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Role of eolian dust deposits in landscape development and soil degradation in southeastern Australia

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Eolian dust plays a significant role in landscape development and landscape processes in Australia. Thin dust mantles, rarely exceeding 3 m in thickness, have been identified across many parts of the Australian landscape, particularly in southeastern Australia. The nature and properties of these dust materials can have a major influence on environmental degradation processes such as salinisation and soil erosion. Despite the existing body of research regarding this topic, there are still conflicting views about the likely sources, transport modes and properties of eolian dust in the Australian landscape. The aim of this review is to synthesise much of the available information and put forward a working hypothesis for the distribution and fundamental properties of dust deposits in southeastern Australia. A conceptual model describing the various dust sources and sinks, and the modes of transport of dust materials both into and out of these source areas, is introduced. The model identifies key source areas, such as the alluvial and lacustrine environments of the Lake Eyre and Murray–Darling Basins, and sinks, such as the Eastern Highlands. Transport rates and paths for eolian-dust materials across the Australian continent are also outlined. The model places particular emphasis on the recycling of dust, whereby sediments sourced from the Eastern Highlands are transported westward via the major alluvial networks, and deposited on floodplains or in terminal drainage systems. These sediments are then available to be reworked into local eolian landforms prior to re-entrainment of the finer materials in the easterly dust pathway. The characteristics of deposited eolian sediments are then outlined in detail, focusing particularly on their particle-size distribution, mineralogical composition, and geophysical and geochemical properties. The review also presents data and images of dust materials sampled from source areas, sink areas, as well as materials that have been deposited by modern dust events. Finally, the role of dust materials in land-degradation processes, particularly soil erosion, is discussed. The degree of reworking of the eolian sediments, the extent of leaching and the level of sodicity are all important in determining soil structural stability and hence erosion potential of these materials.

KEY WORDS: eolian dust, landscape development, soil degradation.

INTRODUCTION

There is an increasing awareness that a better understanding of eolian dust activity in the Australian landscape is critical for many issues. These range from the potential impact of current dust storms on air quality in our cities, to the role of previous eolian activity in soil–landscape processes and landscape evolution. The nature and properties of the dust particles themselves can also have a major influence on environmental degradation processes such as salinisation and soil erosion. Recognising and characterising dust in the landscape is also critical in mineral exploration where it is necessary to distinguish transported dust from *in situ* geological material. Dust is an important component in Late Cenozoic Australian sediments, many of which are found in both the major

basins and the upland landscapes. Much of the dust also originates in these basin areas. A section on dust, therefore, is a critical component of a study of Cenozoic Australian sediments and complements our understanding of coarser-grained eolian deposits.

The first compelling evidence of the influence of eolian dust on soil formation in Australia came from Butler (1956), working on the soils of the Riverine Plain in New South Wales. He noted that the same calcareous, clayey, red sediment blanketed large tracts of the Murrumbidgee and Murray river valleys, irrespective of the underlying lithology, and concluded that it had to be of eolian origin. As discussed by Hesse & McTainsh (2003), Butler avoided using the term *loess*, probably because there was very limited unchallenged evidence worldwide of desert-derived loess at that time. Instead, he used the term *parna* to describe these soils of eolian

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origin, and along with others (van Dijk 1958; Churchward 1963; Beattie 1970; Sleeman 1973; McIntyre 1976; Blackburn 1981), proceeded to characterise features thought to be typical of this material, such as a propensity to exhibit sub-plasticity and the presence of silt-sized microaggregates composed of aggregated clay. As a consequence, for the next 40 or 50 years, most Australian pedologists have regarded the presence of parna as the best (or only) indication of eolian dust accumulation in this country. The parna concept is still quite widely accepted, and there has been considerable recent work on, and several advances in our understanding of, the identification and properties of soil believed to be derived from parna in southern and western New South Wales (Greene & Nettleton 1996; Munday *et al.* 2000; Summerell *et al.* 2000; Chen 2001; Chen *et al.* 2002; Mays *et al.* 2003).

However, there is a growing body of evidence that dust processes were active in Australia in past arid phases (Bowler 1976; McTainsh 1989; Hesse 1994) and are still active today (McTainsh & Pitblado 1987; McTainsh *et al.* 1998). As a result, researchers have started to look beyond the Riverina area for evidence of dust contributions to soils. For example, Cattle *et al.* (2002) identified quartz-rich dust in basalt-derived soil profiles of the Narrabri area of northern New South Wales, and conservatively estimated that 155 mm of dust has been deposited and incorporated into the solum during the Holocene. Similarly, Tate *et al.* (2007) found eolian materials containing 70 μm quartz particles coated with clay on the tops of leucite lava outcrops near Cobar in western New South Wales. Using radiometric techniques, Dickson & Scott (1998) identified thin, silica-rich dust mantles overlying different basement rocks at Blayney in central-western New South Wales, while Walker & Costin (1971), Walker *et al.* (1988), Gatehouse *et al.* (2001) and Johnston (2001) all presented evidence of eolian dust in soil profiles of the eastern highlands of New South Wales. These studies revealed a variety of dust types and occurrences, with some being quartz-rich, some being clay-mineral-rich, some forming readily distinguishable layers and some being mixed with the local soil parent material. In none of these cases

were clay microaggregates, a central tenet of the parna concept, evident. As a consequence of such findings, Hesse & McTainsh (2003) argued strongly that parna should be viewed simply as a subset of the range of loessic mantles or inclusions that exist in eastern Australian soils.

Given that there are conflicting views and explanations as to the likely sources, transport modes and properties of eolian dust in the Australian landscape, the overall aim of this review is to synthesise much of this information and provide a logical explanation of the distribution and fundamental properties of dust deposits in southeastern Australia. The review begins by introducing a conceptual model to indicate the various types of dust sources and sinks and the modes of transport of dust materials both into and out of these source areas. The review then goes on to discuss the role of dust in landscape evolution in Australia, and how the nature and properties of the different types of dust in Australia are significant in soil-landscape processes. Linkages to environmental issues such as salinity and soil erosion are also made. It concludes with suggested future research directions.

CONCEPTUAL MODEL

The conceptual model depicted in Figure 1 encapsulates the current understanding of dust sources, sinks and transport paths in southeastern Australia. This understanding has been developed from previous studies, such as those by McTainsh (1989), Hesse (1994) and Hesse & McTainsh (2003). There are three distinct regions for dust entrainment and deposition: (i) internally draining saline lakes, playas and evaporating basins, typically occurring in the arid parts of Australia; (ii) riverine areas, dominated by floodplains in the Murray-Darling Basin of southeastern Australia; and (iii) upland areas, predominantly represented by the eastern highlands of Australia.

The predominant direction of dust transport is from west to east, with regions (i) and (ii) acting as the main dust source areas for the eastern highlands and Tasman

Sources and Sinks of Aeolian Dust

Figure 1 Conceptual framework identifying key sources, sinks and transport paths for eolian dust materials in southeastern Australia.

Sea to the east (Prospero *et al.* 2002), although McGowan *et al.* (2000) demonstrated that the directionality of dust events along this path displays considerable variation. Furthermore, as indicated in Figure 1, there is an effective feedback mechanism operating, with fine-grained sediment eroded from the eastern highlands being transported via fluvial systems back to the riverine floodplains and internally draining basins of the arid interior. Once deposited, these fluvial sediments may be reworked into relatively local eolian deposits (i.e. lunettes or source-bordering dunes) before being re-entrained and transported further to the east, where they are redeposited across the landscape or in the ocean. This model can be used to link the findings from a range of different studies on eolian dust, and help explain the potential differences in the properties of the dust.

GENESIS AND SOURCES OF EOLIAN SEDIMENT

Alluvial and lacustrine sediments of the Lake Eyre and Murray–Darling Basins [regions (i) and (ii) in Figure 1] are considered to be the main sources of fine-grained dust for contemporary dust storms in southeastern Australia (McTainsh 1989; McTainsh & Lynch 1996; Prospero *et al.* 2002), with Middleton (1984) suggesting that modern dust storm frequencies in cultivated, semiarid areas match or exceed those in arid regions. There is ample evidence to suggest that regions (i) and (ii) have been dominant source areas throughout the Quaternary (Hesse 1994). Unlike loess deposits of North America and Europe, where glacial comminution is assumed to be the main mechanism of silt-sized particle production (Aleinikoff *et al.* 1998; Wright 2001), the main mechanism of eolian particle production in peri-desert areas of Australia is assumed to be desiccation and deflation of fluvial and lacustrine sediments (Tsoar & Pye 1987; Prospero *et al.* 2002; Hesse & McTainsh 2003). In these arid and semiarid environments, remnant

floodwaters containing fluvial sediments are trapped on the floodplain where they are rapidly evaporated. As a result, their dissolved salt load is subsequently concentrated and precipitated. The resultant high electrolyte concentration in the floodwaters can lead to the flocculation of clays, which are deposited on the lakebed. Following extreme drying, the floccules of clay can then rearrange and form dense, sand-sized clay pellets. Bowler (1983) and Greene *et al.* (2006) have discussed a range of possible mechanisms for the formation of these pellets. Figure 2a depicts a typical sample of these clay pellets (100–500 μm in diameter) collected from the shoreline of Lake Millyera in South Australia (J. Magee pers. comm. 2006). These pellets are then available to be saltated and/or disaggregated, and subsequently deflated from the floodplain. Reynolds *et al.* (2007) have also described how wetting and drying processes contribute to the emission of dust from playas in the Mojave Desert, USA. These processes are particularly effective in low-rainfall environments because there is insufficient surface organic matter to promote macroaggregation and provide sufficient protection against raindrop impact. Therefore, under raindrop impact they are highly susceptible to disruption into finer particles. This leaves the resultant mineral grains highly susceptible to entrainment by wind (Bullard & McTainsh 2003). Following this remobilisation, the materials are transported eastwards, primarily as suspended dust, to the eastern highlands [region (iii)] and beyond, where conditions favourable for deposition remove them from the dust path. Figure 2b depicts fine dust particles (20–30 μm in diameter) collected in Canberra following the dust storm of 22–23 October 2002. X-ray diffraction indicated that these dust particles mainly consisted of clays (60%), but also they had a considerable quartz content (35%) (R. A. Eggleton pers. comm. 2005).

Our understanding of the dust recycling mechanism, whereby sediment is eroded from the highlands and transported fluvially back to the floodplains and playas

Figure 2 Scanning electron micrographs of dust: (a) dense, sand-sized clay pellets from the shore line of Lake Millyera in South Australia (scale bar 1000 μm); and (b) fine dust particles collected in Canberra following the dust storm of 22–23 October 2002 (scale bar 20 μm). These micrographs illustrate the difference in size between dust particles in the source and sink regions.

to act as parent material for subsequent dust production, is improved by the findings of Gatehouse *et al.* (2001). They used U–Pb dating of fine-grained zircon separated from dust deposits in the eastern highlands to fingerprint the original source areas of grains entrained from regions (i) and (ii) and deposited as dust in region (iii). Their results show that Paleozoic granites and sediments of the Lachlan Fold Belt, and igneous rocks of the New England Fold Belt, supply the majority of these windblown zircon grains, and that similarly aged zircon grains are evident in the lower reaches of the Murray–Darling Basin, most particularly the Mallee dunefields. This closes the loop of sediment cycling in eastern Australia, indicating that as rocks and sediment of the highlands are weathered and eroded, sediment is carried westward as alluvium, deposited on floodplains, possibly reworked into local eolian landforms and then transported back east as eolian dust (Figure 2b).

TRANSPORT RATES OF EOLIAN DUST IN EASTERN AUSTRALIA

Two broad pathways exhibiting significant spatial and temporal variability (McGowan *et al.* 2001) dominate the transport of dust on the Australian continent. The northwest Australian dust path emanates from central Australia and transports sediment towards and into the

Indian Ocean off northwest Western Australia, while the southeast Australian dust path originates from the Lake Eyre Basin and transports sediment towards the Tasman Sea and New Zealand (Bowler 1976) (Figure 3). However, Hesse & McTainsh (2003) argued from limited data available from the Indian Ocean that the flux to the northwest is more restricted, and somewhat to the north of the position predicted by Bowler (1976). It is estimated that over the last 300–500 ka, millions of tonnes of dust have been removed by the action of wind and deposited elsewhere in Australia and beyond (Petit *et al.* 1983, 1999; Hesse 1994; Evans 1998; Greene *et al.* 2001; Pillans & Bourman 2001; Hesse & McTainsh 2003). Data from Raupach *et al.* (1994), Knight *et al.* (1995), McGowan *et al.* (2000) and McTainsh *et al.* (2005) indicated that major dust storms travelling along the southeast dust path can entrain and transport up to 20 Mt of dust. Significant quantities of this dust are reported to have been deposited in the Tasman Sea between Australia and New Zealand (Windom 1975; Thiede 1979; Hesse 1994; Kiefert & McTainsh 1996; Hesse & McTainsh 1999), at an average rate of 3.8–6.8 Mt/a (Knight *et al.* 1995). For the 1987 dust storm reported by Knight *et al.* (1995), models predict that 1.9–3.4 Mt of dust left the Australian continent (around 40% of the total dust mass), and that up to 3 Mt reached New Zealand. However, these estimates from the models do not provide an indication of the amount of dust that may have been deposited in

Figure 3 Eolian source areas and dust paths in Australia (after Bowler 1976).

the Tasman Sea and Pacific Ocean. Marx *et al.* (2005) identified a clear seasonality in New Zealand dust sourced from Australia, with highest concentrations reported in autumn/winter, following the dominant winter/spring dust storm season in Australia.

Hesse (1994) presented data from Tasman Sea cores indicating that dust deposition rates along these paths during the Last Glacial Maximum were approximately three times greater than at present, a situation that Hesse & McTainsh (1999) attributed to reduced vegetation cover rather than increased wind strength. Bowler (1978, 1998) proposed that the arid Last Glacial Maximum at 25–16 ka was the most active period of dust transport in and around Australia. McTainsh & Lynch (1996) modelled a 52–57% increase in dust activity during this time, and suggested that even these figures may be underestimates.

DEPOSITION OF EOLIAN DUST IN EASTERN AUSTRALIA

The deposition of suspended eolian dust occurs primarily as a result of a reduction in wind velocity and turbulence, although rainfall scavenging represents another important mechanism (Hesse & McTainsh 1999). Factors contributing to gravity-induced fallout include particle size and density, vegetation, topographic barriers, transport height in troposphere, and changes in moisture levels (Tsoar & Pye 1987). In general terms, the size of deposited dust particles is reduced with increasing distance travelled from the source. As a consequence, dust deposits in southeastern Australia tend to fine with increasing distance eastward (Blackburn 1981; Walker *et al.* 1988; Hesse & McTainsh 2003). Imprinted over the deposits of long-distance transported dust is varying amounts of locally or regionally derived dust; these particle size populations generally have much larger modal diameters. The combination of long- and short-travelled dust accounts for the common bimodal particle size distribution observed in dust deposits. McTainsh *et al.* (1997) assert that long-distance transported dust produces deposits with size fractions generally $<5\ \mu\text{m}$, that regionally sourced dust produces deposits of 20–40 μm particles, and that locally sourced dust produces deposits of 50–75 μm particles. In southeastern Australia, the proportional contribution of local or regional dust to the total deposition rate is greater at the more arid western end of the dust path.

Present annual dust deposition rates for southeast Australia are reported by McTainsh & Lynch (1996) to be in the order of 31–44 $\text{t}/\text{km}^2/\text{a}$. Hesse *et al.* (2003) presented rates of 20–50 $\text{t}/\text{km}^2/\text{a}$ on the Central Tablelands of New South Wales, while Chen *et al.* (2002) suggested a minimum rate of 13 $\text{t}/\text{km}^2/\text{a}$ for the Wagga Wagga region during the Late Pleistocene.

Due to the potential accumulation of long-distance, regional and local dust particles, a variety of eolian depositional environments and morphologies are possible. In arid and semiarid zones [regions (i) and (ii) in Figure 1], locally sourced dust commonly accumulates as saltated aggregates in landforms such as lunettes on

the leeward (downwind) side of deflated lake beds or in dunes adjacent to alluvial channels (Chen 1997), while finer-grained dusts have been identified as clay lamellae trapped in sand dunes (Chen *et al.* 2002). Extensive accumulations of remotely sourced dust were first recognised by Butler (1956) as (parna) sheets blanketing the Riverine Plain landscape of southern New South Wales. He suggested that the parna presently observed in these landscapes was transported as silt-sized clay aggregates, sourced primarily from the dunefields of western Victoria and New South Wales. This idea was adopted and developed further by Butler & Hutton (1956), Butler (1958), Beattie (1970, 1972) and Butler & Churchward (1983), and later revised by workers such as Chen (1997). It is interesting to note that Hutton (1980) later recanted his ideas about the eolian origin of these clay aggregates and considered that they could be derived from alluvium. Contention still remains as to the applicability of the term ‘parna’ to these deposits, with several workers suggesting that there is little evidence to support the material classification as anything but desert-derived loess (Dare-Edwards 1984; Hesse *et al.* 2003). Hesse & McTainsh (2003) in particular demonstrated that the ‘parna’ model is poorly substantiated.

More recent characterisations of parna/desert loess deposits in southeast and central New South Wales include Chen (1997), Summerell *et al.* (2000), Hesse *et al.* (2003) and McPherson (2004), while Walker *et al.* (1988) and Gatehouse *et al.* (2001) have described soil profiles where dust is a minor component, rather than the main parent material. Tate *et al.* (2007) used the presence of 70 μm quartz grains to identify an eolian component in the regolith materials in the Girilambone region of New South Wales.

Even assuming an initially uniform distribution of deposited eolian dust across the landscape, the potential for redistribution of such sediment in almost any landscape is high, through a combination of mechanisms driven by wind, water and gravity. Preservation of eolian dust deposits is particularly subject to geomorphic variables such as slope (Summerell *et al.* 2000). Beattie (1972) and Chen (1997) have both demonstrated that the present distribution of these materials in southeast New South Wales has been controlled to a large extent by hill slope and alluvial processes, which also generally incorporates some degree of reworking and dilution with local materials. Consistent with these findings, McPherson (2004) working in the Billabong Creek catchment of southern New South Wales, found that landforms influenced by recent alluvial activity or characterised by hill slopes exceeding 6%, rarely possess recognisable dust deposits.

CHARACTERISATION OF EOLIAN SEDIMENTS

Depending on the volume deposited and the amount of subsequent reworking, dust may be the dominant parent material of a soil profile (e.g. parna/loess), a co-dominant parent material (loessic soil), or a minor component of a soil profile (dust-influenced soil). In those southeastern Australian landscapes where

deposited dust is dominant or co-dominant in the soil profile, a number of properties have been regarded by different workers as more or less diagnostic of this material. These include particle size distribution, mineral suite, sub-plasticity, geophysical and geochemical properties.

Particle size distribution

A bimodal particle size distribution dominated by a significant coarse silt peak, with a lesser peak in the clay/fine silt fraction, is considered by many workers to be diagnostic of a significant eolian component. Such distributions have been identified in materials from many areas of New South Wales and Victoria (Butler 1956; Butler & Hutton 1956; van Dijk 1958; Jessup 1961a, b; Churchward, 1963; Beattie 1970, 1972; Sleeman 1975; Chartres 1982; Walker *et al.* 1988; Acworth *et al.* 1997; Melis & Acworth 2001; Chen 2001; Cattle *et al.* 2002; Hesse *et al.* 2003; McPherson 2004) downwind of their Quaternary source areas. Walker & Costin (1971) measured the particle size of dust collected from snow-patch meadow soils near Mt Kosciuszko, New South Wales. Using dispersed preparations, they showed that 75% of dust deposited to be $<31\ \mu\text{m}$, with a median diameter of around $4\ \mu\text{m}$. Hesse *et al.* (2003) reported a mean modal diameter of $30\ \mu\text{m}$ for samples from the Blayney district of New South Wales, with McPherson (2004) finding similar values in southern New South Wales. Values such as these are within the range defined by McTainsh *et al.* (1997) for regionally sourced dust, and have been consistently shown to differ from other potential parent material sources (Dickson & Scott 1998; Cattle *et al.* 2002). As an example, Figure 4 shows a clear population of silt-sized, quartz particles in a soil profile reported to be 'parna' (Summerell *et al.* 2000), from near Young, New South Wales. Although there are some locally sourced large quartz grains present, the finer quartz grains are remarkably well sorted and evenly distributed throughout a matrix of red clay.

Mineral suite

Mineralogical analysis of dust samples from Australia consistently shows quartz to be the major component, with the clay mineral fraction dominated by kaolinite and illite. There are lesser quantities of other clay minerals such as smectite, along with micas, feldspars and accessory oxides of iron and titanium (Walker & Costin 1971; Kiefert & McTainsh 1996; Dickson & Scott 1998; Cattle *et al.* 2002; McPherson 2004). While mineral composition can provide a guide to the potential presence of an eolian component, its sole use as an indicator is questionable, particularly given the large number of sources of the more common dust components, and the potential problem of clay authigenesis brought about by pedogenic processes.

Sub-plasticity

As previously outlined, a key component of parna-derived soils described by Butler (1956) was their propensity to exhibit sub-plasticity and the presence of silt-sized microaggregates composed of aggregated clay. Mays *et al.* (2003) suggested a mechanism for the development of these aggregated silt-sized particles. They contended that silt-sized clay microaggregates forming slowly in hot, dry environments can exhibit strong clay particle bonding. As a result of enhanced van der Waal's attractions between face-to-face oriented surfaces (Quirk 1994), a material that is stable in waters of low electrolyte concentration is developed. This characteristic, known as sub-plasticity (Butler 1956), indicates a high resistance of the microaggregates to dispersion (McIntyre 1976, 1979) and suggests a lower clay content than is actually present. However, as discussed by Hesse & McTainsh (2003) in their critique of Butler's original diagnostic properties, sub-plasticity develops as a function of hydrological conditions in a variety of parent materials. Therefore, it cannot be considered diagnostic of an eolian material in isolation.

Figure 4 Soil thin-section sampled from the clayey B horizon of a profile near Young, New South Wales, which is derived from a combination of eolian dust and local bedrock. These images, taken using plane-polarised light (a) and cross-polarised light (b), illustrate a distinct population of silt-sized quartz grains in a matrix of red clay. The larger quartz grains are locally derived.

Geophysical properties

The use of geophysical techniques is a relatively new innovation in the investigation of potential eolian materials. The application of downhole electromagnetic and induced conductivity measurement techniques suggests that eolian materials may be distinguished by variations in conductivity and natural gamma activity, reflecting differences in porosity, permeability and material composition (Munday *et al.* 2000). Passive techniques such as airborne gamma-ray spectrometry (radiometrics) have also proven useful in distinguishing eolian sediments from surrounding materials where there is a chemical disparity between the dust and bedrock materials (Dickson & Scott 1998). Gamma-ray spectroscopy can also identify correlations between elevated equivalent thorium and topsoil clay content, a potential characteristic of areas blanketed by dust (Cattle *et al.* 2003; McPherson 2004).

Geochemical properties

The examination of characteristic chemical signatures has been one of the more successful techniques employed in identifying eolian materials. Various elements, such as Zr (Gatehouse *et al.* 2001), Cu, Pb (Marx *et al.* 2005), Nb, Ta, Cr and heavy REEs (McGowan *et al.* 2005), element ratios such as Ti/Zr (Dickson & Scott 1998), and isotopes such as ^{210}Pb (McGowan *et al.* 2005), have proven useful in distinguishing eolian materials from surrounding rock and sediment and in assessing material provenance.

Summary of eolian dust characteristics

While many of these characteristics (with the exception of sub-plasticity) can aid in identifying eolian dust in the landscape, perhaps the most important diagnostic properties of deposited dust are those of particle size distribution and grain morphology. Grain rounding, polishing and iron oxide coatings are seen to be good morphological indicators of eolian dust particles. These two properties are the only ones linking the physical characteristics of the dust material to the processes responsible for its entrainment, transport and deposition. Notwithstanding this, the simultaneous application of several of the techniques mentioned above does represent a means of identifying and characterising eolian materials in the landscape.

ROLE OF DUST IN SOIL-DEGRADATION PROCESSES

In areas where dust has been reworked, but not removed from the landscape, these materials may retain some of their original characteristics, such as particle size distributions (Walker *et al.* 1988) or geochemical signatures (Dickson & Scott 1998; Gatehouse *et al.* 2001). Moreover, the accumulation of dust on different landforms has implications for the evolution of soil properties. The varying physical and chemical processes active in different geomorphic and climatic environments can

result in a divergent pedogenic evolutionary path for the dust materials (Fritsch & Fitzpatrick 1994).

Post-depositional modification of eolian materials is linked to soil-degradation processes through its influences on both soil-surface characteristics, such as crusting and sealing (Greene & Nettleton 1996; Greene *et al.* 1998), and subsoil phenomena, such as salinity and sodicity (Salama *et al.* 1993; Rengasamy & Sumner 1998).

In many parts of southeastern Australia, where the ratio of soil production to denudation is extremely low (Wilkinson & Humphreys 2005), rates of pedogenic development and eolian sediment accumulation are comparable. In such situations, Almond & Tonkin (1999) proposed a model of pedogenesis through 'upbuilding,' whereby each material further down the profile has been subject to the same processes as those above it (Nikiforoff 1949).

During their deposition in an upbuilding scenario, eolian materials diverge in terms of their pedogenic development under different drainage conditions. The establishment of either poorly drained or well-leached conditions in the regolith is strongly controlled by dissolution and precipitation reactions (Yaalon 1997), which regulate the types and phases of minerals present as well as the composition of the soil solution.

Under poorly drained conditions lower in the profile, leaching of materials from the upper profile creates depleted layers. Translocation of these materials from the newer eolian materials and their deposition in the previously leached lower profile results in upbuilding (effectively vertical accretion) of clays and dissolved constituents in the subsoil. It is important to note that many of the dissolved salts will not necessarily come from the eolian materials themselves, but from solutions trapped as a result of reduced hydraulic conductivity and concentrated by processes such as evaporation (Blackmore 1976; Drever & Smith 1978; Acworth & Jankowski 2001; Herczeg *et al.* 2001; McPherson 2004). When the amounts of dissolved salts reach sufficient concentrations, the composition of the clay exchange complex can be adversely affected. This results in a highly unstable clay structure and leads to soil structural degradation processes such as erosion from piping and tunnelling (Rengasamy & Olsson 1991). This is particularly the case when the salt solutions contain monovalent ions such as sodium, which are particularly problematic due to the development of sodicity and dispersive soils (Northcote & Skene 1972).

Under well-drained conditions this initial mobilisation of materials into the lower profile does not occur, and materials are not translocated and deposited in underlying layers. In such circumstances the cation-exchange capacity is dominated by divalent cations such as magnesium and calcium, which tend to develop stable clay structures (Rengasamy *et al.* 1984, 1986; McPherson 2004), and promote the formation of well-structured soils. However, in situations of highly effective leaching, very low pH conditions and toxicities from ions such as aluminium can develop in the regolith (Chartres *et al.* 1990; Helyar *et al.* 1993).

In both cases, pedogenesis reverts to a typical 'top-down' development model (Almond & Tonkin 1999)

when rates of deposition fall below those of soil formation.

In southeastern Australia, evidence of considerable accumulation of dissolved materials, particularly salts, in the regolith, suggests the possibility that many of the eolian materials have been subject to upbuilding following their deposition (McPherson 2004). Cessation of significant eolian deposition during the Late Holocene (Hesse & McTainsh 1999) would have returned the pedogenic system to one of typical top-down development. Under these conditions, the accumulated dissolved materials within the regolith could significantly influence the hydrogeochemical system. Reduced hydraulic conductivity and the presence of increased concentrations of monovalent cations such as sodium, particularly in the lower landscape, can contribute significantly to the soil-degradation processes mentioned previously (McPherson 2004). Downes' (1954) model of salinisation/desalinisation proposed that salt accumulation in the landscape is related to previous arid climatic phases, in which lower rainfall and higher evaporation favour an effective decrease in leaching. With a shift towards wetter conditions, these salts are subsequently mobilised in and leached from the regolith to varying degrees. Downes used this model to explain the pedogenic development of several soil types in southeastern Australia, whose characteristics, particularly with respect to profile differentiation and salt content, cannot be readily explained as having developed under current climatic conditions.

CONCLUSIONS

Throughout the Late Cenozoic, eolian dust has been an important factor in the evolution of the southeastern Australian landscape. Although contemporary rates of eolian dust transport and deposition are lower than those of recent glacial periods, the landforms and soil features developed during those phases of more intense eolian activity persist in various forms in the modern landscape. We propose a conceptual model to describe the processes of eolian dust transport and deposition in southeastern Australia. This model considers the internally draining basins of the arid interior and semiarid floodplains as the two primary sources of eolian dust supplying the southeast Australian dust path, and that the eastern highlands are a prominent sink area for dust travelling along that path. Ultimately, however, the eastern highlands also act as a source area for dust through the fluvial transport of eroded sediment back into the semiarid floodplains and arid drainage basins, effectively creating a dust-recycling system. However, it is important to note that the proposed system is not closed. Some dust is transported to the Tasman Sea (and beyond), while fluvial sediments, which might otherwise become dust source material when deposited on a floodplain, are buried or flushed from the system, and as such are no longer available for eolian transport back to the highlands.

As a consequence of the wide range of climatic and topographic conditions under which dust has accumulated in southeastern Australia, the characteristics of

soil profiles developed from deposited dust also vary considerably. For a number of decades, the belief that 'parna' was the best preserved and most widespread type of eolian dust deposit hampered efforts to identify other deposits of dust that had undergone more substantial pedogenesis and/or reworking. Only in recent times has it become clear that eolian dust can be an important contributor to, or indeed dominant parent material of, soil profiles in riverine and highland environments. The characteristics that have been most useful in identifying these dust inputs have been particle size distribution and geophysical properties, while geochemical properties have shown utility in assessing dust provenance.

Due to the relatively recent advances in our understanding of dust distribution, few studies have addressed the impact of eolian dust additions on soil-degradation processes. Deposition of these fine-grained materials, which may or may not have a salt component, in higher rainfall regions inevitably results in the dissolution and movement of soluble constituents. This is true whether the salts are present in the dust materials themselves or introduced through other mechanisms such as rainfall. Depending on the degree of reworking of sediment and the extent of leaching, soil structural stability may be affected by increased concentrations of monovalent cations such as sodium. This can lead to clay dispersion, and in many circumstances, the development or enhancement of degradation processes such as sodicity and soil erosion. It is likely that the soil degradation in at least some areas of eastern New South Wales is largely due to the eolian dust component within the soil, but further work is required to confirm this. More work must also be done to derive a protocol for assessing the extent of dust incorporation into the landscape.

The 'parna' concept has blinkered the view of pedologists and geomorphologists, who have typically looked for a continuous mantle of red clay as evidence of eolian dust deposition. In agreement with many other workers, it is suggested that 'parna' should simply be regarded as a clayey variant of desert loess, many forms of which exist in southeastern Australia. Furthermore, due to the connotations of the term 'parna,' it is recommended that its usage be minimised or stopped altogether. It is suggested that all such materials be reported using a description which more accurately reflects the composition and origin of the material (e.g. clayey loess).

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