water conditions (Bowler, 1986; Ullman and Collerson, 1994). However, the only direct indicator of higher lake levels is an elevated beach ridge on the southern margin of Lake Frome, with an inferred minimum age from recrystallised shells of 41.56 ± 1.49 ka (Gardner et al., 1987). The beach ridge is probably contemporary with the Lower Sands of the lacustrine sequence and coincides with an interval of widespread alluvial deposition and high lake-levels in southeast Australia, before giving way to increasing aridity (Bowler and Wasson, 1984). The LGM was a time of widespread aeolian activity and deflation evident in the Lake Eyre basin (Magee, 1998) to the north (Fig. 1), and in the gypsum dune formations dated to ~23 ka, that form the present islands of Lake Frome. The high silt content of the fine-grained lithofacies prompted Bowler et al. (1986) to propose aeolian activity coeval with the resumption of lacustrine deposition. Cores from the Tasman Sea show high rates of aeolian dust flux during the LGM (Hesse, 1994), but the Vostok dust record reveals a sharp and progressive decline in dust content after ~21 ka (Fig. 3).

Ker (1966) and Draper and Jensen (1976) noted the role of present-day extreme rainfall and runoff from the eastern Flinders Ranges in providing water to Lake Frome. Sedimentary evidence shows that the lake sediments were primarily derived from the Flinders Ranges. Luly (2001) considered that the high quantities of charcoal characteristic of the fine-grained deposits were probably washed in with the sediment. The chronostratigraphy of Bowler et al. (1986) showed far higher sedimentation rates for the fine-grained lithofacies than for the coarser Holocene sediments. Since the playa lake occupies much of the basin and relief in the immediate catchment is subdued, we would expect low sedimentation rates. This contradiction prompts us to question the prevailing assumption that the fine sediments represent a distal lacustrine facies and hence deep water conditions.

An alternative interpretation of the fine-grained lacustrine facies and its rapid sedimentation rates is based on the assumption that these sediments were derived from the erosion of loess mantles in and around the ranges. Such erosion would lead to an influx of very high suspension loads to the basin over short intervals. Bromide deficiencies in the brines of all major playa lakes in the region (Draper and Jensen, 1976; Johns, 1968), the lack of saline bedrock outcrops and Ker's (1966) observations of steadily increasing salinity in shallow aquifers towards the Lake suggest that the salts are derived from second cycle brines. It is proposed that they were transported intermittently along the southeast dust path (Bowler, 1976) during glacial intervals from the exposed continental shelf and desiccated playa lakes (Crocker, 1946). LGM deflation of gypseous sediments flooring Lake Torrens is recorded in source-bordering dunes of gypsum sands deposited on the eastern playa lake margin (Williams, 1973; Schmid, 1985).

Diagenetic gypsum bands in the laminated section of the lower part of the fine-grained lithofacies, extending from ~120cm beyond the inferred disconformity at 346cm, are likely to reflect rapid evaporation events (Draper and Jensen, 1976). This inference is consistent with the dry summer months interpreted from the pollen evidence for this sedimentation interval (Singh and Luly, 1991). Both the salinity and the strontium isotope records discussed earlier support this model. According to the gypsum chemistry, the first transition from hypersalinity to low salinity was a rapid but brief event, indicative of a sudden concentration of surface waters reaching Lake Frome between ~21-20 ka. This was followed by a second period of low-salinity towards 16 ka. Apart from two gypsum crystals at 97cm and 93cm, indicating a low-salinity brine chemistry, no further gypsum precipitated until the top of the Holocene 'clayey band'. Na^{+}/Ca^{2+} ratios of these two gypsum crystals suggest again a low-salinity precipitation environment (Ullman and McLeod, 1986, Table 1), which is in accord with the pollen record indicating the resumption of summer rainfall (Singh and Luly, 1991).

Ullman and McLeod (1986) interpreted the general absence of gypsum bands between and after these times in terms of a freshwater phase with salinity levels below that of gypsum precipitation, with a subsequent loss of gypsum crystals above the 'clayey band' through deflation. However, the findings could equally reflect the strong influence exerted by sediment type on the occurrence and spatial distribution of minor elements (Draper and Jensen, 1976). Accordingly, during intervals in which an allochthonous loess-derived suspension load was rapidly accumulating in the playa lake, the brine chemistry was altered by the addition of Ca^{2+}-ions reducing the excess of $SO4^{2-}$-ions, established throughout the whole salinity range in the present groundwaters and brines of Lake Frome (Ullman and McLeod, 1986). If so, the gypsum-based palaeosalinity record would register brief intervals of fluctuations in the brine chemistry caused by inundations with runoff waters introducing a Ca^{2+}-rich loess-derived suspension load to the lake system.

Assuming that the 'clayey band' interposed between the sandy units represents eroded loess mantles, the gradual decline and termination of this particular depositional regime towards 16 ka can be explained by environmental changes in the catchment area and by a shift of the dominant precipitation regime. Lower sedimentation rates in the upper 65cm of the fine-grained lithofacies coincide with a marked reduction in the occurrence of laminations and gypsum bands. While Singh and Luly (1991), in line with previous workers, interpret this finding to indicate shallower depositional conditions, they could equally result from a more restricted supply of allochthonous fines. The return to a coarser-grained shore facies, consisting of autochthonous weathering products, could reflect two interdependent trends: a gradual depletion of easily erodible loess mantles and stabilisation of its remnants by vegetation.

The pollen record is consistent with this inference. Dramatic changes in the vegetation cover occurred concomitantly with the termination of the fine-grained lithofacies. During this transitional period, a reduction in intensity and magnitude of frontal precipitation events induced stress on the woody elements, witnessed by the sharp decline of *Callitris* and a subsequent increase in charcoal. The collapse of *Callitris* woodlands, as opposed to the synchronous increase in *Eucalyptus* pollen, may indeed reflect Aboriginal burning (Luly, 2001), but evidence of human presence in the region is sparse and not well dated. Thereafter, rising temperatures, more humid conditions and a southward shift of monsoonal incursions led to the colonisation of the region by subtropical grassland communities from the north (Fig. 2). While *Callitris* woodlands had probably only supported a sparse understorey (Singh and Luly, 1991), which would have little affected runoff, Gramineae exert a stabilising effect on unconsolidated sediment. By increasing surface roughness and infiltration rates, they are likely to have reduced runoff flow velocities and erosion rates and possibly favoured linear incision. Hence, whatever remained of the loess mantles was at this point stabilised and retained within the catchment.

The deterioration of the stabilising grass cover with the gradual retreat of summer monsoon incursions was interrupted by a short-lived recovery in the pollen count of Gramineae towards ~5 ka. Apparently simultaneously, a second flux of fine-grained sediments is recorded in the Lake Frome record as the 'clayey band' (Fig. 2), and reflected in the parent material of the youngest palaeosols on the piedmont plain. It is possible that this inferred short phase of increased precipitation (Singh and Luly, 1991) led to renewed incision of the valley-fills in the Flinders Ranges, again providing fine sediments to the depocentres.

Interpretation of silty sediments within the drainage lines and piedmont plains of the Flinders Ranges

Subsequent to a more than 10 ka long interval of minimal deposition, the fluvial system of the Brachina Creek was suddenly accumulating a massive sequence of loess-derived alluvium. The bulk of the Brachina Silts appears to have been deposited within ~2 ka, possibly within two or three groups of episodes of rapid deposition ~20.2 ka, 19.4 and 18.2 ka (Fig. 3). Rapid sedimentation rates

(Fig. 2), and the morphologic context of the bedding planes levelling out pre-existing relief upstream of confined gorges suggests palaeoflood as a likely depositional model (Haberlah, 2006). The pollen evidence from Lake Frome indicates that these terminal LGM floodwaters may reflect frontal winter precipitation events.

At the same time, the dunes east of Lake Frome were probably stabilised during the soil-forming interval of the Moko Palaeosol (Callen et al., 1983), with peaks at ~19.4 and ~18.2 ka. This period of widespread pedogenesis further coincides with the rapid sedimentation rates established for the fine-grained lacustrine facies. As soil-forming intervals are indicative of surface stability, a coeval direct input from wind-blown dust (Bowler et al., 1986) to Lake Frome seems unlikely. The youngest dates for the Moko and Motpena Palaeosols coincide with colonisation of the region by subtropical grasslands as a consequence of increasing temperatures and the onset of summer monsoon incursions to these latitudes. Consequent stabilisation of the loess remnants and dunes at the base of the alluvial fans prevented further large-scale erosion.

Gradually increasing aridification caused a decline in Gramineae before their sudden albeit short-lived recovery prior to ~5 ka. As the vegetation cover became sparser, aeolian sands were mobilised again as witnessed by the capping of the Motpena palaeosol on the northern Lake Torrens piedmont plain (Williams, 1973). Coinciding with the deposition of the lacustrine 'clayey band', weak soil formation in the distal reaches of the alluvial fans of the western piedmont plain took place, with the Nacoona Palaeosol postdating ~7 ka. The fluviatile fine-grained parent material of the youngest pedogenic interval, and the conspicuous 'clayey band' interrupting the coarser lacustrine sedimentation in Lake Frome, could reflect the erosive effect that the final revival of monsoonal incursions had on the once more largely barren landscape.

The source of the pedogenic carbonate segregations is as unresolved as the provenance of the gypsum in the valley-fills and playa lake deposits. Callen et al. (1983) suggest fluctuating groundwater tables as the most likely cause of carbonate precipitation in the palaeosols, but the carbonate horizons of the Lake Torrens piedmont plain developed in well-drained locations (Williams, 1973). We consider that the carbonate is of allochthonous aeolian origin, blown in and deposited as loess accessions (Williams and Nitschke, 2005). Strontium isotope studies (Dart et al., 2005; Lintern et al., 2006) support early suggestions of a marine provenance and aeolian introduction of carbonate constituents within the southern Australian regolith (Crocker, 1946; Fairbridge and Teichert, 1953).

Conclusion

Facies changes in Australian playa lakes have been used to infer lake-level fluctuations. We propose an alternative interpretation of such changes in lacustrine records as a result of variations in sediment load brought in by local streams. The lacustrine sedimentary sequence of Lake Frome correlates well with intervals of erosion and stabilisation of loess mantles inferred from valley-fill formations within the Flinders Ranges and intervals of calcareous soil formation on the slopes of adjacent piedmont plains. Erosion is likely to have been triggered by intense rainfall on mostly bare surfaces, a scenario supported by the pollen data.

An onset of terminal Pleistocene frontal winter precipitation as early as ~20.2 ka stripped the loess mantles from the slopes of the Flinders Ranges and adjacent piedmont plains. The eroded fine-grained sediment was rapidly washed into valley bottoms and structural depressions, choking the gorges and in places causing backflooding and prolonged ponding. Similar deposits were washed from the piedmont plains into the terminal playa lakes. According to our interpretation, these fine sediments in the lake floor do not represent a distal lacustrine facies indicative of deep lake-level environments, nor are they suggestive of prolonged humid conditions. On the contrary, the fine-grained lacustrine depositional regime was prone to rapid evaporation as reflected by the closely spaced displacive gypsum bands. The rapidly accumulating fine-grained lithofacies rather record the unique effect of terminal Pleistocene floods on a highly erosive loess-mantled environment.

From ~16 ka onwards, a rise in temperatures and regular monsoonal incursions resulted in the colonisation of the loess mantle remnants by grassland. A dramatic reduction in suspension load is likely to have caused the termination of the aggradational regime of the fine-grained valley-fill formations within the ranges. At the same time, the deposition of a sandy lithofacies began in Lake Frome, characterised by an absence of gypsum precipitation and slow sedimentation rates. This coarser lacustrine sedimentation regime was only interrupted once over a short-lived interval terminating ~5 ka reflected in the intercalated 'clayey band'. Both pollen and palaeosol records suggest that it is linked to the return of a dominantly frontal precipitation regime to the region that was preceded by increasing aridification and a demise in stabilising plant cover.

Fine-grained deposits of similar age and appearance occur as remnants within the valleys of the Great Escarpment of Namibia and the Sinai Peninsula of Egypt and appear to have been laid down during discrete flood events (Srivastava et al., 2006; Rögner et al., 2004). Loess was established as the allochthonous source for both locations (Yaalon and Dan, 1974; Eitel et al., 2001).

Evidence for sporadic but intense precipitation events during the terminal Pleistocene include TL dated river deposits in the Riverine Plains (Page et al., 1996), (Fig. 1). Just to the south, a high-resolution 500 ka record of relative water excess necessary for speleothem formation was established using $^{230}Th/^{234}U$ dating. Accordingly, "greater effective precipitation levels for the southeastern interior of Australia" (Ayliffe et al., 1998, 149) only occurred during transitional periods between glacial maxima and warm interstadial and interglacial climate regimes. Barrows et al. (2001) have dated the three most recent glacial advances in the uplands of southeast Australia to 32 $\pm$ 2.5 ka, 19.1 $\pm$ 1.6 ka and 16.8 $\pm$ 1.4 ka, using the cosmogenic isotope ^{10}Be, (Fig. 1). Apart from low temperatures, advances of glaciers require substantial amounts of precipitation. Inferred periods of increased snowfall seem to coincide with the timing of fluvial aggradation of the Lower and Upper Units of the Brachina Silts in the Flinders Ranges, and the timing of their subsequent incision. Still within the Eastern Highlands, lake level fluctuations are preserved in the elevated beach ridges of Lake George to the north, (Fig. 1). Although the chronostratigraphy is complex (Coventry and Walker, 1977; Singh et al., 1981; Pietsch, 2006), it seems that the lake attained its highest still-stand at ~33 ka, followed by a number of high but progressively lower water levels after ~20 ka. The beach ridges of Lake George prompted Galloway (1965) to propose a minevaporal model to explain pluvial features in an otherwise arid glacial Australian landscape. We suggest that the fluctuating lake levels could reflect the onset of deglacial rainfall events in a largely unvegetated cold landscape. Sea-surface temperatures around Australia were up to 9-7°C lower than today until 20.5 $\pm$ 1.4 ka (Barrows and Juggins, 2005). The marine oxygen isotope records show that maximum global ice volumes were only attained some 2 ka later. Temperature amelioration inferred from the Vostok ice core (Petit et al., 1999), (Fig. 1), and from temperature-dependent amino-acid racemization in ^{14}C-dated emu eggshells for low-latitudes of Australia did not begin until ~17 ka. The 3.5 ka interval in-between is likely to have been characterised by moisture transport towards the continent.

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Depositional models of late Pleistocene fine-grained valley-fill formations in the Finders Ranges, South Australia

(similar version published in: Fitzpatrick, R.W., Shand, P. (eds.) 2007, *Regolith 2006—Consolidation and dispersion of ideas*. Cooperative Research Centre for Landscape Environments and Mineral Exploration, Perth, 122-126)

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Introduction

Although the general climatic development of Australia during the late Quaternary is well established (Chappell & Grindrod, 1983; Kershaw & Nanson, 1993; Veevers, 2001), detailed regional palaeo-environmental knowledge remains limited. This is particularly the case for the semi-arid landscapes located between the continent's arid interior and the humid coastal areas (Harrison, 1993; Hesse et al., 2004). Semi-arid environments are very susceptible to hydrologic changes related to variation in precipitation, temperature, vegetation and associated evapo-transpiration. They can therefore be considered key regions in reconstructing the environmental impact of global warming and rising sea levels during the last deglacial termination. In the Australian context, fundamental questions such as the latitudinal shift of the westerly winds and the trade wind-dominated subtropical zone during the last glacial interval remain to be established (Harrison, 1993; Shulmeister et al., 2004). Recent studies date the onset and southward incursion of the summer monsoon to as early as ~15 ka cal. BP (Miller et al., 1997; Wyrwoll & Miller, 2001), decoupling it from more gradual changes in low-latitude summer insolation forcing, a conclusion that needs to be tested by independent palaeo-environmental data.

So far, the main obstacle for regional-scale Quaternary palaeo-environmental reconstructions in Australia has been the limited availability of continuous sedimentary records from semi-arid and arid regions. This is especially the case for the period leading towards and culminating in the Last Glacial Maximum (LGM), during which terminal playa lakes occupying large structural basins dried out and were actively deflated (Schmid, 1985; Harrison, 1993; Magee et al., 1995). Consequent dust entrainment can be expected to result in loess accumulations (i.e. terrestrial deposits of dominantly silt-sized lithogenic wind-blown dust) in down-wind desert margins (Smith, et al., 2002). Loess sequences are globally recognised as valuable terrestrial proxies for reconstructing palaeoclimatic changes (Liu, 1987). One problem with Australian loess deposits is their generally limited thickness and irregular and discontinuous distribution. However, in many cases they still need to be identified and dated. Moreover, the nature of their deposition remains ambiguous and ill-defined (Hesse & McTainsh, 2003).

Fine-grained valley-fill formations in the Finders Ranges

The semi-arid Flinders Ranges are seasonally influenced by winter precipitation associated with frontal systems embedded in the Southern Westerlies, and summer monsoonal incursions from the north (Gentilli, 1972; Schwerdtfeger & Curran, 1996). The tilted, uplifted and dissected Precambrian and Palaeozoic sedimentary rocks form a sequence of weathering-resistant ridges with a wide distribution of peaks rising up to 1,170 m above the surrounding plains (Preiss, 1987; Drexel & Parker, 1993). They act as an orographic barrier that can be expected to amplify palaeo-environmental changes related to changes in the precipitation regime. The central Flinders Ranges hosts one of Australia's best preserved loess-derived sedimentary sequences: the late Pleistocene fine-grained valley-fill formations occupying the Brachina and Wilkawillina drainage systems (Callen & Reid, 1994; Cock et al., 1999; Williams et al., 2001; Chor et al., 2003; Williams & Nitschke, 2005). Radiocarbon and luminescence dating of the stratigraphic section 'Slippery Dip' established a continuous depositional record from ~33 to ~17 ka cal. BP, followed by incision and erosion that exhumed the underlying bedrock topography (Williams et al., 2001). This interval embraces the intensification and peak glacial conditions of the last glacial cycle and extends into the Deglacial, associated with the most significant and rapid climate changes in the past 120 ka (Petit et al., 1999).

Depositional models and palaeo-environmental implications

The depositional nature of the late Pleistocene Brachina valley-fill formation, unconformably overlying Neoproterozoic shales and effectively filling in a deeply dissected palaeo-relief, has been repeatedly reinterpreted over the past years. These interpretations range from Pleistocene lake deposits (Callen & Reid, 1994; Cock et al., 1999), wetland deposits (Williams et al., 2001), to "floodplain deposits in perennially wet grassy meadows" (Williams & Nitschke, 2005; 25). The latest study emphasises the importance of aeolian contributions as the source of the fine-grained sediments. However, the mode of their deposition, the causes behind the tabular sub-horizontal bedding planes and laminations, and the reason for their postglacial degradation remain to be unequivocally identified. This formation and similar terrace deposits along drainage systems throughout the Flinders Ranges record important geomorphological events at an exceptionally high temporal resolution and continuity for terrestrial records embracing the LGM. Yet they cannot be used for palaeo-environmental interpretations unless the processes involved in their formation and degradation are fully resolved.

Comparable gently sloping terrace remnants of fine-grained valley-fill formations have been reported from other parts in the world such as the Sahara (e.g. Linstädter & Kröpelin, 2004) and the Sinai Peninsula (Issar & Bruins, 1983). However none display such striking geomorphologic and lithostratigraphic similarities as the 'Namib Silts' in the catchments of the Great Escarpment which delimits the Namib Desert along a near-longitudinal line between 32°S and 14°S. The age range between ~30 and ~8 ka cal. BP for these "loessic alluvial deposits" (Eitel et al., 2001; 57) is similar to that of the valley-fills in the Brachina catchment of the Flinders Ranges (Cock et al., 1999; Williams et al., 2001). Ephemeral streams are eroding the deposits under present arid climatic conditions.

Terrace remnants of up to 25 m thickness are preserved in protected localities such as the mouths of tributary valleys (Ward, 1987). Over the past 30 years, studies on the Namib Silts resulted in various competitive depositional models that can be divided into three groups.

Lake deposits:

Initial observers proposed a lacustrine origin caused by dune damming (Goudie, 1972; Scholz, 1972; Rust & Wieneke, 1974; 1980), similar to the first interpretation of the late Pleistocene Brachina formation (Callen & Reid, 1994; Cock et al., 1999). Since, gently sloping gradients of the tabular fine-grained deposits were established for multiple catchments in the Great Escarpment (Hövermann, 1978) and in the Flinders Ranges (Williams et al., 2001), ruling out lacustrine emplacement.

High-energy flood deposits:

Various studies assume that the silt formations were deposited during flash-flood events with rapid sedimentation from heavily laden high-energy floodwaters, partly backflooding tributary side valleys (Ollier, 1977; Heine, 1987; Ward, 1987; Smith et al., 1993; Heine & Heine, 2002; Srivastava et al., 2005). According to this scenario, occurrences of laminated sequences upstream of confluences (e.g. 'Slippery Dip') would represent slackwater deposits (Kochel & Barker, 1982; Zawada, 1997).

Low-energy floodout deposits:

An alternative explanation is offered by attributing the fine-grained formations to low energy accumulations of river endpoints (Marker, 1977; Marker & Müller, 1978; Vogel, 1982; Eitel & Zöller, 1995; Rust, 1999; Eitel et al., 2005). Continuous headward retreat of endoreic streams is suggested to result in successive upstream deposition of their suspension load, and to account for the apparently unchannelled nature of the aggradational surfaces.

Aeolian loess accessions:

An alternative working hypothesis presented here takes into account the recently established accumulation of loess mantles in the Flinders Ranges from the deflated bed of Lake Torrens (Williams & Nitschke, 2005), and in the Great Escarpment from the western Kalahari (Eitel et al., 2001). Accordingly, the silty unchannelled aggradational surfaces could reflect aeolian loess accessions. Loess can absorb gentle precipitation and runoff (Yair, 1987; 1994) and could therefore absorb weak intermittent rainfalls associated with cold fronts embedded in prevailing westerly winds. A moist surface could sustain perennial grass vegetation and successfully entrap more loess, with grasses growing upwards as dust accretion proceeds (Pye, 1995). Net deposition would further be enhanced by diurnal mesoscale wind circulation systems such as sea- and salt lake breezes, anabatic valley winds and nocturnal katabatic drainage flows (Tapper, 1991; Schwerdtfeger, 1996;

Sturman & Tapper, 2006). In this scenario, laminated successions such as 'Slippery Dip' could perhaps be interpreted as areas of seepage that were able to sustain prolonged growth of cryptogamic crusts (Verrecchia et al., 1995).

Each of these morphodynamic sedimentation models stipulates a fundamentally different palaeo-environment. High-energy flood deposits require intense precipitation events, with layered to laminated sedimentary sequences reflecting episodic large-magnitude flood events. Low-energy floodouts or 'river-end deposits' would indicate a shortening of the river course by decreasing runoff and reflect a successive aridification of the upper catchment. Aeolian loess accessions suggest a stable low rainfall regime, drawing attention to the influence of wind-blown material on the catchment hydrology. Hence, in order to infer any palaeoclimatic, palaeohydrologic and palaeo-environmental conclusions from these exceptional terrestrial archives, the processes responsible for their aggradation and subsequent erosion need to be resolved first.

Chronostratigraphic approach

So far, existing sedimentological studies describing lithology, sedimentary structures, particle-size distribution, mineral composition, sediment colour, carbonate and microfossil content have failed to unambiguously establish the depositional environment of the fine-grained formations. This may be due to the allochthonous, uniform aeolian nature of the sediments (Eitel et al., 2001; Williams & Nitschke, 2005), or simply reflect post-depositional bioturbation (Smith et al., 1993). In the absence of clear sedimentological and lithological evidence, an alternative way to determine the morphodynamic modus operandi responsible for the aggradation of the valley-fills is suggested here. By establishing a chronostratigraphic transect along the thalweg of the terrace remnants, new detail concerning their sedimentation will be revealed.

The discussed hypothetical morphodynamic models can be expected to result in unique temporal-spatial deposition patterns. Combining detailed mapping of lithofacies associations with radiocarbon and luminescence dating provides a means to distinguish and to test each model. High-energy flood deposition is characterised by synchronous deposition of thick sedimentary sequences over great expanses along the main channel and into the mouth of tributaries (Zawada, 1997). Given that the depositional mode is event-driven, discrete sequential tabular bedding planes should produce similar ages across their lateral and vertical expanse. Low-energy floodout deposits on the other hand are characterised by a gradual upstream migration of the sedimentation focus. Therefore, ages of aggradational surfaces should decrease along the thalweg in an upstream direction. In contrast, loess deposits blanket the landscape. Their net deposition rate varies according to the local topography, surface properties and the path of dust storm events. However, overall deposition can be expected to be gradual and largely synchronous across the thalweg and across various catchments.

Conclusion

Continuous high-resolution terrestrial records covering the culmination and termination of the last glacial cycle are scarce for the semi-arid mid-latitudes of Australia. In the past years, loess-derived valley-fill formations in the central Flinders Ranges were identified and dated to cover this climatically important interval. These formations are here linked to similar well-studied fine-grained terrace remnants in Namibia. However, their former depositional environment remains controversial and requires to be more firmly established before any palaeoclimatic and palaeohydrologic conclusions can be inferred. Sedimentological studies so far could not resolve their genesis, possibly due to their uniform nature based on the aeolian provenance of the material. By applying a chronostratigraphic approach in reconstructing the former temporal-spatial pattern of deposition along transects of thalwegs across multiple catchments, more conclusive evidence for any of three discussed potential depositional environment can be obtained. Current research by the author has the aim to resolve the ongoing international debate on the nature of these conspicuous late Pleistocene fine-grained valley-fill formations or ‘Silts’, presently eroding under semi-arid to arid climatic conditions.

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A call for Australian loess

(similar version published in *Area* (2007) **39.2**, 224–229)

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Abstract

The term 'loess' for silty terrestrial deposits of aeolian origin is widely avoided in the Australian context. This seems to be linked to a prevailing notion among Australian geoscientists that loess is an inherently periglacial late Pleistocene sediment and hence negligible on the mainland. Addressing this conception, loess is presented here as a product of both cold and hot semi-arid environments and therefore a widespread feature in Australia. The adoption of a non-prescriptive definition of loess will align the variety of local descriptions with overseas terminology. More importantly, it will relate hitherto only vaguely-defined wind-blown dust occurrences to a broader palaeo-environmental concept.

Keywords

Australia, loess, dust, wind-blown, parna

Introduction: the Australian liaison with loess

Australian Earth Science writers generally avoid the use of the term 'loess' to denote aeolian silt deposits. In the reference list of Hesse and McTainsh's (2003) recent review on Australian dust deposits the word 'loess' does not appear in the continental context. Instead a variety of descriptive and local terms are used, including: 'parna' (Butler 1956), 'aerosolic quartz' (Alloway et al. 1992), 'continental dust' (Hesse 1994), 'wind transported dust' (Kiefert 1995), 'aeolian dust' (Hesse and McTainsh 1999), 'windblown dust' (Gatehouse et al. 2001), 'lithogenic fluxes' (Kawahata 2002) and 'allochthonous, aeolian mineral grains' (Stanley and De Deckker 2002). Related terrestrial deposits are referred to as 'aeolian dust mantles' (Butler 1982), 'aeolian accessions' (Chartres et al. 1988), 'aeolian mantles' (Hesse et al. 1998), 'aeolian dust deposits' (Chen 2001) or simply 'dust deposits' (Hesse and McTainsh 2003). It is puzzling why the term 'dust', which is only vaguely defined, indicative of long-term suspension and embracing a variety of non-lithogenic aerosols (Pye 1987), is preferred to 'loess', a well-established geomorphologic concept with an extensive international literature.

Two reasons have been reiterated in conversations with the local geoscientific community: one that loess is inherently linked to glaciation and therefore has had a limited impact on mainland Australia during the Late Pleistocene (Barrows 2001); and, the second that Australian loess is a unique local variation distinct from other global loess occurrences.

Whereas the Australian pioneers of regolith geology such as Hills (1939), Crocker (1946) and Gill (1953) readily identified fine-grained terrestrial sediments as loess, Butler (1956) for the first time discriminated them from the then known global loess occurrences. He deemed the high clay content of the local deposits to be incompatible with the existing definitions of loess and coined the term 'parna' (Butler 1956, 1974). In addition, at a time when deserts were still believed to contract during 'pluvial' glacial intervals, he looked in vain for studies identifying loess deposits in the present-day deserts of Australia and concluded that "hot loess [ie. 'desert loess'] … [is] more hypothetical than real" (1956:147). Butler's approach towards Australian loess and his concept of parna have been most influential for the reason that they were institutionally adopted during the active CSIRO soil surveys of the 1950s and 1960s (Hesse and McTainsh 2003). However, since the 1960s Quaternary research has established that the arid Australian continental interior expanded and attained its greatest extent during glacial maxima (Bowler and Wasson 1984, Williams 2000). Deserts are now recognized as source areas of loess entrainment, even for the classic Chinese 'glacial loess' deposits (Derbyshire 1983). Furthermore, subsand-sized aeolian deposits are embraced in the present understanding of loess, regardless of their clay content, a characteristic regarded as primarily source-dependent and not the effect of dissimilar geomorphic processes (Dare-Edwards 1984). The absolute clay content of Australian dust deposits has yet to be established for a representative number of well-controlled sites, despite remaining the main reason to differentiate ‘parna’ from other international ‘desert loess’ occurrences (Hesse and McTainsh 2003).

It is therefore the intention of this paper to challenge the prevailing belief among many Australian geoscientists that loess is primarily a periglacial phenomenon. The argument put forward here is that loess-generating environments are essentially semi-arid, a climatic condition characterising vast tracts of the Australian continent during the late Pleistocene. To begin with, a definition of loess to include that of the continental context is suggested.

Loess – a non-prescriptive definition

Following the application of the German word ‘Löß’ by Karl Caesar von Leonhard (1824) to describe silty deposits along the Upper Rhine Valley and the English adoption of the term ‘loess’ by Lyell (1833), many authors have proposed their own definitions of the material. These have depended on the various processes deemed to be essential for its generation and were limited by the scope of their field experience. Of those, who have made wide-ranging international observations, Pye (1995) provided a practical generic definition which facilitates comparative studies from various climatic regimes and landscapes: "[Loess is] … a terrestrial clastic sediment, composed predominantly of silt-size particles, which is formed essentially by the accumulation of wind-blown dust" (Pye 1995:654). Pye further stresses that loess deposits are often characterised by syn- or post-depositional reworking caused by weathering, bioturbation and pedogenic processes. These result in variable calcium carbonate and clay contents, but contrary to Butler’s conception (Butler 1956, 1974) he suggests that neither their presence nor absence should be used as diagnostic criteria.

Obviously, a non-prescriptive definition by itself lacks conviction if processes that have led to the accumulation of the ‘classic’ loess sequences in Central Asia and China are assumed to be glacial and periglacial and therefore need to be ruled out in the Australian context. Any satisfactory geomorphologic term must indeed relate to specific modes of genesis of the material and landforms. Loess therefore has to refer to more than just aeolian silt (Pécsi 1990). In order to demonstrate that loess is primarily the product of semi-arid environments, the essential conditions for loess formation, i.e. silt generation and surficial concentration of erodible deposits, are discussed. Further, the fundamental process-orientated similarities between classical ‘glacial loess’ and Australian ‘desert loess’ are examined in more detail.

Discussion: linking loess-generating processes in periglacial and hot desert environments

Two key issues underlie loess-generating processes. The first is the question of modi capable of breaking and splitting up the generally sand-sized quartz crystals of igneous and metamorphic rocks. The second is that of mechanisms operating in their release and concentration in non-cohesive deposits in the landscape which can subsequently be deflated by wind.

A classic and still well disseminated idea of silt production is that of 'glacial grinding' (Hardcastle 1889, Smalley 1966). Since the introduction of this concept, many other more important large-scale mechanisms generating silt-sized material have been discovered and subsequent observations and laboratory studies cast doubt on its capability to produce substantial amounts of silt (Whalley 1979, Haldorsen 1981, Nahon and Trompette 1982, Derbyshire 1983, Sharp and Gomez 1986, Wright 1995, Wright et al. 1998). Therefore, regardless of the continuing popularity of this concept which is still being propagated by a number of authors (Smalley et al. 2005), glacial grinding will be neglected in the ensuing discussion of silt-generating processes. Only those that could be empirically verified in field observations supported by laboratory simulations to produce substantial amounts of silts will be considered further.

Over the past decades, a variety of weathering processes and geomorphological transport processes were demonstrated to be capable of silt generation. These will now be linked to the most favourable climatic regimes in which they operate, and to subsequent silt-sorting mechanisms.

Weathering processes

A number of observations and empirical studies have focused on physical weathering processes as silt-generating mechanisms.

Frost shattering was first noticed on Mount Kenya by Zeuner (1949) to generate silt-sized particles. His observations were supported by later laboratory experiments (Brockie1973, Moss et al. 1981, Lautridou and Ozouf 1982, Wright et al. 1998). The potential of frost shattering processes to generate silt depends on properties of the source material and environmental controls such as the occurrence of salt, affecting the moisture absorption and ice crystallisation processes (Pye 1987).

Haloclasty alone causes weathering and the disintegration of rocks and sediments. The ability of salt weathering to generate significant quantities of silt-sized particles has been demonstrated by Goudie (1977) on archaeological brick building structures of the Harappa Culture, on glacial till in the

Karakoram Mountain Range of Pakistan (Goudie 1984), in the Sahara (Goudie and Watson 1984) and in laboratory experiments (Goudie and Viles 1995).

Both physical weathering processes are most active and common within semi-arid climates, irrespective of the prevalent temperature regime. In contrast, chemical weathering and pedogenic processes are dependent on more temperate and humid conditions. Nahon and Trompette (1982) demonstrated that chemical weathering acts as an important loess-producing mechanism throughout all geologic epochs (see also Berg 1927). They argue that the key role of glaciations in the process of loess generation is that of erosion and entrainment of the pre-glacially weathered debris and the subsequent concentration of silts by glaciofluvial melt-waters (see also Warnke 1971, Whalley 1979, Pye 1995, Wright 2001).

However, the sequence of chemical weathering, erosion, transport, sorting, concentration and final surficial re-deposition of readily erodible fine-grained material is not restricted to the periglacial parts of the world. On the contrary, it is paralleled in many hot semi-arid to arid environments. During the Mesozoic, Australia’s landscape was highly weathered (Hill 1999, Twidale 2000). Fines, resulting from processes such as weathering remain trapped in cohesive weathering mantles until the inherited regolith is eroded and the clay and silt fractions are sorted and concentrated into surficial deposits by the action of running water. In the Quaternary endoreic environment of central Australia, the suspended load eventually settled in inland drainage depocentres such as the tectonic basins presently occupied by playas, salinas or lakes. To be entrained by wind, the surface of these deposits has to desiccate and the fine-grained material dispersed and exposed. Silt and clay deflation therefore requires geomorphologically ‘active’ surfaces, which are typical of semi-arid climates promoting a course of inundation and desiccation events. During glacial intervals, basins like those of Lake Eyre, Lake Torrens and the Murray Basin repeatedly dried out (Hesse et al. 2004) exposing vast repositories of loess-sized sediments to deflation.

Transport processes

Other studies have focused on geomorphological transport processes capable of rapid particle size reduction and the production of substantial quantities of silt.

Moss (1972) conducted field experiments in the Murrumbidgee catchment area and noticed a rapid downstream disintegration of quartz due to crushing and abrasion in the bedload. Violent motion between moving boulders, pebbles and bedrock projections causes the comminution of coarse particles until silt-sized grains escape further disintegration by suspension. His observations were confirmed by subsequent laboratory experiments (Moss et al. 1973, 1981). More recent independent tumbling experiments by Wright and co-authors (1993, 1998, 2001), simulating high-energy fluvial systems of mixed-sized sediments, support the capability of fluvial abrasion to generate significant amounts of silt.

Aeolian systems are also capable of producing considerable quantities of silt. Attrition between saltating sand particles was first described by Knight (1924). Subsequent laboratory studies (Whalley et al. 1982, Smith et al. 1991, Wright 2001, Bullard et al. 2004) identified aeolian abrasion as the cause of the typical rounded morphology of dune sand grains. During the process of edge rounding, substantial quantities of silt-sized fines are chipped off. Apart from chipping and spalling of grains, aeolian abrasion can also remove and release clay coatings, a process likely to be particular important in the reddened dune fields of Australia (Bullard and White 2005).

Although past emphasis on geomorphic transport processes capable of silt-generation has often been placed on glacial grinding, comparative quantitative laboratory studies established that the two most effective ones are fluvial and aeolian abrasion (Wright et al. 1998). Turbulent high-energy fluvial environments capable of carrying a bedload of a wide range of particle sizes do exist in periglacial environments during periodic, poorly-sorted glaciofluvial outwash events. Episodic flash floods channelled into ephemeral river beds are similarly significant. Both systems display intermittent discharge which creates active surfaces from which freshly generated silt-sized particles can be readily mobilised and entrained by wind. Aeolian abrasion is mainly active in semi-arid and arid environments with bare, sparsely vegetated surfaces and drifting sand. Therefore, abrasion will generate silt both in dune fields forming on glacial outwash plains and in active sand seas characteristic of parts of the Sahara and the interior of Australia during the glacial intervals.

Conclusion: loess – not just another term but a concept

The variety of mechanisms and processes operating in generating, sorting and concentrating silt-sized grains for subsequent entrainment by wind and aeolian deposition as loess operate both in periglacial and hot semi-arid environments. Rates of silt particle formation and sorting and concentration processes are considerably lower under hyper-arid and glacial conditions than semi-arid and periglacial environments. Arid and glacial environments are climatically more stable and characterised by low weathering rates, relatively stable atmospheric conditions and a high proportion of land surfaces protected by crusting, gravel-armouring and glacier ice, respectively (Pye 1995). The fundamental process-based similarities between ‘glacial loess’ and ‘desert loess’ suggest that a comprehensive loess definition is readily applicable to Australian terrestrial occurrences of ‘aeolian dust mantles’ or any of the variety of other terms listed at the beginning of this paper.

Ultimately, the issue is not just about a difference in terms. The power of words, especially in the scientific context, is that they embody and relate concepts. Loess sequences, even if they appear considerably reworked and pedogenically altered in their present state, are indicative of specific former conditions regarding dust source proximity, airflow regimes, climatic gradients and vegetation cover. Loess entrainment requires a geomorphologically active, regularly ‘disturbed’ landscape over a period of time. High net deposition rates in turn require particular surface properties in terms of moisture, vegetation and topography. Furthermore, loess exerts various significant impacts on the hydrology, geochemistry and flora in regions where it is deposited (Yair 1994). These aspects are all relevant for Quaternary landscape reconstructions and palaeo-environmental interpretations. Calling appropriate aeolian dust deposits ‘loess’ can change not only the way we look at them, but also how we look for them as comparable occurrences in the international literature or during identification in the field.

Acknowledgments

I am grateful to Dr. Andreas Schmidt-Mumm who supported my scholarship application at a crucial time and helped me to settle down in Australia. I also thank the Graduate Centre of the University of Adelaide for offering the Integrated Bridging Program (Research) and in particular Margaret Cargill for her excellent introduction to the Australian scientific discourse. My supervisors Martin A. J. Williams, Steven M. Hill and Victor Gostin and the reviewers are thanked for inspiration and critical feedback.

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Response to Smalley's discussion of 'A call for Australian loess'

(similar version published in *Area* (2008) **40.1**, 135–136)

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Abstract

A concise response to Smalley's discussion of my 'Call for Australian loess' paper (Haberlah 2007, Area 39 224–9) elaborating on past and possible future Australian contributions to the international loess debate. The suggested idea of dividing loess into three separate categories 'glacial loess', 'desert loess' and 'mountain loess' is questioned by emphasising common links.

Key words:

Australia, loess, dust, parna, 'desert loess', 'mountain loess'

Right from the opening lines of the discussion section in my paper (Haberlah 2007) it becomes clear that one could not possibly wish for a more appropriate scholarly reply and discussion of my dismissive stance of an imperative glacial link to loess than from Ian Smalley (Smalley 2008). When Smalley was pioneering the idea of glacial grinding as a (the) key loess-generating process more than four decades ago (Smalley 1966), he firmly associated the formation and nature of loess to glaciation. His ideas had a profound effect on the perception of loess in areas in the world such as continental Australia, where glaciation over the Last Glacial Maximum was negligible.

When now the same author who is still perceived by many as the outspoken proponent of ‘glacial loess’ revisits his conceptions of the nature and formation of loess in light of an increasing number of ‘discoveries’ of desert loess clearly detached from glaciation, this should not be taken lightly. It is particularly instructive to follow his historical insight on how the whole debate developed until present, and the role Australian geoscientists played in it. Smalley demonstrates the important impact Butler’s early denial of a significant desert-loess relationship in Australia (Butler 1956) had on the conceptionalisation of the nature of loess and its assignment to the glacial domain a decade later. In the 1970s, it was once again an Australian CSIRO scientist who strongly advanced the loess debate by demonstrating defects in quartz particles facilitating their breakage into silt-sized detritus. The observations by Moss (Moss and Green 1975) set the ground for the recognition of fluvial generation of silt as opposed to glacial grinding.

Smalley expands my argument that silt-generating environments are quintessentially semi-arid environments irrespective of prevailing temperatures by adding a spatial dimension to the debate. He highlights the fact that under both peri-glacial and semi-arid climatic conditions, high relief is crucial in providing the geo-energy required for the key silt generating mode of fluvial comminution. This could prove to be an important point made in the future of loess discussion and necessitates more detailed spatial studies of loess occurrences in relation to the drainage of major mountain ranges. I readily support the notion that high relative relief is as essential for the generation of sufficient silt-sized particles as is the intermittent nature of transportation, sorting and deflation from both glacial outwash and from wadis and episodically inundated floodplains of larger river systems. However, I question that they necessitate a separate category as proposed with ‘mountain loess’. Perhaps they are but the second neglected link between ‘glacial’ and ‘desert’ loess? Could loess generation require the twofold process of erosion and fluvial comminution most effectively operating in high mountain ranges to produce and sort substantial quantities of silt, and then the winnowing of these from outwashes, floodplains and terminal depocentres resulting in their aeolian redistributing most effective in semi-arid environments? Further studies and time will tell.

For the immediate future, Smalley in his discussion presents us with a roadmap of what it takes to put Australia on the global loess map. I can only second his call for detailed granulometric and mineralogical studies and approaching the big question on where, how and when loess was generated in the Australian landscape. Since his call for such practical steps will likely be followed by a number of researchers, I would like to conclude my response with a note of caution based on experience gained from ongoing research on loess-derived alluvium in and around the Flinders Ranges, South Australia (i.e. Haberlah et al. 2007). Since Australian loess seems to consist of coarse and very coarse silt-sized clay aggregates, the application of a well-conceived, appropriate granulometric protocol is crucial. It should best be tested in controlled settings where, for example, subtle upward-fining trends can be anticipated (i.e. couplets of loess-derived slackwater deposits). Basic field texturing is problematic due to the tendency of loess aggregates to gradually disperse on application of mechanical force. This characteristic attribute was first described for the loessic soils of the Riverina of SE Australia and termed 'subplasticity' by Butler (1955). It has since been the topic of much research by Australian CSIRO geoscientists (i.e. McIntyre 1976). Dispersion protocols developed for laboratory studies (i.e. Walker and Hutka 1976; Chittleborough 1982) should now be called upon to develop reliable protocols that ensure that the original transport-stable aggregates and not artefacts of physical and chemical pre-treatment are measured. As importantly, an appropriate and sufficiently accurate method of particle-size analysis should be employed avoiding 'analytical breaks' between multiple sizing techniques (McTainsh and Duhaylungsod 1989). Since the Coulter Multisizer covers the complete size range of loess and allows sizing of minimally dispersed transport-stable aggregates as well as fully dispersed particulates at submicron resolution (McTainsh et al. 1997; Leys et al. 2005), it is suggested as most suitable for a comparative granulometric study of Australian loess. A coordinated effort in this respect and the application of the same protocols in other desert loess domains of the world could perhaps be the next significant contribution out of Australia to the international loess debate?

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