Are sand dunes of the lower Lachlan floodplain a graveyard for parna?

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Abstract

Æolian dust deposits are widespread in southeastern Australia, and are thought to have had a significant influence on soil properties and landscape evolution. However, the characteristics of pure Æolian materials and the true extent of their distribution in this region remain unclear. This is due largely to the comparatively low rate of deposition, which has allowed for incorporation of dust into the receiving solum, thus obscuring its origin and particular properties. The dominant model for Æolian dust deposits in southeastern Australia is ‘parna,’ an aggregated material comprised of clay, carbonate and silt-sized quartz, and thought to have been deposited across the Riverine Plain. On the lower Lachlan floodplain at Hillston, the western border of the proposed zone of parna deposition, source-bordering sand dunes occur as a repeated feature. A number of these sand dunes have been found to contain a distinct component of fine material that is possibly Æolian in origin. To ascertain the likely provenance of this fine material, and to assess whether it conforms to the notional model for parna, three source-bordering sand dunes were studied. Soil was sampled from each of three distinct phases identified within the three dunes: (1) an upper-slope phase of coarse brown sand, (2) a mid-slope layer of red, possibly clay-enriched, sand and discrete clayey lamellae and (3) a lower slope phase of coarse sand dominated by an accumulation of carbonate ‘glaebule’ structures. Granulometric properties of the material in each phase were assessed by particle-size analysis, the clay mineral suite was determined by x-ray diffraction, micromorphological features examined in thin section, and grain morphology assessed using scanning electron microscopy. The clay-enriched phase of each dune revealed a distinctly bimodal particle-size distribution, with one conspicuous particle population in the 30–60 µm range, and another in the fine-silt/clay range (<10 µm). Such bimodality is considered characteristic of southeastern Australian Æolian dust deposits. The abundance of illite and kaolinite in the clay mineral suite of the upper two dune phases, coupled with a conspicuous absence of smectite, further suggests an allochthonous Æolian origin, as the surrounding floodplain is smectite-rich, and inherently low in illite. Micromorphological features within the clay-enriched phase, including abundant anisotropic argillans (clay-coatings), and a laminated arrangement of 30–60 µm particles indicate that this clay is a depositional feature, illuviated from surface horizons and re-deposited at depth. A similar illuvial origin is suggested by the fine crystalline nature of the calcium carbonate accumulation, ubiquitously coating the matrix mineral grains of the lower dune phase. No discrete ‘parna’ aggregates were identified, however all the necessary components (30–60 µm quartz grains, clay, and carbonate) were identified as separate entities, spatially separated within each dune. The consistency of these features between the three dunes further supports the hypothesis of an analogous Æolian dust accession. This dust would have been spread uniformly across the landscape, potentially playing an important role in pedogenesis of the agriculturally important regional soils.

Keywords: Æolian dust; Parna; Source-bordering dunes; Micromorphology; Clay mineralogy; Granulometry
1. Introduction

The deposition of aeolian dust is known to have been an active factor in the process of soil formation and landscape evolution on every continent. Aeolian dust has been broadly defined as a suspension of windblown particles of diameter less than 100 \( \mu \text{m} \), or a deposit of such particles (Pye, 1987). Extensive, thick mantles of loess (aeolian dust deposit), often over 100 m deep, cover up to 10\% of the world’s land surface (Pye and Sherwin, 1999), being particularly prevalent in central and eastern China, the Midwestern Plains of the United States, and Central Europe. These fertile loess mantles are of major agricultural importance (Jackson et al., 1972). Whilst Australia lacks thick loess mantles, the extensive dune fields of Australia’s arid interior attest to the importance of aeolian processes in the evolution of the Australian landscape (Wasson et al., 1988). Significant quantities of dust must also have been entrained during storms associated with the formation of these dune fields, and subsequently carried far beyond the desert margin. Virtually all Australian soils have a component of dust accession, though its significance at a given location can be difficult to determine (McKenzie et al., 2004) and as such the true extent and nature of aeolian dust deposits in Australia are not entirely identified and characterised (Hesse and McTainsh, 2003).

Bowler (1976) originally identified two general dust paths occurring in Australia: (1) the northwest dust path, which extends from the arid interior west to the Indian Ocean, and (2) the southeastern dust path, which sweeps dust from the Lake Eyre Basin and western Murray-Darling Basin across southern NSW and Victoria out over the Tasman Sea. Most research attention has focused on the southeast dust path and inland areas of southern NSW and Victoria, where the dominant model of Australian aeolian dust deposits, the clay-rich, calcareous ‘parna,’ was pioneered by Butler in 1956. Butler (1956) proposed that parna was distinct from loess in both its composition and origin, and that it occurs as a relatively uniform, thin sheet covering the whole landscape irrespective of relief. Parna consists of aggregates formed during the erosion of soils (clay pans and playa lakes) in the arid zone, and as a result is composed chiefly of secondary minerals bound to a companion sand grain, in contrast to the often glacially-derived primary mineral fragments that form characteristic loess. Accordingly, soils formed from parna will differ further from those formed from glacially-derived loess in that they have effectively already passed through one cycle of weathering, being composed almost entirely of secondary minerals.

Aeolian dust has been identified and described in a number of soils throughout southern Australia, although not all of these aeolian dust deposits conform to the benchmark model of parna. Considerable variation in morphological and mineralogical properties of dust has been reported, and this variation is largely related to the nature of, and distance to, source areas. Fine-grained, quartz-rich aeolian dust deposits occurring in soils of the Namoi Valley in northern New South Wales
described by Cattle et al. (2002) differ considerably from the clay-rich calcareous parna soils of southern NSW as described by Butler (1956) and Beattie (1970). Since the inception of the parna model of æolian dust, there has been some debate as to its validity. A number of authors suggest that the model of parna is poorly substantiated (Dare-Edwards, 1984; Hesse and McTainsh, 2003), and that the term parna should be abandoned altogether. Hesse and McTainsh (2003) suggest that æolian dust deposits of Australia bear a strong similarity to conventional definitions of desert-derived loess, and that treating parna as material distinct from loess has restricted the role and progress of Australian scientists in æolian dust research. Parna may be considered as a subset of loess, or as ‘desert loess.’

The deposition of æolian dust and its subsequent in situ modification has important implications for landscape evolution and pedogenesis. In turn, the deposition of dust will also have important human and economic implications, including the addition of nutrients and salts to soils and the accumulation of agriculturally important loess soils. Accessions of dust may have a variety of effects on soil development, ranging from minor or intermediate roles to total dominance of genesis (Yaalon and Ganor, 1973; Simonson, 1995). Accordingly, soils that have received accessions of dust may be divided into three broad groups: (1) those comprised entirely of æolian material, (2) those in which dust accessions are important but not dominant, and (3) those in which dust accessions have played only a minor role in genesis, but have modified one or more soil properties. For the purpose of this paper, these three categories will be referred to as (1) Loess, (2) Loessic, and (3) Dust-affected. As asserted by Smalley and Smalley (1983), even small accessions of dust can have significant effects on soil development, such that “in practical and economic terms [dust] as a constituent may be as important as loess as a deposit.”

Loess deposits are frequently comprised of silt-sized primary mineral fragments produced by glacial grinding, and are most prevalent in Northern Hemisphere countries. The thickest and most extensive loess deposits are found on the fertile Loess Plateau of central China, where depths of up to 300 m have been recorded (Derbyshire, 1983). The thickness of loess deposits shows significant variation, and “parna-loess” deposits of southern Australia correspond to the lower limit of thickness. Beattie (1970) described parna mantles of several metres thick on the Riverine Plain of southern New South Wales, and æolian dust deposits on the NSW Central Tablelands are approximately one metre thick (Gatehouse et al., 2001).

Loessic soils are polygenetic, being derived from both local material and æolian dust accessions. Loessic deposits are more prevalent in Australia than loess deposits, and occur on much of the Murray-Murrumbidgee Riverine Plain as a thin, finely textured mantle of ‘parna.’ This category incorporates soils where dust has affected individual horizons, and soils where dust
accessions have proceeded simultaneously with development and affected it significantly. Given the capacity for weathering processes to obscure the aeolian origin of soil material, loessic deposits are likely to be more widespread than is generally accepted.

The term “dust-affected” describes soils that have been only slightly modified by dust accretion. The main features of dust-affected soils include modifications to texture, mineralogy (including salt-content) and fertility that can be attributed to the presence of aeolian dust, as well as morphological features such as clay bands and pedogenic carbonate concretions. One of the most common features of dust-affected soils is a silty surface horizon (Simonson, 1995), a feature observed in dust-affected basaltic soils of southern Victoria (Jackson et al., 1972), and basalt-derived Vertosols of the northern NSW Namoi Valley (Cattle et al., 2002). Dust deposition also frequently provides a significant nutrient input to soils, even in areas where the rate of deposition has been insufficient to produce recognisable deposits (Hesse et al., 2003).

Given that the accession of dust to soils will impart properties not necessarily related to those developed by the weathering of underlying parent material, characterisation of the dust, its origin, nature and rate of deposition is essential to understanding soil development in receiving areas (Walker and Costin, 1971). Despite the fact that the widespread existence of parna deposits in south-eastern Australia has been conjecturally accepted for almost fifty years (Butler, 1956), dated or quantified records are extremely rare (Hesse and McTainsh, 2003). No detailed descriptions of parna sections have been published, and furthermore, no parna mantles have been directly dated (Hesse and McTainsh, 2003). Moreover, the characteristics of pure parna have not been determined (Chen et al., 2002). To adequately assess the role of aeolian dust, or ‘parna’ in pedogenesis of soils of south-eastern Australia, there is a need for more rigorous characterisation and understanding of the form and weathering pathways of pure parna.

On the western border of the proposed zone of parna deposition (Butler, 1956), an unusual accumulation of fine material has been observed in a number of sand dunes which border paleochannel tributaries of the lower Lachlan River. In a study of dunes showing similar features at Wagga Wagga in southern New South Wales, Chen et al. (2002) suggested that the dunes had functioned as dust traps, and hence possibly contain pure parna. If the fine material in sand dunes of the lower Lachlan is indeed parna, then the dunes provide a unique opportunity to characterise relatively pure aeolian dust deposits.

Thus the aims of this project are:

• To characterise the morphological and mineralogical properties of fine material trapped in three source-bordering sand dunes on the Lachlan floodplain at Hillston
• To consequently determine whether this fine material is of a local or allochthonous origin
• To ascertain whether the dunes contain intact parna or the weathering products of parna, according to Butler’s (1956) traditional model for parna.

2. Materials and methods

2.1 Regional setting and study sites

Three sampling sites in the lower Lachlan Valley of southern New South Wales were selected for the purpose of this study. The sampling sites were located on two irrigated cotton-producing properties, “Merrowie” and “Brooklyn,” which are 10 km north and 20 km west of the township of Hillston, respectively. For the purpose of this report, the sampling sites located on the property “Merrowie” will be referred to as “M1” (6306388 mN, 0360009 mE) and “M2” (6307546 mN, 036 0931 mE), and the “Brooklyn” site will be referred to as “B1” (6295644 mN, 0339686 mE).

The climate of the study region is best described as semi-arid and temperate, with an evenly distributed average annual rainfall of 366 mm, and average potential evaporation of 1825 mm. At Hillston average summer daily temperatures range from 18.1–33.2ºC and average winter daily temperatures range from 3.8–14.8ºC (Bureau of Meteorology, 2005).

The sampling region is situated within the partly active alluvial floodplain of the lower Lachlan River catchment (Fig. 1a) and the terrain is flat to slightly undulating. The alluvial agricultural soils of the lower Lachlan Valley were described by Onus et al. (2003) as Red, Brown and Grey Vertosols, according to the Australian Soil Classification (ASC; Isbell, 1996). Within the alluvial plain at Hillston a number of distinct physiographic sub-units occur: (1) ephemeral channels, (2) confined stream terraces, (3) riverine floodplains and (4) source-bordering dunes (Cattle et al., 2003). Source-bordering dunes (sand-mounds), often up to 10m high, are a repeated feature within the alluvial plain of the Lachlan River, and were formed by the aeolian reworking of paleochannel bed-load sand (Cattle et al., 2003). A common feature of these sand dunes is a deflated structure, exposing the presence of a 1–2 m thick reddish (apparently clay-enriched) layer in the upper part and an accumulation of carbonate on the lower slope. Three dunes exhibiting these distinct features were chosen as the sampling sites for the purpose of this study (M1, M2 and B1) (Fig. 1b).

2.2 Sampling

At each of the three sampling sites the macromorphological features of the dunes were described. Macromorphological features included the appearance of three distinct phases (summarised in Fig. 2) that appeared to be consistent for all dunes. Photographs of each phase are shown in Fig. 3, 4 and 5.
Fig. 1. Location of (a) the Lachlan River Catchment (Australian Government Department of Agriculture, Fisheries and Forestry, 2004) and (b) sampling sites, as indicated by the arrow points.
The uppermost phase (thickness 1–3 m, and denoted as ‘s1’) consisted of coarse, mostly loose sand showing minimal structural development, except at M1, where a poorly developed laminated structure was evident (Fig. 3b). The second phase (thickness 1–2 m, and denoted as ‘cs2’) was comprised of red (2.5 YR 5/6) and apparently clay-enriched sand.

Within the cs2 phase of B1, thin semi-continuous lamellae of dark red clay-enriched sand were also present (Fig. 4a). The lower phase (thickness 3–6 m, and denoted as cas3) comprised coarse, massive, calcareous sand with a surface and sub-surface accumulation of carbonate structures classed as ‘glaebules’ (Fig. 4a and b), which showed substantial variation in size (1–30 cm length). The abbreviated nomenclature assigned to each phase in Fig. 2 (i.e. s1, cs2 and cas3) will be used throughout this paper.

Fig. 2. Typical sequence in a source-bordering sand-dune within the lower Lachlan Floodplain.

At each study site bulk soil was sampled from a number of locations within each of the three phases described in Fig. 2. A number of shallow pits (depth <1 m) were excavated at each dune to allow soil profile description. Soil was also sampled from within and below thin clay lamellae observed at a depth of 60 cm within the cs2 phase of B1 (Fig. 4a).

Undisturbed soil samples to be used for thin section preparation were collected in nine Kubiëna tins. Three of these Kubiëna tin samples were taken at site B1; at 20 cm depth within cs2, from the clay lamellae at depth within cs2 (Fig. 4a), and from 30 cm depth within the cas3 phase. At the M1 dune, two Kubiëna tin samples were taken from the cs2 phase and one at 30 cm depth within the cas3 phase. One Kubiëna tin sample was extracted from the cs2 phase of the M2 dune (Fig. 4b), and two from the cas3 phase of the M2 dune (Fig. 5b); of these, one was extracted from 5 cm depth, and the other from 40 cm depth.
Fig. 3. Photographs of the s1 phase of two dunes: (a) B1 dune and (b) M1 dune showing s1 coarse sand exposed in a quarry.

Fig. 4. Photographs of the cs2 phase of two dunes: (a) B1 dune, showing clay lamellae at 60 cm depth within the horizon of clay accumulation, and (b) M2 dune, showing more diffuse clay accumulation and associated platy structure.
2.3 Granulometric analyses

The particle size distribution of soil material from each phase in each of the three dunes was determined using the pipette method (Gee and Bauder, 1986) for material < 20 µm, and dry sieving for material > 20 µm. Particle size was classified according to the International system for soil texture classification, where clay is defined as particles less than 2 µm in diameter, silt as particles of 2–20 µm, fine sand as 20–200 µm and coarse sand as 200–2000 µm (Minasny and McBratney, 2001).

In addition, the non-clay fraction (2–400 µm) of four samples was analysed using a Coulter Multisizer 3, a precision electronic sizing instrument which allows for the accurate identification of sediment populations within the particle size distributions. The Coulter Multisizer is based on the electrical sensing zone (ESZ), or Coulter Principle, and produces very high resolution analysis of up to 256 size classes per sample (McTainsh et al., 1997). The four samples used for this high-resolution analysis were taken from the diffuse cs2 phase of each of the three dunes (B1, M1 and M2) and from the clay lamellae observed at depth within the cs2 phase of B1. When referring to the results of this high resolution particle size analysis, and in other references to particle size elsewhere in this paper, the USDA/FAO particle-size classification, whereby silt is defined as those particles of 2–50 µm diameter (Minasny and McBratney, 2001), will be used unless otherwise stated.
2.4 Mineralogical analyses

2.4.1 Clay mineral suite

Clay suspensions obtained during the granulometric analysis were retained and used to produce oriented aggregates for X-ray diffraction analysis. For each soil sample, the clay suspension was applied to two separate ceramic tiles under suction. A 2 mol L⁻¹ solution of KCl was then applied to one tile of each pair in two washing treatments, and a 2 mol L⁻¹ solution of MgCl₂ applied to the other tile in the same way. All tiles were then washed four times with distilled water to remove excess salts (Brindley and Brown, 1980).

The clay mineral suite of each sample was then determined by X-ray diffraction of the two tiles, using a Siemens® Diffraktometer 5000. The samples washed with KCl were analysed air-dried and following heat treatments of 100, 300 and 550°C. Those treated with MgCl₂ were analysed air-dried and following solvation with glycerol. All analyses were conducted using Cu-Kα radiation. KCl tile readings spanned the range 2-15° 2θ, and MgCl₂ tile readings spanned the range 2-30° 2θ, with a step width of 0.02°. Clay mineral suite was determined for each phase of each of the three dunes.

2.5 Micromorphological analysis

Thin sections of undisturbed soil from each dune were studied. These thin sections were prepared using soil collected in Kubiëna tins, as described in section 2.2. The soil was dried in the Kubiëna tins (16 × 8 × 5 cm) at 40°C and then impregnated with a polyester resin for six weeks. Vertically-oriented thin sections 30 μm thick were produced from the impregnated soil and mounted on glass slides. Optical properties of the thin sections were viewed under both plane polarised light and cross polarised light using a petrographic microscope, and photographed. The micromorphological descriptions follow Bullock et al. (1985).

2.6 Grain morphology and elemental composition

Soil samples were viewed by scanning electron microscopy (SEM). Selected samples from the cs2 phase of M2 and B1, the s1 phase of M2 and the clay lamellae of B1 were mounted on aluminium SEM stubs using double-sided tape, and coated with gold using a “sputter coater” in order to improve conductivity. These samples were then observed and photographed using a Philips SEM 505. X-ray analysis was used to determine elemental composition of selected grains within samples.
3. Results and Discussion

3.1 Granulometric properties

Particle size characteristics of the three phases within the three sampling dunes are summarised in Fig. 6. The values displayed in Fig. 6 are averages of samples taken from a number of slopes within each dune. All samples from the s1, cs2 and cas3 phases of each dune show a similar pattern in particle size distribution. Sand comprises >75% of total particles in all phases of all dunes, and within this size fraction, coarse sand predominates over fine. The proportion of coarse and fine sand shows some variation, however. In general, there is an accumulation of fine sand in the cs2 phase. The M2 dune appeared to have a much larger proportion of fine sand (over 34% in all phases) than the other two dunes. There was also a significant increase in fine sand content from the clay lamellae in B1 cs2, to a zone directly below the clay lamellae (an increase of over 15%, or double).

![Graphs showing particle size distributions for M1, M2, and B1 dunes.](image)

Fig. 6. Average particle size distributions (coarse sand defined as particles of diameter 200–2000 µm, fine sand as 20–200 µm, silt as 2–20 µm and clay as < 2 µm diameter) for the three sampling sites.
In all dunes the clay and silt content (all particles < 20 µm diameter) showed a marked trend, increasing from the s1 to the cs2 phase, and decreasing again in the cs3 phase (Fig. 6). The clay and silt maximum values ranged from 5–17% and 1–3% respectively.

Most stabilised aeolian sand dunes are known to contain a component of ‘fines,’ or silt and clay-sized particles. The presence of these fines can be related to a suite of post-depositional weathering processes, which includes the infiltration of aeolian dust (Tchakerian, 1999). This process is largely accomplished by grain translocation (occurring with the movement of rainwater, dew and groundwater) and mineral disaggregation over time (Tchakerian, 1999). The infiltration of aeolian dust is thus a plausible explanation for the similar accumulation of fine material (silt and clay) in a specific zone of the three spatially separate sampling dunes.

The high resolution particle size distributions of samples from the cs2 phase of each dune are shown in Figs. 7, 8 and 9, and the particle size distribution of the clay lamellae within cs2 of the B1 dune is shown in Fig. 10. For all samples the population of grains in the 200–400 µm range represents the coarse sand matrix of the existing sand dune. Whilst there appear to be differences between the histograms produced at each site, a number of features consistent with accepted properties of aeolian materials are apparent.

Whist ‘typical’ loess shows a poorly-sorted, unimodal particle size distribution (Pye and Sherwin, 1999) typical aeolian clay sheet deposits of the Riverine Plain are bimodal in texture, with a mode in the clay size fraction and also in the coarse silt or fine sand fractions (Dare-Edwards, 1984). Accordingly, bimodality of texture was found to be apparent to varying extents in all of the samples analysed in this study (Figs. 7,8,9,10).

Blackburn (1981) asserted that the size of the companion sand, or non-clay fraction, is widely variable, changing progressively with distance from source. Close to the source region dunefields the non-clay mode of saltated aeolian aggregates has been found to be over 300 µm (Dare-Edwards, 1984), whilst further east the non-clay mode of aeolian material decreases to a size that is consistently between 30 and 60 µm (Butler and Hutton, 1956). Beattie (1970) recorded a pronounced mode in the 30–60 µm range in the non-clay fraction of layered parna deposits in the eastern Riverina; whilst Sleeman (1975), observed a similar peak in the 30–60 µm size range of parna layer skeleton grains at Pyramid Hill in northern Victoria.

The non-clay fraction of each of the study samples showed a distinct mode in the coarse-silt/fine-sand size-range (20–60 µm), which in a number of cases became more pronounced following dispersion (Figs. 7 and 9). This mode was most prominent in the cs2 phase and clay lamellae of the B1 dune and in the cs2 phase of the M2 dune, and least prominent in the cs2 phase of the M1 dune.
Fig. 7. High-resolution particle size histograms for B1 cs2, (a) minimally dispersed and (b) fully dispersed.

Fig. 8. High-resolution particle size histograms for M1 cs2, (a) minimally dispersed and (b) fully dispersed.

Fig. 9. High-resolution particle size histograms for M2 cs2, (a) minimally dispersed and (b) fully dispersed.

Fig. 10. High-resolution particle size histograms for B1 clay lamellae, (a) minimally dispersed and (b) fully dispersed.
Further, the obvious proclivity of each histogram towards a finer particle size distribution following full dispersion suggests that some of the clay-sized particles are actually transported as silt-sized aggregates, or as coatings on larger grains.

The shift in modes following full dispersion of the B1 cs2 phase soil (Fig. 7) suggests that the sample originally consisted of 40 µm quartz grains aggregated with some clay. The clay-silt aggregates likely resisted dispersion initially (Fig. 7a), but more vigorous dispersion resulted in the collapse of these aggregates and a resultant change in particle size distribution (Fig. 7b). The M2 cs2 sample returned a similar, though more pronounced, shift in modes from a largely unimodal distribution with a ‘shoulder’ in the 60–70 µm range, to a clearly bimodal distribution with one mode at 50 µm and another at 2 µm (Fig. 9b). This shift in modes suggests that the original M2 cs2 sample consisted of 50 µm quartz grains aggregated with substantial amounts of fine silt and clay. This subplastic character has been recognised in most para deposits (Dare-Edwards, 1984).

Bimodality and positive skewness in particle size distribution is a consistent feature of ‘clayey-loess’ throughout the world. The M1 cs2 particle size histogram (Fig. 8b) is more or less congruent to that of a dust-enriched topsoil of the northern NSW Namoi Valley (Cattle et al., 2002), and also to a clayey loess sample from the northern Negev, Israel, described by Pye and Sherwin (1999). The placement of the primary mode (in either the fine silt or clay size range) is dependent on the degree of weathering of the deposit (Pye and Sherwin, 1999), as well as the nature of the original source material.

The M1 cs2 particle size histogram (Fig. 8) is quite different from those of all other samples, both in its largely unimodal character, and also by the dearth of a significant modal shift following full dispersion. There is a minor mode in the M1 coarse silt-size range (40–60 µm) (Fig. 8). Initial particle size analysis showed that the cs2 phase of the M1 dune contained less material < 20 µm than the same phase in both other dunes (Fig. 6), which in part explains the lack of a significant silt or clay mode following high resolution particle-size analysis. Erosion may provide an alternate explanation for the lack of silt and clay, as the cs2 sampling sites at M1 were considerably more exposed than the equivalent sites at M2 and B1. Assuming the aeolian material has been uniformly deposited across the landscape, as suggested by Butler (1956), the past and present processes acting at these sites will be reflected in the degree of preservation of the aeolian material. This includes post-depositional surface processes such as wind and water erosion; if the aeolian deposit had not been adequately stabilised these processes may have removed and redistributed the dust.

The B1 clay lamellae also exhibited a relatively constant particle size distribution following both minimal and full dispersion (Fig. 10). The B1 silt mode (20–60 µm) is more pronounced than that of M1 (Fig. 9). The overall B1 particle-size distribution (Fig. 10a) is comparable to that
described by Walker et al. (1988) in loessic soils of southeastern Australia, where a similar, largely unimodal distribution with a pronounced population of grains in the coarse silt-range, and a more finely textured ‘shoulder’ was obtained. Similar particle-size distributions have been described in Northern Hemisphere loess deposits (Pye and Sherwin, 1999).

Previous aeolian dust research in eastern Australia has interpreted the presence of a particle-size mode in the 30-60 µm range as typical and indicative of aeolian dust accessions (Beattie, 1970; Blackburn, 1981; Walker et al., 1988; Cattle et al., 2002).

3.2 Mineralogy

The clay-mineral suite of the fine material within the sampling sites was determined to (1) ascertain whether it could be differentiated from the surrounding floodplain material, and (2) assess any incongruity between phases and between dunes that may indicate an aeolian provenance. In all phases (s1, cs2, cas3) at all sites (M1, M2, B1) illite and kaolinite were found to dominate the clay-mineral fraction. Smectite was a dominant mineral only in the cas3 phase, a feature that was consistent for all three sampling sites (Table 1). Smectite also appeared as a minor mineral in the s1 and cs2 phases of M2 and B1, and was absent from these phases at the M1 sampling site. Additional minerals present ubiquitously in minor amounts within the clay-size fraction include quartz and mica. Interstratified phyllosilicates (smectite-illite) were present in small quantities in most samples. X-ray diffraction traces for the clay mineral suite of all samples are included in Appendix 1.

Table 1
The dominant and sub-dominant minerals present in the clay-size fraction of soil from three sampling sites

<table>
<thead>
<tr>
<th>Dune phase</th>
<th>Sampling site</th>
<th>Dominant minerals</th>
<th>Sub-dominant minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1</td>
<td>M1</td>
<td>Illite, kaolinite, smectite</td>
<td>Quartz, interstratified minerals, mica</td>
</tr>
<tr>
<td></td>
<td>M2</td>
<td>Illite, kaolinite</td>
<td>Smectite, quartz, interstratified minerals, mica</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>Illite, kaolinite</td>
<td>Smectite, quartz, interstratified minerals, mica</td>
</tr>
<tr>
<td>cs2</td>
<td>M1</td>
<td>Illite, kaolinite</td>
<td>Quartz, micas</td>
</tr>
<tr>
<td></td>
<td>M2</td>
<td>Illite, kaolinite</td>
<td>Smectite, quartz, interstratified minerals, mica</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>Illite, kaolinite</td>
<td>Smectite, quartz, interstratified minerals, mica</td>
</tr>
<tr>
<td>Clay lamellae</td>
<td>B1</td>
<td>Illite, kaolinite</td>
<td>Quartz, interstratified minerals, mica</td>
</tr>
<tr>
<td>Sub-clay lamellae</td>
<td>B1</td>
<td>Illite, kaolinite, smectite</td>
<td>Quartz, interstratified minerals, mica</td>
</tr>
<tr>
<td>cas3</td>
<td>M1</td>
<td>Illite, kaolinite, smectite</td>
<td>Quartz, interstratified minerals, mica</td>
</tr>
<tr>
<td></td>
<td>M2</td>
<td>Illite, kaolinite, smectite</td>
<td>Quartz, interstratified minerals, mica</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>Illite, kaolinite, smectite</td>
<td>Quartz, interstratified minerals, mica, vermiculite</td>
</tr>
</tbody>
</table>

Studies of modern east Australian dust indicate that the dominant clay minerals are illite and kaolinite, and that suspended dusts contain no or low amounts of smectite (Kiefert and McTainsh,
1995). Furthermore, in a review of aeolian dust deposit studies of southeastern Australia, Hesse and McTainsh (2003) concluded that clay mineralogy is overwhelmingly of illite and kaolinite at sites where there is sufficient reason to suggest that the clay is of an aeolian origin. Illites frequently form the majority of clay minerals in soils of temperate climates, especially in soils formed on sediments (Kiefert and McTainsh, 1995); however Allen and Hajek (1989) suggest that illite is usually only a minor constituent in Vertosols. Accordingly, Cattle et al. (2003) reported that quartz, smectite and kaolinite are the dominant clay minerals in the floodplain area surrounding source-bordering dunes on the lower Lachlan floodplain. Thus if the dune clay samples are dominated by a clay-mineral (illite) that is not abundant in the local floodplain soils an allochthonous aeolian origin for the dune clay is plausible.

Whilst Dare-Edwards (1984) suggested that parna deposits had not been found to contain any definitive minerals that would allow for consistent identification, a number of studies of aeolian sediment in eastern Australia have noted a clay-fraction mineralogy dominated by illite and kaolinite. Walker and Costin (1971) and Johnston (2001) recorded the dominance of illite and kaolinite in clay-dominated dust accessions similar to parna, in the Australian Alps. Further inland, Beattie (1970) described parna deposits of the Riverine Plain as dominated by illite and kaolinite, and Chartres et al. (1988) found that loessic soils across eastern New South Wales were enriched with illite and randomly interstratified clay minerals.

The soils of the floodplain surrounding each of the sand dunes are Vertosols and therefore smectite-rich. If the fine material sampled from each dune was indeed wholly derived from the surrounding floodplain, smectite would be expected to comprise a substantial portion of the clay-mineral suite. Instead, in most samples smectite was a subordinate mineral only, with the exception of the cas3 phase of all dunes, the s1 phase of M1 and a zone directly below clay lamellae in the cs2 phase of B1. If the smectite in cas2 were totally locally-derived, it would be reasonable to expect a uniformly significant distribution of smectite throughout all phases of the dunes. The restricted distribution of smectite within each dune suggests that the smectite is not locally-derived, but allochthonous and likely to have an aeolian origin. Whilst smectite is not generally known to be a major constituent of parna, and is rarely a component of modern-day dust suspensions (Kiefert and McTainsh, 1995), its presence in aeolian sediments of eastern Australia has been recorded in a number of studies (Cattle et al., 2002; Chen et al., 2002). Kiefert and McTainsh (1995) assert that the smectite content of dust decreases with distance from source, as smectite often forms large aggregates not conducive to transport over long distances.

If smectite was deposited on the dunes as a constituent of parna aggregates which subsequently disaggregated, the fine mineral size of smectite would allow for preferential illuviation from the
upper phases of the dunes; a mechanism that perhaps partly explains its accumulation in cas3. Pye and Sherwin (1999) found that smectite dominates the 0.2 µm clay fraction of soils, whilst illite dominates both the fine and coarse fractions; accordingly smectite may feasibly have illuviated beyond the zone of maximum clay (illite and kaolinite) accumulation (cs2).

Pye and Sherwin (1999) cautioned that some care needs to be taken when interpreting the clay mineral suite of an aeolian soil, as some clays can form post-depositionally as a result of \textit{in situ} weathering. Accordingly, the smectite in cas3 may alternatively have formed pedogenically, \textit{in situ}. Allen and Hajek (1989) suggest that smectite can be formed pedogenically where leaching is restrictive because of low precipitation (as is apparent at the study area), or where there is an abundant supply of bases and/or silica. The readily observable prevalence of calcium carbonate in the cas3 phase suggests that there would have been an abundant supply of bases (namely Ca\textsuperscript{2+}) available for the neo-formation of smectite in this phase. Further, the smectite component of soils in semiarid regions, whilst frequently derived from parent sediment, is also known to arise from synthesis in the lower subsoil of such environments. Allen and Hajek (1989) suggest that this trend not only indicates neo-formation of smectite in the lower horizons, but also (1) instability in the upper horizons, and (2) preferential translocation of the smectite. It is unclear at this juncture which process or combination of processes is responsible for the appearance of smectite as a major mineral in the cas3 phase of each dune.

\subsection*{3.3 Micromorphological features}

The micromorphological features of thin sections sourced from a number of locations within each dune (Section 2.5) were described, and the descriptions follow Bullock et al. (1985).

\subsubsection*{3.3.1 Phase of clay accumulation (cs2)}

Photomicrographs of this phase of each dune, in addition to the clay lamellae of B1, are shown in Figs. 11 and 12. The soil mass consists predominantly of detrital mineral grains and some fine material. In each dune the microstructure is varied, but is dominantly bridged grain or compact grain, with some areas of massive structure, depending on the concentration of fine material. Total porosity is less than 20\% in the B1 soil, and approximately 30-40\% in the M1 and M2 soils. In addition to simple and complex and compound packing voids, some vughes are also present, while floral channels also appear as a minor feature in all samples.

The coarse mineral fraction is overwhelmingly dominated by abraded quartz grains in all samples, ranging in diameter from 10 µm to 1000 µm, although the average grain size is 20–70 µm. Minor coarse mineral components (frequency less than 5\%) include plagioclase feldspar, epidote
and tourmaline. Occasional concretions of iron oxide and manganese dioxide (20–40 µm diameter) were also present in all samples, and very rare small rutile grains were observed in the B1 sample. The coarse mineral skeleton grains are dominantly angular to rounded, poorly sorted single mineral grains with variable sphericity. Some quartz grains (usually those ≥ 70 µm) exhibited unusual striated or cross-hatched surface weathering patterns.

In all samples the fine mineral material consists chiefly of brown to reddish brown clay-sized material displaying moderate anisotropy under cross-polarised light. Interference colours produced by the clay material under cross-polarised light suggest that 2:1 clay minerals (likely illite and smectite) predominate, and that kaolinite (generally optically isotropic) is also present. Although kaolinite is usually transparent under transmitted light, it is frequently stained by iron-oxides and thus shows a brown or reddish brown colour, similar to that of the thin sections here described.

The elementary fabric (related distribution between the coarse and fine material) varies between chitonic (coarser units surrounded by a cover of smaller units, indicated by ‘C’ in Figs. 11, 12 and 13) and porphyric (large fabric units occur in a dense groundmass of smaller units, indicated by ‘P’ in Figs. 11 and 12), a trend related to the concentration and distribution of clay-sized material. Fig. 11b illustrates the contrasting fabrics well. In all dunes there appears to be a layered or laminar structure whereby clay and fine-medium sand is accumulated in laminations (there generally showing a porphyric or close chitonic fabric), between which clay accumulation is minimal and a single grain structure or bridged structure and chitonic fabric preponderate (Fig. 11b and d). The porphyric fabric is most pronounced in B1 because of the generally greater clay content.

Fine material occurs primarily as clay coatings (argillans) on larger grains (Figs. 11c and 12c) or as pore infillings or clay plugs (Fig. 11a). Sleeman (1975) described similar features in a loessic red-brown earth in northern Victoria as ‘wüstenquarz,’ or “illuviation embedded ferri-argillans.” The argillans here occur primarily as limpid-speckled, continuous and non-continuous laminated (and some non-laminated) coatings around skeleton grains, packing voids and channels.

Argillans, indiscriminately coating large mineral grains, are the dominant textural pedofeature in this phase for all dunes. Whilst there is some conjecture as to the origin of argillans (a weathering feature or a depositional feature), they are generally thought to result from translocation and deposition of clay from upper horizons. As such, argillans are important in providing a record of current and past eluviation-illuviation processes (Bullock et al., 1985). The moderately-strongly anisotropic alignment of clay within the argillans, the indiscriminate nature of their distribution, and the micro-laminated structure observed within certain zones (Fig. 11a) throughout the cs2 phase all indicate that the clay is a depositional feature in cs2, rather than a result of in situ mineral weathering.
As can be seen from Fig. 11b and Fig. 12d, clay accumulation occurs in laminated manner, whereby zones of minimal clay and dominantly single grain structure intersperse the clayey, porphyric zones. Dust deposition processes have been known to confer a characteristic fine laminar structure, particularly in features such as lunettes (clay dunes) (Bowler, 1976), however more frequently the primary depositional fabric and mineral organisation is altered significantly by post-depositional pedogenesis. The coarse mineral grains that occur within the zone clay accumulation in Fig. 11b show substantial variation in both size and shape, thus largely negating the possibility that the clay is a direct depositional feature. The laminations in Fig. 11b and Fig. 12d are more likely to have been formed post-depositionally by illuviation from overlying horizons, and the fine mineral grains within the laminations are likely to have illuviated together with the clay.

Fig. 11. Photomicrographs of the source-bordering dune samples viewed under plane polarised light. (a) cs2 phase of the B1 dune, showing porphyric fabric (P), and a laminated clay plug as indicated by the red arrow, (b) cs2 phase of B1 showing laminated structure and contrasting chitonic (C) and porphyric fabric, (c) clay lamellae within the cs2 phase of B1 dune, red arrow indicates fragmented clay coat (papule), and (d) zone between clay lamellae in lower cs2 of the B1 dune, showing dominantly chitonic fabric (C).
The mobilisation of clay and silt-sized particles and their downward translocation with infiltrating water (argilluviation or lessivage) is one of the most common pedogenic processes associated with aeolian dust deposits. Numerous studies have shown that argilluviation of aeolian clay and silt is responsible at least in part for the formation of important pedological features such as argillans (Sleeman, 1975), argillic horizons (Beattie, 1970), clay lamellae (Kemp and McIntosh, 1989) and zones of decreased permeability (Chartres, 1983). Micromorphological features here described support an aeolian origin, whereby the clay material was deposited, disaggregated, illuviated and subsequently re-deposited lower in the profile. Further, the irregular morphology of the laminated clay layers and the discrete clay lamellae on a macro-scale (Fig. 4) discredit the
notion that direct deposition was responsible for their formation, and indicate mobilisation and illuviation of clay as a far more likely elucidation (Chen et al., 2002).

Micromorphological features that further support the hypothesis of aeolian deposition include the abundance of well-sorted 40–70 µm sized quartz grains within the laminated zones of all cs2 phases. The photomicrographs shown in Figs. 11 and 12 demonstrate the presence of this 40–70 µm sized quartz population, and Fig. 11b and Fig. 12d depict the sorting of these grains into an approximately laminated structure. This laminated structure is evident in all dunes, where the 40–70 µm grains tend to accumulate within the clayey lamina, and larger quartz grains occur between these laminae (Fig. 11b). The presence of such fine-grained, abraded quartz grains is consistent with aeolian transport.

The propinquity of fine-sand and silt-sized grains (40–80 µm) directly underlying the discrete clay lamellae in M1 (Fig. 12b) and B1, forming a relatively impermeable zone, may support the contention that the lamellae formed as a result of illuviation, rather than direct deposition. Further illuviation of fine material was possibly restricted by this relatively impermeable zone where continuous pore space is restricted. This zone may also represent the extent of the wetting front.

3.3.2. Phase of carbonate accumulation (cas3)

Photomicrographs of the cas3 phase of each dune are shown in Fig. 13. The soil mass consists predominantly of detrital mineral grains and some scarce fine material. The microstructure is relatively consistent within this phase of each dune, being dominantly compact or single grain and bridged grain. Irregular nucleic concretions (glaebules) composed of coarse mineral grains cemented with crystalline calcite appear consistently as a salient pedofeature in this phase of each dune. Porosity is approximately 40% overall, but commonly less than 10% within the calcite glaebules, and is dominated by compound packing voids, as well as relatively rare floral channels. Close-packed bridge structure predominates within the calcite glaebules.

As in the cs2 phase, the coarse mineral fraction of the cas3 phase in all dunes is dominated by abraded quartz grains ranging in diameter from 10 µm to 1000 µm. The average quartz grain size in this phase is 80–200 µm. Minor (frequency less than 5%) mineral components in the coarse grain fraction include bullet shaped zircon grains (100–150 µm diameter), orthoclase feldspar (100–200 µm diameter) and subrounded grains of hornblende (50–200 µm diameter). The coarse mineral skeleton grains show variable sphericity and are dominantly angular to rounded, and poorly sorted.
Fig. 13. Photomicrographs from the cas3 phase of the source bordering dunes. PPL = plane polarised light, XPL = cross polarised light. (a) Zone within a carbonate glaebule from the M1 dune (PPL), (b) zone within a carbonate glaebule from the M2 dune (XPL), (c) calcite coating birefringent grain in the M1 dune (XPL), (d) the border of a calcite glaebule from the B1 dune, showing the contrasting fabrics (C = chitonic, P = porphyric) (XPL).

The fine mineral material in all cas3 samples consisted chiefly of calcite, with some brown to reddish clay and iron-oxide also present. The clay component exhibits a low degree of anisotropy under cross-polarised light, and associated interference colours indicate that the dominant clay minerals present are kaolinite and 2:1 minerals (illite and smectite). Both the clay and the iron-oxides are present largely as thin, incomplete coatings on and bridges between detrital grains.

Extreme birefringence and distinctive interference colours make secondary micritic calcite readily observable in thin sections (Figs. 13b,c,d). Here calcite is present as dense crystals in abundant glaebules where it forms micritic hypocoatings that cement quartz grains of varying size (10–100 µm) and shape (spherical, sub-spherical, and tabular). The shape of the concretions is irregular, though dominantly sub-spherical, and size shows substantial variation within the range 10–3000 µm. Whilst present at all sites, calcite glaebules are most prevalent in the cas3 phase of...
B1, and in the subsoil of M2 cas3. In the topsoil zone of M2 cas3, calcite was often present as incomplete coatings, or fragments of coatings, rather than as discrete glaebules.

The elementary fabric of this phase is monic or chitonic outside of the calcite glaebules, where fine material is relatively scarce, and porphyric within the glaebules, where calcite crystals form a groundmass of varying density. Fig. 13d illustrates the contrasting fabrics within the cas3 phase of the B1 dune. The fabric of smaller glaebules is frequently close-porphyric, and pore space generally increases with the overall size of the glaebule. Calcitic pedofeatures are consistent in their properties and abundance in all three study sites.

Calcite is relatively soluble and as such calcitic pedofeatures are common in many soils, particularly in arid and semi-arid areas where soluble minerals are more likely to persist and accumulate (Dultz and Kühn, 2005). Calcitic pedofeatures are formed when deposited carbonates are dissolved, distributed throughout the soil profile with infiltrating water, and re-precipitated as coatings on existing grains, voids or plant structures, and as void or root-channel infillings (pseudomorphs) (Bullock et al., 1985).

Aeolian dust frequently contains a carbonate component, and one of the most common features of soils developing in aeolian deposits is a horizon of secondary carbonate accumulation, or ‘caliche,’ particularly in arid and semi-arid regions (Simonson 1995). Carbonate transported in aeolian dust is readily dissolved, redistributed and precipitated throughout the developing soil profile (Pye 1987), forming various secondary features, ranging from incipient coatings and diffuse accessions, to the formation of a hardened layer. Accordingly, numerous studies of loess and loessic soils of southeastern Australia have identified subsoil zones of diffuse secondary carbonate accumulation (Butler, 1956; Beattie, 1970; Chartres, 1983). Similarly, one of the most common characteristics of loess deposits in the Northern Hemisphere is the abundance of secondary carbonate accumulations (Dultz and Kühn, 2005), including ‘loess-doll,’ a pedogenic carbonate concretion commonly occurring in the subsoil of Chinese loess profiles (Derbyshire, 1983).

Micromorphological features, including the fine crystalline nature of the calcite, which indiscriminately coats detrital grains, suggest that the accumulation of calcite in the cas3 phase of each of the study sites is the result of a re-distribution of deposited carbonate. This carbonate is likely to be derived from an allochthonous source, as there is no abundant local source of carbonate. Butler’s (1956) original model of ‘parna’ included a carbonate content of 5 to 25 %, varying inversely with distance from the source region. Accordingly, carbonate observed within the cas3 phase at each of the study sites (M1, M2 and B1) plausibly arrived as a constituent of an aeolian aggregate (parna), and owing to its readily soluble nature was subsequently dissolved and
redistributed to the lower parts of the profile, forming the glaebules which occur as a repeated feature.

3.3.3 Aggregates of soil mineral material

Whilst the dominant model of parna is a clay-silt aggregate, no micromorphological studies on dust-affected soils of southeastern Australian have found any clay aggregates (Hesse and McTainsh, 2003), except as rare occurrences (Chartres, 1983). The absence of parna aggregates has been attributed to breakdown due to in situ weathering, including wetting and drying (Sleeman, 1975). No discrete parna aggregates were identified in the thin sections from this study; however, components that fit Butler’s (1956) model for parna were identified as separate entities, spatially separated within each dune. The between-dune consistency of the micromorphological features in each phase supports the hypothesis of an analogous, æolian origin.

3.4 Grain Morphology and elemental composition

A number of samples were selected from each dune for analysis using scanning electron microscopy (SEM), to observe morphological grain attributes and determine elemental composition. Elemental analysis confirmed that the dominant mineral present in all samples is quartz, whilst clay minerals (kaolinite, illite) are present only as a sub-dominant constituent. The most apparent morphological feature across all samples from the cs2 phase was the presence of a thin coating of fine material covering the matrix quartz grains.

The presence of a substantial population of 30–70 µm grains within the cs2 phase of each dune was also confirmed by scanning electron microscopy, as exemplified in Figs. 14e and f, taken from M1 and B1 respectively. The widely accepted ‘typical’ size for æolian grains in southeastern Australia falls within this coarse silt-fine sand range (30–70 µm) (Dare-Edwards, 1984), as previously discussed (Section 3.1).

Grain shape showed some variation both within and between all samples. Pye and Sherwin (1999) suggest that the shape of æolian dust grains is a reflection of mineral composition, mode of formation and the degree of pre- and post-depositional modification induced by weathering. Dust grains derived from secondary sources, such as the clayey æolian dust described in southeastern Australia, will tend to be more rounded and may be coated with clay-sized minerals. Accordingly, the sub-rounded 30–70 µm quartz grains evident in Figs. 14a, c, e and f are conceivably of an æolian origin, and are comparable to rounded æolian aggregates described by Mays et al. (2003) in northern Victoria.
Fig. 14. Scanning electron micrographs taken from the cs2 phase of sampling sites. Views of (a) a 50 µm quartz grain with adhered clay particles from M1, (b) an angular 50 µm quartz grain from M2, (c) clay coating bridging quartz grains in M2, (d) smooth clay coating on quartz grain within the B1 clay lamellae, (e) a population of 30–70 µm grains in M1 and (f) a similar population of 30–70 µm grains and aggregates within the clay lamellae of B1.

The shape of aeolian grains is not well specified, however, and is a conjectural issue. Indeed, a number of authors suggest that active aeolian sand grains tend to be sub-rounded to sub-angular, rather than rounded (Stapor et al., 1983; Tchakerian, 1999). The as yet unfathomed origin of the
highly angular, clay-coated quartz grain in Fig. 14b, which conforms to the known size-constraints of aeolian particles, but not to the tacit template for shape, is a case in point.

SEM may be used to distinguish between various depositional environments and weathering characteristics, based on the nature and frequency of quartz-grain surface microfeatures, such as adhered particles, and surface etching. Particles of silt and clay adhered to the surface of quartz grains are the “combined result of electrostatic forces, mechanical and chemical weathering processes and post-depositional modifications, such as movement of surface moisture and groundwater, and infiltrating aeolian dust” (Tchakerian, 1999). Accordingly, SEM analysis of the cs2 samples indicates that argilluviation has been an important post-depositional weathering process. Most of the quartz grains subjected to x-ray analysis for elemental composition in this study were coated with a thin veneer of clay and silt-sized minerals, dominantly kaolinite, but also smectite and illite. Fig. 14c, where two contiguous quartz grains are bridged by a thin coating of clay (kaolinite), demonstrates this feature well. The ubiquity of the clay coatings (argillans) across all grains, and the presence of bridging structures (Fig. 14b) suggest that the clay is of an illuvial origin, rather than a result of in situ weathering of coarse mineral grains. Further indicative of argilluviation is the smooth, laminated nature of the clay coating in Fig. 14d, where clay particles are aligned in a parallel manner, an archetypal property of argillans.

3.5 Is there any clayey-loess of allochthonous origin present in these dunes?

The nature and the distribution of fine material ‘trapped’ within the three source-bordering sand dunes at Hillston would suggest that it has not been sourced locally. As the sand dunes rise well above the level of the floodplain they are unlikely to have received fluvial deposits, thus the presence of any fine material will be a result of either aeolian deposition, or weathering of coarse mineral grains in situ. The unique properties of this fine material, coupled with its distinctive pattern of distribution within the dunes discredit the notion that it has been formed by in situ weathering of matrix mineral grains.

The relative consistency of macromorphological features between all three spatially separated dunes suggests that they have been subject to similar depositional and subsequent pedogenic processes. The distinctive red, clay-enriched phase (cs2) of each dune may logically be interpreted as illuviated aeolian dust. The between-dune consistency of this phase in terms of colour, mineralogy, particle size characteristics and morphology supports this contention. Red clayey bands in dune sequences have been found in other parts of the world and some are also interpreted as illuviated aeolian dust. (e.g. Jorgenson, 1992; Page et al. 2003; Holliday and Rawling, 2005).
irregular, wavy morphology of the thin clayey lamellae at B1 suggests that this feature has formed as a result of illuviation, rather than direct deposition (Chen et al., 2002).

The presence and macromorphology of the unusual phase of carbonate glaebule accumulation (cas3) provides further evidence of aeolian accession. There is no abundant local source of carbonate that could satisfactorily explain the occurrence of this phase. Secondary calcareous deposits have been commonly associated with aeolian deposits across southeastern Australia. Beattie (1970) described an accumulation of secondary calcite deposits in the subsoil of panna soils in southern New South Wales, and the ubiquitous presence of carbonate in many soils of southeastern Australia has variously been ascribed to aeolian dust accession (Page et al., 2001).

As asserted by Hesse and McTainsh (2003), the principal and most readily-distinguishable component of Australian dust and dust deposits is silt-sized quartz (up to 70 µm). Accordingly, preliminary evidence for dust deposition within the study sand dunes includes the bimodal particle size distributions of the cs2 material, which show distinct populations of grains with a diameter around 50 µm. This size corresponds to the dust modes identified in soils of southeastern Australia (Beattie, 1970; Blackburn, 1981; Walker et al., 1988; McTainsh and Duhaylungsod, 1989; Cattle et al., 2002;).

The clay mineral suite of the upper two dune phases is dominated by illite and kaolinite, consistent with the mineralogy determined in a number of studies on aeolian sediment in eastern Australia (Kiefert and McTainsh, 1995). The conspicuous absence of smectite as a dominant mineral in all but the cas3 phase further points to an allochthonous origin for the fine material, as the surrounding floodplain soils are Vertosols, and known to be rich in smectite and comparatively low in illite (Cattle et al., 2003). The dominant presence of smectite in the cas3 phase of all dunes is not able to be satisfactorily explained at present. The restricted distribution of this smectite suggests that it is unlikely to have been sourced from the surrounding floodplain. Possible preferential translocation of aeolian smectite from the upper phases, or neo-formation in situ, mediated by the abundance of Ca\textsuperscript{2+}, are suggested as possible mechanisms to explain this feature.

Micromorphological examination of the cs2 and cas3 phases indicates that clay is unlikely to have been produced by in situ weathering, or to have been directly deposited. Rather, clay present in these phases appears to have been illuviated post-aeolian deposition. The abundance and indiscriminant distribution of strongly anisotropic argillans in the cs2 phase are consistent with illuviation. Argillans are known to be a common pedofeature associated with aeolian deposits. Further, the laminated arrangement of fine (30–70 µm) quartz grains within the cs2 phase suggests that this material may have illuviated with or before the aeolian clay, and possibly has formed a relatively impermeable layer that impedes further translocation, perhaps partly elucidating the
morbidity of the discrete clayey lamellae at B1. The calcium carbonate glaebules abundant in the
ca3 phase were also found to be a pedogenic feature. The fine crystalline nature of the calcite
which ubiquitously coats the matrix mineral grains of the lower dune phase suggests that this
material was solubilised and translocated from surface horizons, and re-precipitated at depth.
Scanning electron microscopy analysis further supports the notion of aeolian accession. Grain
features such as size and shape that are consistent with aeolian transport, as well as the presence of
extensive clay coatings were identified.

All three profiles discussed here provide evidence consistent with in situ weathering of aeolian
dust material such as ‘parna’. The spatial separation of ‘parna’ components into different phases of
the dunes is an expression of the relative mobility of these minerals. Calcium carbonate is relatively
soluble and would have readily have dissolved in and translocated downwards with infiltrating
water, hence its accumulation in the lower dune phase. Clay minerals, which move largely in
suspension rather than solution and are thus not as mobile as soluble salts, have therefore illuviated
a comparatively shorter distance, and accumulated higher in the dune.

Hesse and McTainsh (2003) suggest that there is very little clear evidence of the presence of
clay aggregates in transported dust, and as such their importance in Australian dust processes and
deposits is still unclear. The sand dunes used in this study provided an opportunity to characterise a
possibly relatively pure dust deposit, and whilst no discrete aggregates that conform to the
traditional model of parna (Butler, 1956) were identified, the individual components of this model
were identified as separate entities. This material is likely to have an aeolian origin, but the manner
in which it was deposited, either as aggregated ‘pellets’ of parna, or as discrete materials, remains
an issue of conjecture. Pedogenic processes such as leaching, clay translocation and pedo-turbation
leading to aggregate dispersion, may explain the absence of aggregates in these soils (Mays et al.,
2003).

The most plausible explanation for the enrichment of the source-bordering dunes with silt-sized
quartz, clay and carbonate, is through aeolian accession The consistency of mineralogy, particle size
characteristics, and both macro- and micromorphological features between all the three dunes,
suggests that reinforces the credibility of this notion.

3.6 Implications

Due to the nature of aeolian processes, it’s expected that aeolian material with a suite of
characteristics congruent to that identified within the source-bordering sand dunes will have been
uniformly deposited in the surrounding landscape. Regardless of the total volume deposited, this
aeolian sediment will have had some role to play in pedogenesis of the receiving soil. The
translocation and transformation of deposited ãolian dust and its constituents can have important implications for soil development, imparting properties not necessarily related to the weathering of underlying parent material.

Despite the fact that ãolian deposits of southeastern Australia have commonly referred to as ‘parna’, and conjecturally accepted as distinct from other loess sediments for fifty years, the model of parna is poorly substantiated, and the position of parna in the broader context of loess research remains to be clarified (Hesse and McTainsh, 2003). In the endeavour to better characterise and define parna, more detailed and rigorous analysis of its particle-size, mineralogical and geochemical characteristics are required. Once the basic physical and chemical properties of the dust are known, the true extent of its distribution can be identified, and the role it has played, and continues to play in soil formation and landscape evolution better appreciated.

4. Conclusions

Virtually all Australian soils are thought to contain a component of ãolian dust accession, however the characteristics of pure ãolian materials and the true extent of their distribution remain unclear. This study found that fine-grained material trapped in three source-bordering sand dunes on the lower Lachlan floodplain is likely to contain the constituents of a relatively pure ãolian deposit. Each of the sampling dunes exhibited three distinct phases of soil material, namely: (1) an upper-slope phase of uniform coarse brown sand, (2) a mid-slope layer of red, clay-enriched sand and discrete clayey lamellae and (3) a lower slope phase of coarse sand dominated by an accumulation of carbonate ‘glaebule’ structures. The granulometry, mineralogy and micromorphology of fine material identified in the sand dunes indicate an allochthonous ãolian origin.

Granulometric analysis revealed an accumulation of clay and silt within the cs2 phase of each dune. Within this phase a distinctly bimodal particle size distribution was identified, whereby one conspicuous particle population occurred in the 30–60 µm range, and another in the fine-silt/clay range (<10 µm). Such bimodality is considered characteristic of southeastern Australian ãolian dust deposits, and is frequently used as a diagnostic property.

The clay mineral suite of the upper dune phases was dominated by illite and kaolinite, which is consistent with the known composition of both suspended ãolian dust and ãolian dust deposits of southeastern Australia. The surrounding Vertosol floodplain is dominated by smectitic clay minerals, and is inherently low in illite, hence the conspicuous absence of smectite as a dominant mineral in the upper dune phases further suggests that the clay is likely to be derived from a remote source. Smectite was a dominant mineral in the lower phase of all dunes, however. This anomaly cannot be satisfactorily accounted for at this point, although preferential illuviation of smectite from
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the upper phases, or neo-formation in situ mediated by an abundance of soluble bases in the lower
dune phase may be involved.

In addition to the unique granulometric and mineralogical properties of these fine particles, their
micromorphological arrangement in, and relationship to, the sand dune matrix material also points
to an æolian origin. The extensive and indiscriminant distribution of features such as argillans, clay
plugs and wüstenquarz throughout the mid-dune phase of all dunes suggests that argilluviation has
been a dominant pedological process, and discredit the possibility that this clay has weathered in situ from matrix mineral grains. Similar processes of translocation and deposition appear to be
responsible for the occurrence of fine-grained crystalline calcite that bridges matrix mineral grains
in the lower phase.

Micromorphological analysis, both in thin section and using scanning electron microscopy
identified an abundance of silt-sized (20–70 µm) quartz grains, known to be the principal
component of Australian dust and dust deposits. These quartz grains were accumulated in the mid-
dune phase of all dunes, and frequently occurred in a wavy laminated structure. The laminated
structure suggests that these grains may have been translocated downwards with infiltrating water,
perhaps concurrently with the clay particles. Scanning electron microscopy revealed a prevalence of
ubiquitous clay coatings and a dominantly sub-rounded shape, which is consistent with æolian
transport.

The consistency of morphological and mineralogical features for all three dunes supports the
hypothesis of an analogous dust accession, and suggests that similar soil forming processes have
taken place, namely the translocation and transformation of this deposited æolian dust. The
dominant model for æolian dust in southeastern Australia is ‘parna,’ a clayey, calcareous material
thought to have been transported as sand and silt-sized aggregates. Whilst no discrete aggregates of
parna were identified, all the necessary components (30–60 µm quartz grains, clay, and carbonate)
were identified as separate entities, spatially separated within each dune. It would appear that these
source-bordering sand dunes have acted as ‘dust traps’ and contain the breakdown products of a
‘parna-like’ deposit. Given the nature of æolian processes, soils of the entire region are likely to
have received inputs of this ‘parna-like’ dust. The subsequent in situ weathering of this dust is
likely to have played an important, though as yet unquantified, role in pedogenesis of the
agriculturally-important soils of the lower Lachlan valley.
5. Acknowledgments

I would like to thank my supervisor, Dr. Stephen Cattle for introducing me to the intriguing (though sometimes enigmatic) world of pedology, and for his enthusiasm, commitment, generosity and calm guidance throughout the year.

I would also like to acknowledge and thank all of the Soil Science staff for their assistance, ideas and support.

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A further special thanks to Penelope Grist, for your patience and support.

Finally, thankyou to my family, for your never-ending confidence and encouragement throughout my time at university.

6. References


Appendix

Particle size data: pipette method

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<th>Sampling Site</th>
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