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Late Quaternary eolian dust in surficial deposits of a Colorado Plateau grassland: Controls on distribution and ecologic effects

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Abstract

In a semi-arid, upland setting on the Colorado Plateau that is underlain by nutrient-poor Paleozoic eolian sandstone, alternating episodes of dune activity and soil formation during the late Pleistocene and Holocene have produced dominantly sandy deposits that support grass and shrub communities. These deposits also contain eolian dust, especially in paleosols. Eolian dust in these deposits is indicated by several mineralogic and chemical disparities with local bedrock, but it is most readily shown by the abundance of titaniferous magnetite in the sandy deposits that is absent in local bedrock. Magnetite and some potential plant nutrients (especially, P, K, Na, Mn, and Zn) covary positively with depth (3–4 m) in dune-crest and dune-swale settings. Magnetite abundance also correlates strongly and positively with abundances of other elements (e.g., Ti, Li, As, Th, La, and Sc) that are geochemically stable in these environments. Soil-property variations with depth can be ascribed to three primary factors: (1) shifts in local geomorphic setting; (2) accumulation of relatively high amounts of atmospheric mineral dust inputs during periods of land-surface stability; and (3) variations in dust flux and composition that are likely related to changes in dust-source regions. Shifts in geomorphic setting are revealed by large variations in soil texture and are also expressed by changes in soil chemical and magnetic properties. Variable dust inputs are indicated by both changes in dust flux and changes in relations among magnetic, chemical, and textural properties. The largest of these changes is found in sediment that spans late Pleistocene to early Holocene time. Increased dust inputs to the central Colorado Plateau during this period may have been related to desiccation and shrinkage of large lakes from about 12 to 8 ka in western North America that exposed vast surfaces capable of emitting dust. Soil properties that result from variable dust accumulation and redistribution in these surficial deposits during the late Quaternary are important to modern ecosystem dynamics because some plants today utilize nutrients deposited as long ago as about 12–15 ky and because variations in fine-grained (silt) sediment, including eolian dust, influence soil-moisture capacity.
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1. Introduction

The inputs of rock-derived nutrients to ecosystems, along with pedogenic and geomorphic processes that distribute nutrients on landscapes, are fundamental aspects of ecosystem dynamics. This paper describes compositional features of late Quaternary surficial deposits (including modern and buried soils) in a semi-arid grassland on the central Colorado Plateau, southwestern United States (Fig. 1). The current work builds on an earlier study of the geomorphic evolution of upland settings of the region (Reheis et al., 2005) and on investigations of certain physical and chemical properties of shallow (generally the upper 50 cm) substrates (Reynolds et al., 2001a; Neff et al., 2005; Reynolds et al., 2006). These investigations recognized the presence of eolian dust in soils of this study area and its importance in contributing a large proportion of the nutrients at these shallow depths. The central aims of the current study are to (1) characterize textural, mineralogical, and chemical properties that might indicate dust and nutrient

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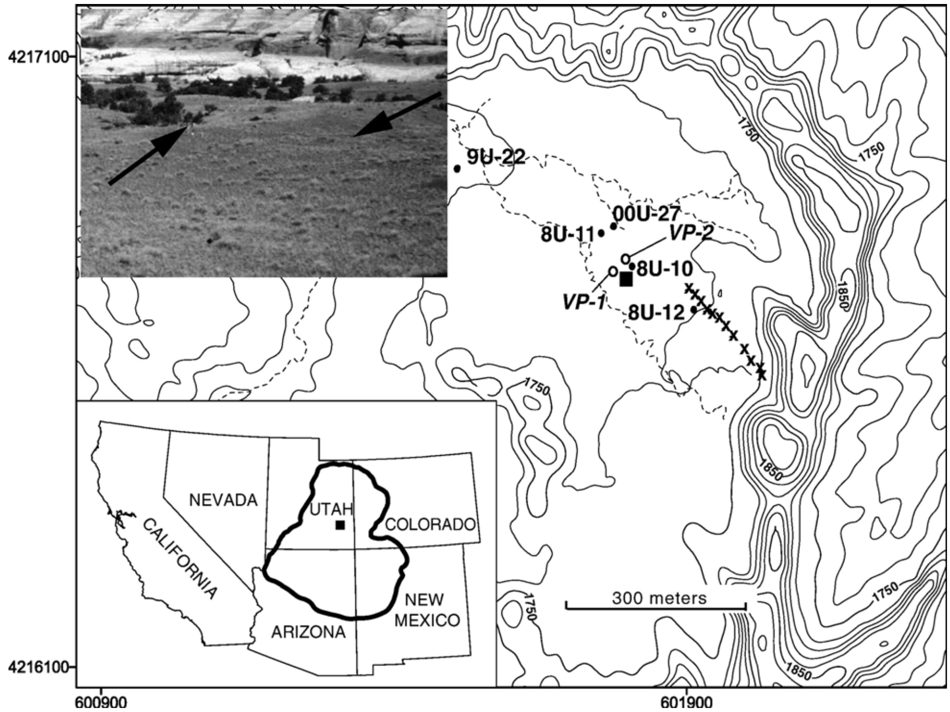

Fig. 1. Topographic map (20-m contour intervals) of the study site showing locations of auger holes (closed circles), soil pits (open circles), sampling sites for transect (×; 0 to 10-cm depths), and dust collector (solid square; 38.094568°N; 109.839124°W). Dashed lines denote ephemeral drainages. Map is based on contoured 30-m DEM grid (Druid Arch 7½′quadrangle) supplemented by 102 GPS control points calculated with differential correction. Universal Transverse Mercator (UTM, Zone 12N) northing and easting in meters. Horizontal datum is NAD 27. Inset photograph shows locations of dust-collector site (arrow on left side) on the crest of a vegetated, stabilized dune and hole 00U-27 (right-hand arrow) in a dune swale, in a view northwestward across the study area. Inset map shows location of the study area (square) within the Colorado Plateau (thick line).

contents of deeper substrates, (2) determine the causes for variations in these properties that are presumed to elucidate changing conditions of landscape stability in the study area as well as, perhaps, environmental change in dust-source areas; and (3) assess the potential ecologic importance of these variations.

The biogeochemical importance of dust in diverse terrestrial ecosystems is gaining increased recognition. Dust may contribute to fertility in highly weathered tropical settings (Swap et al., 1992; Chadwick et al., 1999; Vitousek et al., 2003) and in dryland settings (Capo and Chadwick, 1999; Neff et al., 2005; Reynolds et al., 2006). For drylands having typically low bedrock weathering rates, the biogeochemical importance of dust may depend strongly on the initial nutrient status of local bedrock, with increasing importance of imported dust likely associated with decreasing nutrient contents of bedrock (Reynolds et al., 2006).

In this study, we examine a rare setting that has never been grazed by domestic livestock (Kleiner and Harper, 1972; Belnap and Phillips, 2001). This condition enables us to evaluate changes in soil properties in the absence of disturbance that may greatly affect near-surface properties in this environment. Recent investigations of nearby sites have documented strong effects of grazing on mineralogic, chemical, and textural attributes of near-surface soil and surficial deposits (Neff et al., 2005; Reynolds et al., 2006). Although we present results from a limited area underlain by only one geologic rock unit (the Lower Permian Cedar Mesa Sandstone), the interpretations apply to a vast area, because the Cedar Mesa and similar nutrient-poor rocks underlie large areas of the Colorado Plateau (McKee, 1979). Determining the distribution of eolian dust in this and other dryland settings contributes to our understanding of the co-evolution of landscapes and ecosystems, and it elucidates how past geologic processes might influence contemporary ecosystem dynamics, depending on the depths of modern roots and numerous factors that control nutrient and water uptake (McDonald et al., 1996; McFadden et al., 1998; Miller et al., in press).

2. Setting, study site, and sampling

The study area is in the Needles district of Canyonlands National Park in the central part of the Canyonlands physiographic section of the Colorado Plateau (Hunt, 1956) (Fig. 1). The Canyonlands region is near the boundary between winter-dominant and summer-dominant precipitation, and it supports broad areas of high-elevation (~1500 to 1900 m), cold-desert grassland and shrubland between deeply incised canyons. Annual precipitation near the study area has averaged about 21 cm between 1980 and 2005 (http://www.wrcc.dri.edu/summary/climsmut.html). Much of the vegetated landscape in the Needles area consists of aprons of sandy surficial deposits that slope gently away from exposures of Cedar Mesa Sandstone. The Cedar Mesa consists dominantly of white eolian quartzose sandstone and interbedded red, arkosic beds (redbeds) of sandstone and silty sandstone (Condon, 1997). Fine-grained hematite, occurring primarily as translucent rims on silicate grains, colors the redbeds and commonly imparts light reddish hues to sandy surficial deposits derived from the Cedar Mesa Sandstone.

This report describes an investigation of surficial sediment in Virginia Park, a sheltered basin (∼200 ha at 1720 m asl) containing vegetated, stabilized sand sheets and a few linear dunes surrounded on three sides by sandstone walls and bounded on the southwest by a canyon (Fig. 1). Most of the study area is characterized by mixed plant communities of shrubs (mainly *Ephedra viridis* and *Atriplex canescens*) and native perennial bunchgrass (*Stipa comata*, *Stipa hymenoides*, and *Hilaria jamesii*), with cover by non-native cheatgrass (*Bromus tectorum*) generally higher in *Hilaria* communities. The spaces among plants are occupied by mature associations of biologic soil crust (BSC), mainly cyanobacteria, lichens, and mosses (see Belnap and Lange, 2003).

Reheis et al. (2005) described the late Quaternary geomorphic development of the site on the basis of physical properties and optically stimulated luminescence age (OSL) determinations of surficial deposits from auger holes, hand-dug soil pits, and arroyo exposures. Multiple sequences of locally derived sand are separated by poorly to moderately developed soils (Bk/C to Btk/C, respectively). Maximum thickness and age of the deposits are unknown. Nevertheless, sampling and modern relief between dune crests and swales suggests at least 10 m of accumulated sediment in the central basin, becoming thinner on flat bedrock exposures at some margins. The oldest documented eolian sand, which was sampled at a depth of 1.6 m in an arroyo cut remote from auger holes, gave an OSL age of ∼46 ka. This sand and its associated paleosol are likely equivalent to one of two deeper paleosols and related sand units encountered in the auger holes (Reheis et al., 2005).

The uppermost 40–50 cm of the basin fill consists of a sand layer, in which a weakly developed soil is forming. The modern soil is welded with a more developed paleosol represented by a sharp increase downward in both silt and clay (Reheis et al., 2005). Each auger hole penetrated a second buried soil at a depth of ∼1.3 to 1.8 m that is typically thinner and less developed than the upper paleosol. Auger hole 9U-22 encountered another weakly developed paleosol at depths of 2.8–3.2 m. The degree of pedogenesis in each paleosol likely represents at least a few thousand years of surface stability that was interrupted by renewed sand activity (Reheis et al., 2005).

OSL dating of coarse-grained quartz (Reheis et al., 2005) from a soil pit near a dune crest (VP-1, close to hole 8U-11) provided ages of 8.6 ± 0.3 ka for the upper thin sand and 13.8 ± 0.4 ka for the first buried sand. Ages of 4.2 ± 0.2 ka for the upper thin sand and 7.7 ± 0.2 ka for the first buried sand were determined at a nearby dune swale site about 40 m down slope (VP-2, near hole 8U-10). Reheis et al. (2005) considered possible explanations for these results, suggesting that the younger ages in the swale site reflect transport and concentration of fines from topographically higher dune crests into adjacent swales by wind eddying and sheetwash. Surfaces at Virginia Park are stable today with no evidence for significant wind-driven redistribution of sediment, on the basis of (1) dense BSC cover, (2) near-absence of mobile sand, and (3) wind-erosion monitoring there since 1998 (Reynolds et al., 2003a).

Prior investigations recognized the presence of atmospheric dust in sandy surficial deposits, in both the region (Reynolds et al., 2001a) and Virginia Park (Reynolds et al., 2006). Dust in these deposits is indicated primarily by the presence of titanium-bearing magnetite grains, identified on the basis of measurements of isothermal remanent magnetization (IRM) combined with petrographic observations. The sedimentary bedrock of the region and the study site (Huntoon et al., 1982; Billingsley et al., 2002) lack such magnetite (Reynolds et al., 2001a). The presence of B horizons in sandy eolian deposits elsewhere have been attributed to eolian dust inputs (Yaalon and Ganor, 1973).

At Virginia Park, the uppermost sediment (0–10 cm) in the sandy surficial deposits, derived primarily from sandstone bedrock, typically contains 5–40% fines (silt plus clay), depending on geomorphic setting and slope (excluding drainages and depressions). These large variations in texture as well as in some mineralogic and chemical properties across the study site are primarily related to geomorphic setting. As an expected example, coarser grained sediments (more sand) characterize the crests of vegetated, stabilized dunes compared with swales between dune crests (Reheis et al., 2005). As another example, atmospheric dust in the surficial deposits increases systematically (ranging from 2% to 18% of the surface soil mass) down a low-gradient slope from a bedrock headwall into the middle of Virginia Park (Reynolds et al., 2006; transect sites in Fig. 1). This trend in dust concentration parallels the down-slope increases in total fines (18–39% of surface soil mass), in most potential nutrient elements, and in chemically immobile elements, such as titanium (Reynolds et al., 2006). A combination of winnowing by wind and down-slope sediment transport in runoff likely accounts for the near-surface distribution of eolian dust and locally derived fines, a trend also observed in previous research in eolian landscapes (e.g., Yair, 1990) noted later in this paper. Eolian dust has ecologic importance for this setting, contributing roughly 40–80% of the rock-derived potential nutrient stocks in the upper 10 cm of soil over most of the sampled slope (Reynolds et al., 2006).

For the current study, we analyzed samples from auger holes described by Reheis et al. (2005) and Goldstein et al. (2005). The auger holes were 2.5–4.0 m deep and were sampled approximately every 10–20 cm. Three auger holes

(8U-11, -12; 9U-22) were located on the crests of three separate linear dunes, and two auger holes (8U-10 and 00U-27) were placed about 60 m apart in the same dune swale that is associated with the dune-crest setting at hole 8U-11 (Fig. 1). Magnetic, textural, chemical, mineralogic, and age data from all sites and samples discussed in this paper have been tabulated by Goldstein et al. (2005).

3. Laboratory methods

3.1. Magnetic methods

Information on the abundance of magnetic minerals, as well as on magnetic grain size of magnetite (magnetic domain state), in this surficial setting is provided by magnetic-property measurements (Reynolds et al., 2006; see also Thompson and Oldfield, 1986). Concentration of magnetite was determined using isothermal remanent magnetization acquired at 0.3 Tesla (T) ($IRM_{0.3\ T}$). Concentration of hematite was calculated as $(IRM_{1.2\ T} - IRM_{0.3\ T})/2$, referred to as hard IRM (HIRM) (King and Channel, 1991). The ratio, $IRM_{0.3\ T}/IRM_{1.2\ T}$, called the S parameter, is a measure of the relative proportion of magnetite to all Fe oxides, including hematite. High S values indicate large amounts of magnetite relative to hematite (a maximum value of 1), and decreasing values indicate increasing amounts of hematite. Information about the origins of magnetic minerals may be found in their magnetic grain size, which reflects magnetic domain structure and not necessarily particle size of magnetic grains. Frequency-dependent magnetic susceptibility (FDMS) was determined to test for the presence of ultrafine (<30 nm) superparamagnetic magnetite or maghemite grains, which may form under pedogenic conditions (e.g., Dearing et al., 1996).

The identification of magnetic minerals was confirmed using reflected-light microscopy. In this way, reliable identification of different Fe–Ti oxide minerals can be made on grains larger than about 3 μm, and the presence of iron oxide can be discerned from grains as small as about 1 μm. The grains were prepared in polished grain mounts after they had been isolated from the bulk sediment in a pumped-slurry magnetic separator described by Reynolds et al. (2001b).

3.2. Chemical and sedimentologic methods

Major, minor, and trace elements were determined using inductively coupled plasma-atomic emission spectroscopy (ICP-AES; Lichte et al., 1987) analyses on bulk samples, yielding detectable values for 27 elements. Elemental concentrations are useful for interpretations about the origins of the surficial sediments, on the basis of contrasts with associated bedrock, and their possible modification by post-depositional chemical reactions.

Particle size was determined as volume percentage using a laser-light scattering method capable of measuring particles between 0.05 and 3480 μm. Prior to analysis, all samples were prepared by digesting organic matter and $CaCO_3$ using 30% H_2O_2 and 15% HCl, respectively, and were disaggregated in a Na-hexametaphosphate solution. Concentration of calcium carbonate (calcite) percent was measured using a Chittick apparatus (Machette, 1986) involving acidification of a sample in 6 N HCl and measurement of the volume of liquid displaced by evolved gas.

4. Results

Textural, magnetic, and chemical results indicate changes in depositional settings at most sample sites during late Pleistocene and Holocene development of the landscape. The results also suggest that dust amounts and compositions have changed several times during basin filling. The following sections emphasize results that bear on the distribution of eolian dust in the different landscape settings. The dune-swale setting contains a more thorough record of Holocene and late Pleistocene dust input and redeposition than do dune-crest or sand-sheet settings, because this relatively low-energy environment has accumulated a thicker deposit of finer-grained sediment.

4.1. Results from dune-swale settings

The sediments underlying a modern dune swale contain broadly similar patterns of variation in texture, magnetic properties, and chemistry (Figs. 2 and 3). For example, silt (4–63 μm) content generally increases upward to the youngest paleosol; these increases track gradual decreases in sand content (not shown). Silt is enriched in both paleosols relative to the dune and sand-sheet parent material, with much greater enrichment in the upper paleosol.

Magnetite abundance (IRM) corresponds closely with silt content and is highest in the upper paleosol (Figs. 2–5). Hematite abundance (HIRM) shows a similar pattern but remains high above the upper paleosol (Figs. 2 and 3). The high concentration of magnetite in the upper paleosol corresponds to increases in magnetite content relative to hematite as indicated by increasing values of S parameter (Figs. 2 and 3). The lowest paleosols in swale holes 8U-10 and 00U-27 are more poorly developed than younger ones, as noted by Reheis et al. (2005), and they show only slight enrichments in silt, magnetite, and hematite relative to surrounding sediment.

Many chemical properties in the swale setting vary closely with magnetite and hematite abundance. For example, the depth profile of titanium, which is strongly

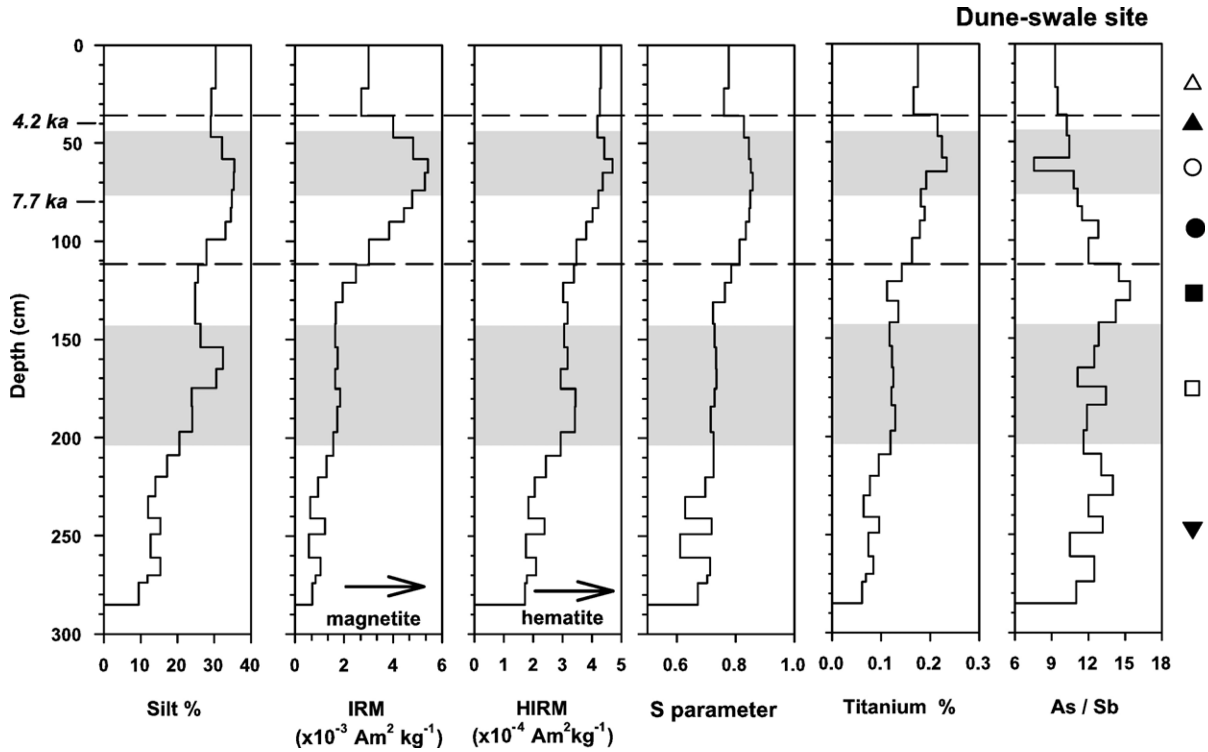

Fig. 2. Depth plots of some physical and chemical properties from a dune-swale site, auger hole 8U-10. IRM, isothermal remanent magnetization; HIRM, hard IRM (see text for explanations for magnetic properties, including the *S* parameter). Shaded areas denote paleosols. Different markers are adjacent to their corresponding depth intervals. For example, the inverted triangle denotes all samples below the lower paleosol. Dashed lines separate non-paleosol intervals that are indicated by different markers. OSL dates from adjacent soil pit (VP-2; Fig. 1) are shown on depth axis (4.2 ka at 40 cm depth and 7.7 ka at 80 cm depth; see text for details).

associated with rock-derived magnetite, is closely similar to that of IRM in swale hole 8U-10 (Fig. 2). Nearly all analyzed elements show similar correspondence to IRM and silt abundance (data in Goldstein et al., 2005), as illustrated in plots of IRM against Ti, Fe, Na, K, Zn, and Mn, as examples (Fig. 6).

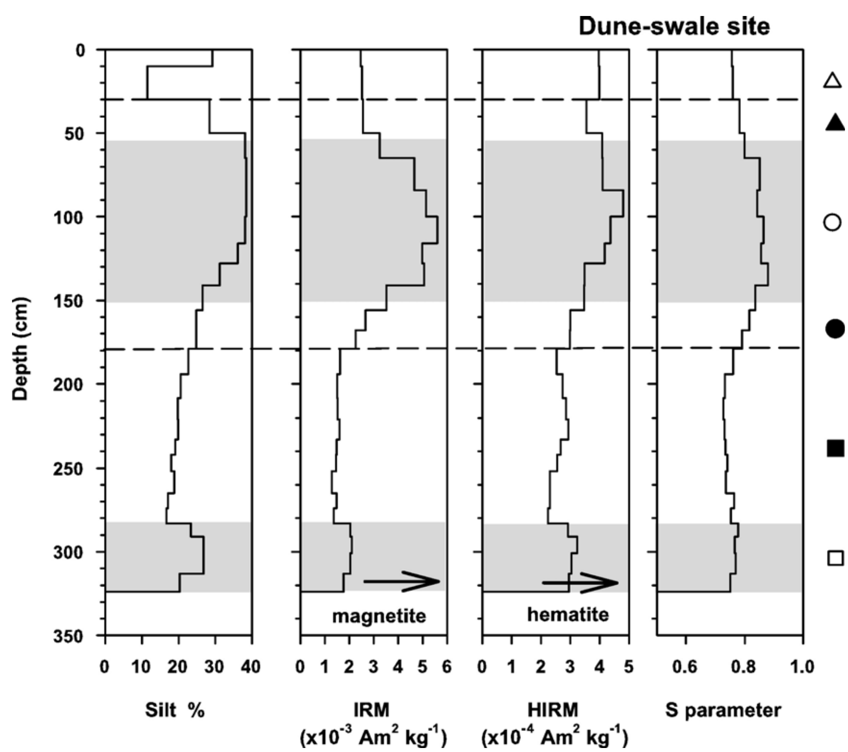

Fig. 3. Depth plots of some physical properties from a dune-swale site, auger hole 00U-27. Axis labels, shading, and lines as in Fig. 2.

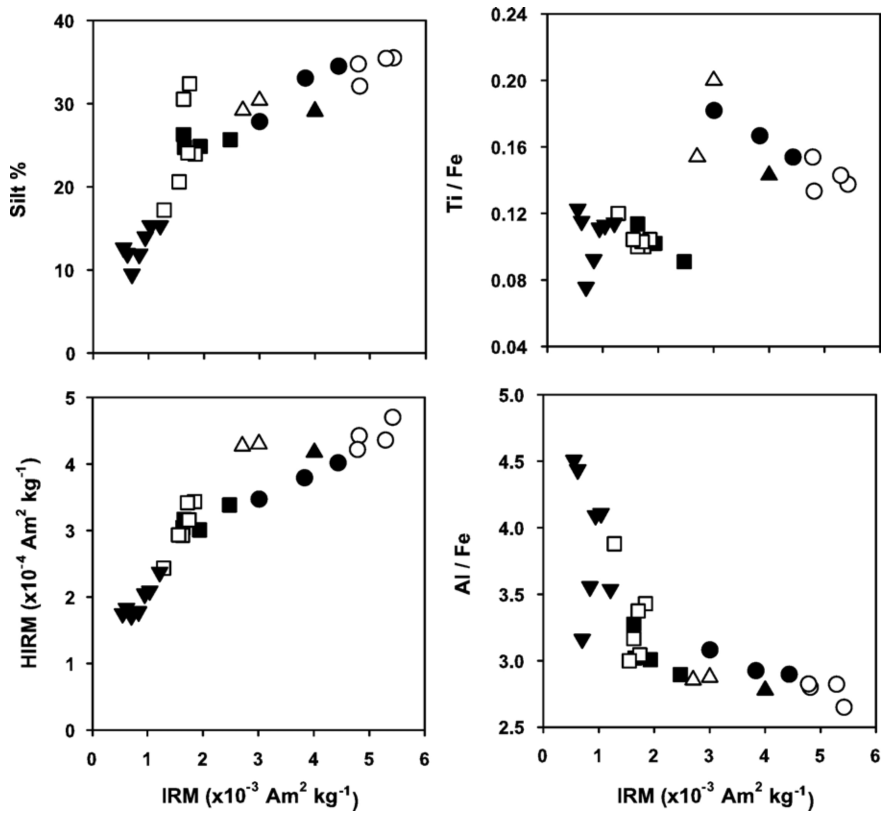

Fig. 4. Isothermal remanent magnetization (IRM) plotted against silt, hard IRM (HIRM), and values of Ti/Fe and Al/Fe, in dune-swale hole 8U-10. Symbols as indicated for depth intervals in Fig. 2.

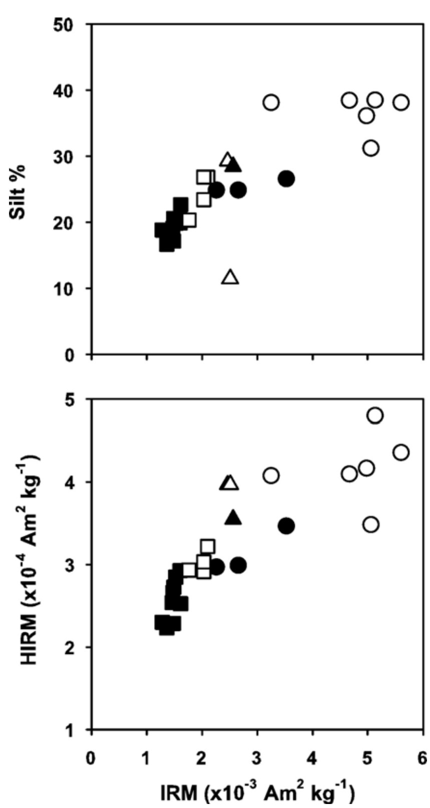

Fig. 5. Isothermal remanent magnetization (IRM) plotted against silt and hard IRM (HIRM) for dune-swale hole 00U-27. Symbols as indicated for depth intervals in Fig. 3.

4.2. Results from dune-crest settings

The textural and magnetic properties of sediments sampled in dune-crest holes (holes 8U-11, 8U-12, and 9U-22; Fig. 1) show some similarities but also differences among holes (Figs. 7–9) and in comparison with dune-swale holes. As an example, amounts of magnetite and silt correspond in crest holes 8U-11 and 9U-22 (Fig. 10), although not as closely as in the dune-swale holes (Figs. 4 and 5). These relations are seen also for magnetite and titanium and many other elements in sediment above the lower paleosol in crest hole 8U-11 (Fig. 11). Deeper sediment shows little variation in physical and chemical properties. In textural and magnetic patterns, most of the upper 2 m of crest hole 9U-22 resemble the dune-swale holes; silt content increases upward (~ 12% to 55%) into the youngest paleosol (Fig. 9), mirroring systematic decreases in sand content (Goldstein et al., 2005). High sand abundance at the top of crest hole 9U-22 may reflect recent stabilization of this dune-crest setting. In crest holes 8U-11 and 9U-22, magnetite amounts decrease in the zone of increasing silt directly above the upper paleosol (Figs. 7 and 9). This relation suggests that a large proportion of silt in this zone is derived from bedrock that surrounds the study area. The deepest paleosol in crest hole 9U-22 is not strongly expressed from laboratory results on texture and magnetic mineralogy.

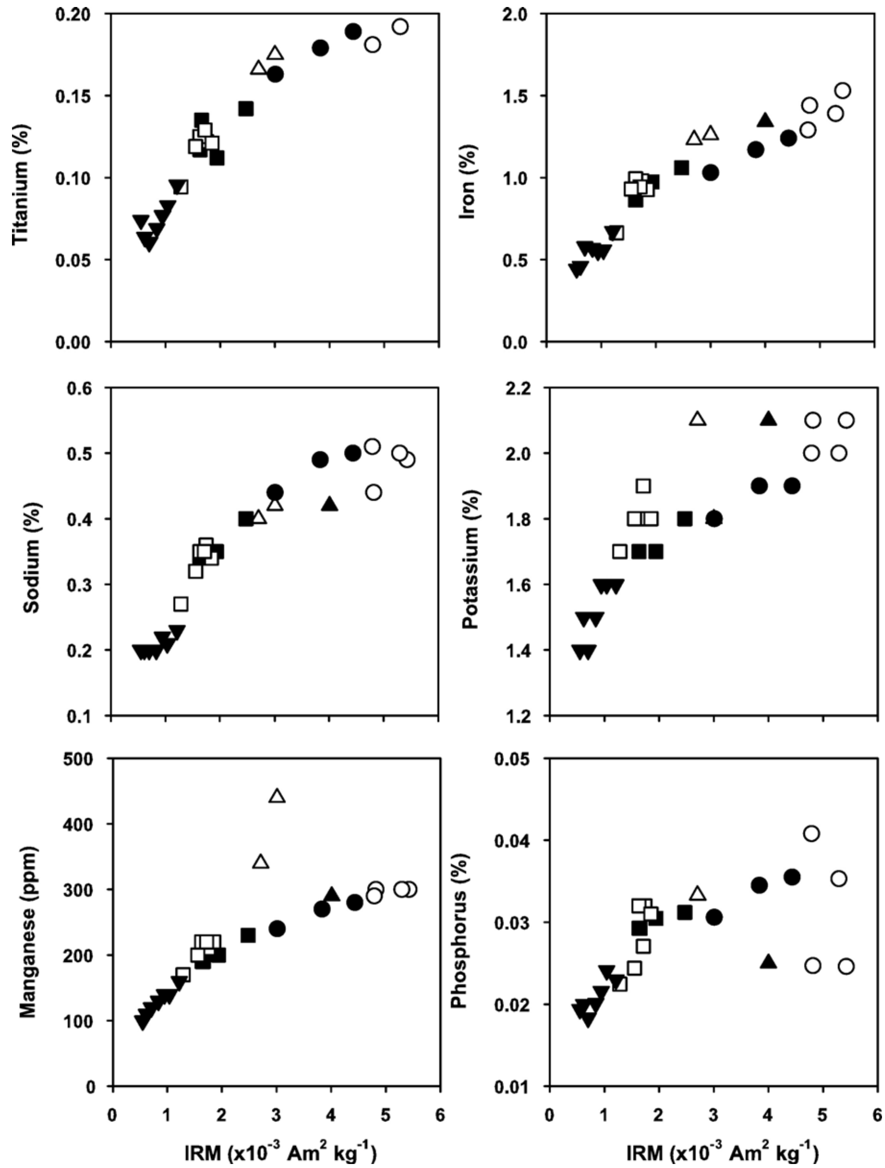

Fig. 6. Isothermal remanent magnetization (IRM) plotted against selected elements for dune-swale hole 8U-10. Symbols as indicated for depth intervals in Fig. 2.

4.3. Petrographic observations

Petrographic examination reveals that surficial deposits in Virginia Park contain magnetite particles in many different forms and associated with a variety of other Fe–Ti oxide minerals. Very small (<10 μm), angular particles of magnetite and titanomagnetite are the most abundant component of magnetic-mineral separates. Some larger (20–50 μm) magnetite and titanomagnetite particles vary sporadically in amount with depth. Magnetite shows no evidence of dissolution, such as preferential removal of magnetite and consequent concentration of residual titanium dioxide (see Rosenbaum et al., 1996), or other pervasive or common low-temperature alteration processes. The surrounding Cedar Mesa Sandstone lacks magnetite, except for very rare inclusions of magnetite in detrital quartz grains (Reynolds et al., 2006).

5. Discussion

5.1. Evidence for mineral dust inputs during the late Quaternary

Magnetic, textural, chemical, and petrographic results indicate that the late Quaternary surficial deposits of Virginia Park comprise both locally derived sand from the Cedar Mesa Sandstone and atmospheric mineral dust. Evidence for eolian dust includes the presence of magnetite particles having a variety of compositions and mineral associations and the absence of such particles in the

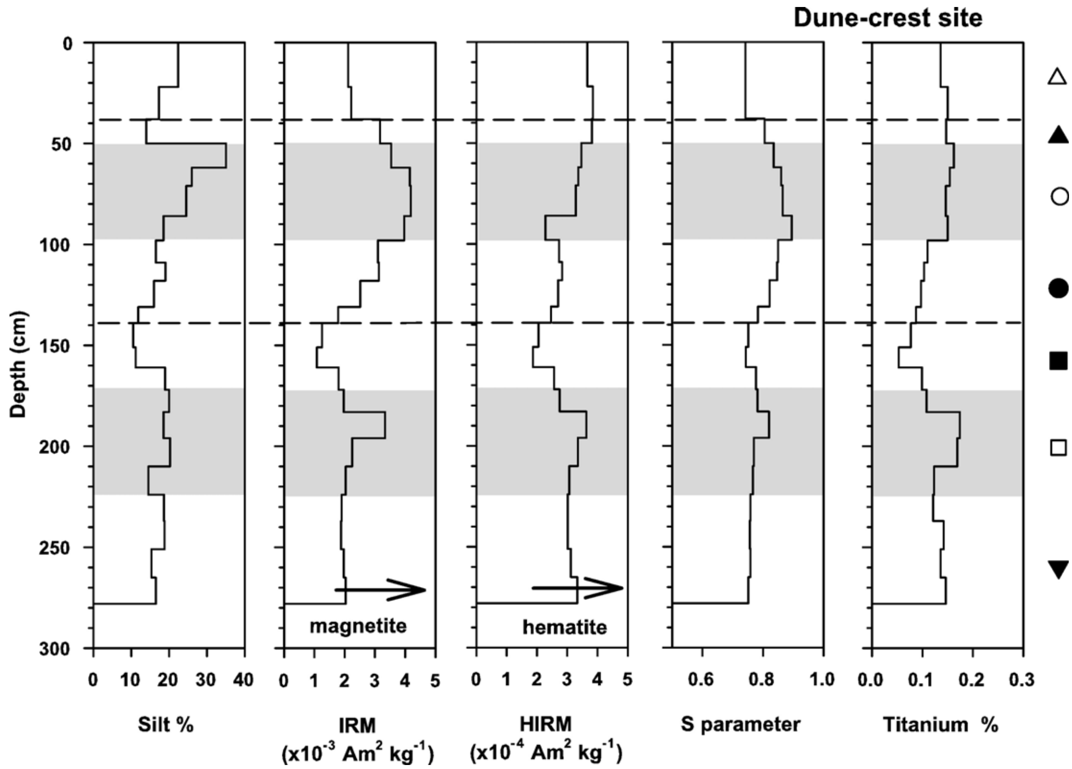

Fig. 7. Depth plots of some physical and chemical properties from dune-crest hole 8U-11. Axis labels, shading, and lines as in Fig. 2.

surrounding sandstone that contributes most sediment to the small basin. These sediment sources were earlier recognized across Virginia Park in shallow (0–10 cm depth) sediment, in which dust abundance could be estimated from magnetite concentrations (Reynolds et al., 2006). The results of the current study show that magnetite concentration (IRM

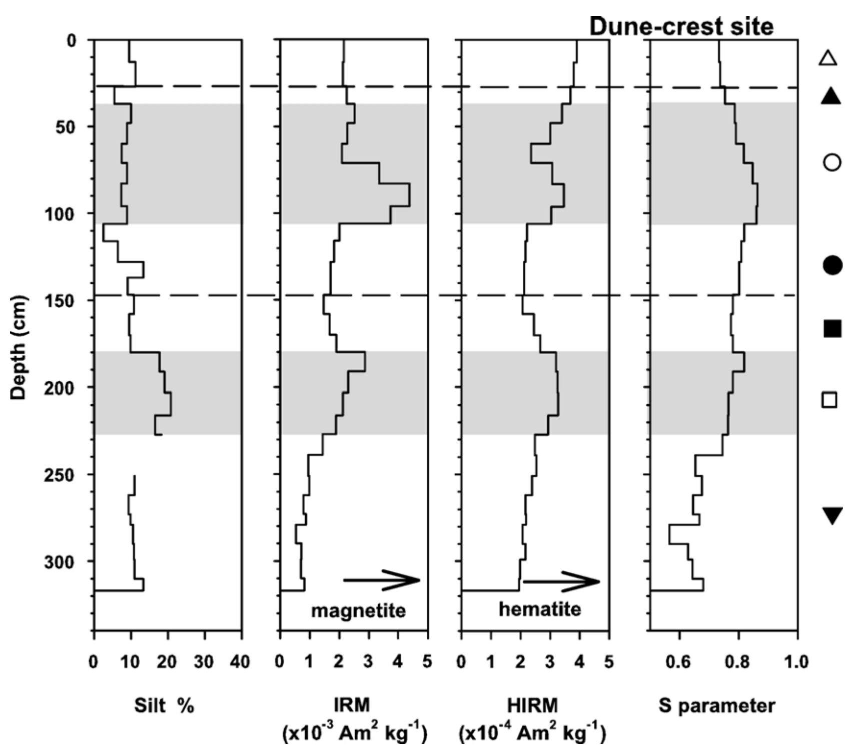

Fig. 8. Depth plots of some physical properties from dune-crest hole 8U-12. Axis labels, shading, and lines as in Fig. 2.

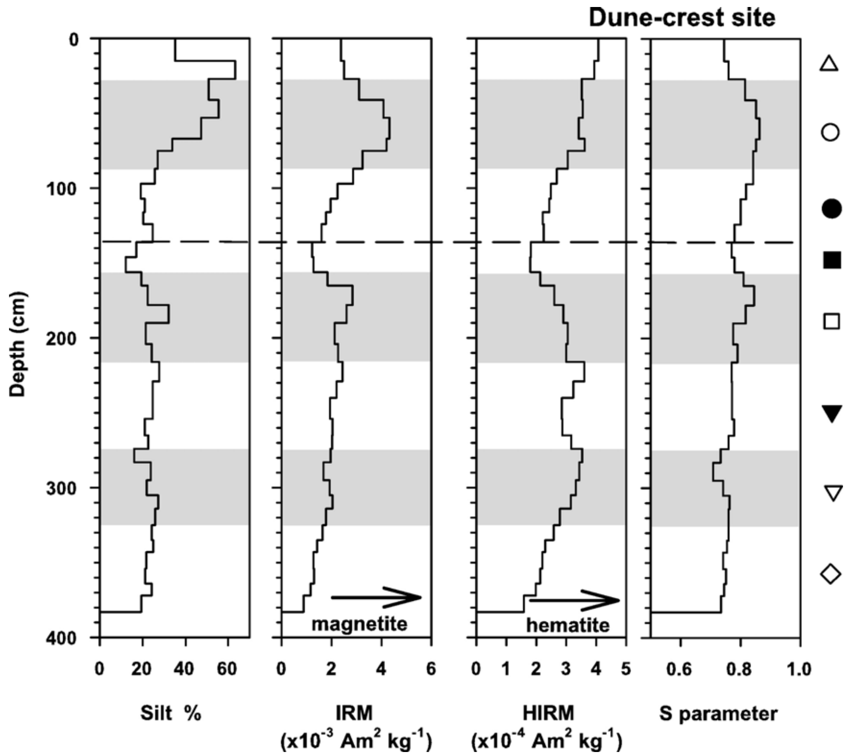

Fig. 9. Depth plots of some physical properties from dune-crest hole 9U-22. Axis labels, shading, and lines as in Fig. 2.

value) is a proxy for eolian dust in older, deeper deposits of Virginia Park, as it is in shallow sediment. Evidence for this conclusion stems from (1) high, positive correspondence of IRM to Ti and to other chemically immobile elements, and (2) the petrographic observations of magnetite and associated Fe–Ti oxide minerals.

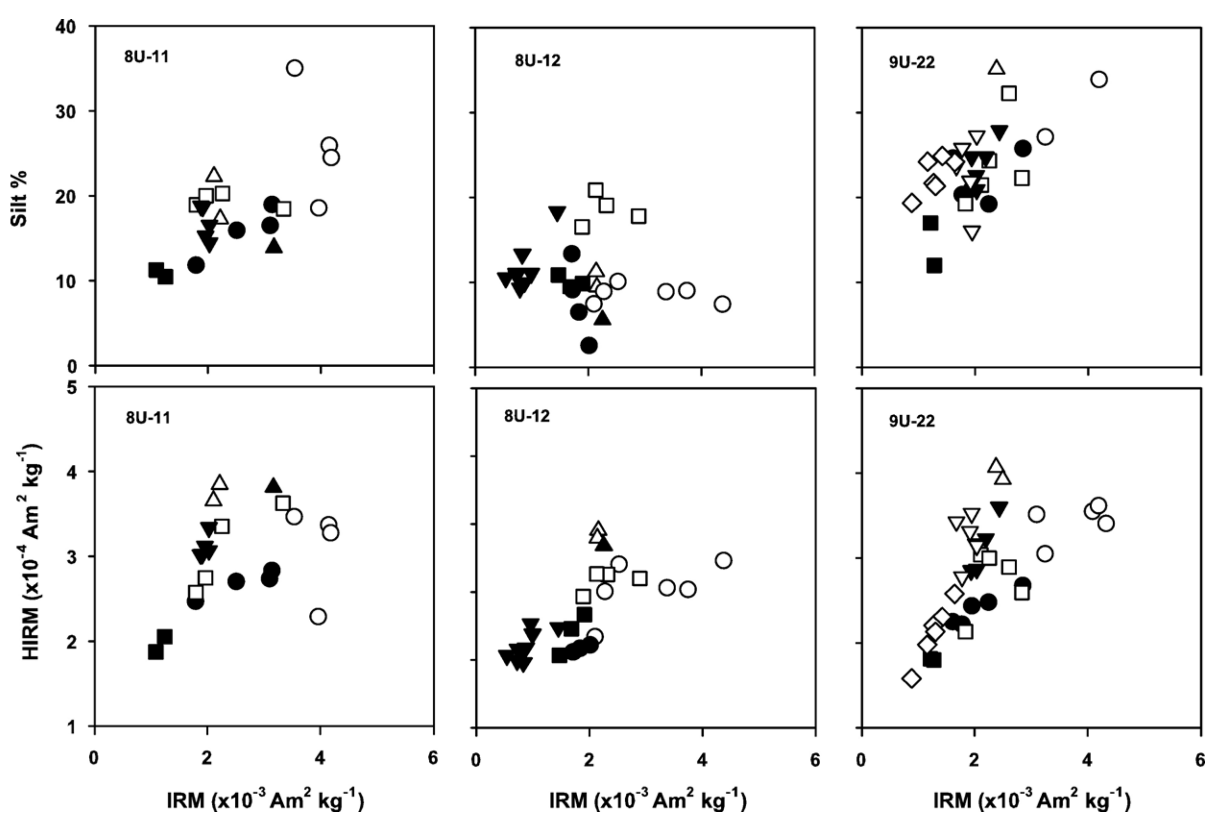

Fig. 10. Isothermal remanent magnetization (IRM) plotted against silt and hard IRM (HIRM) for dune-crest holes 8U-11, 8U-12, and 9U-22. Symbols as indicated for depth intervals in Fig. 7 for hole 8U-11, in Fig. 8 for hole 8U-12, and in Fig. 9 for hole 9U-22.

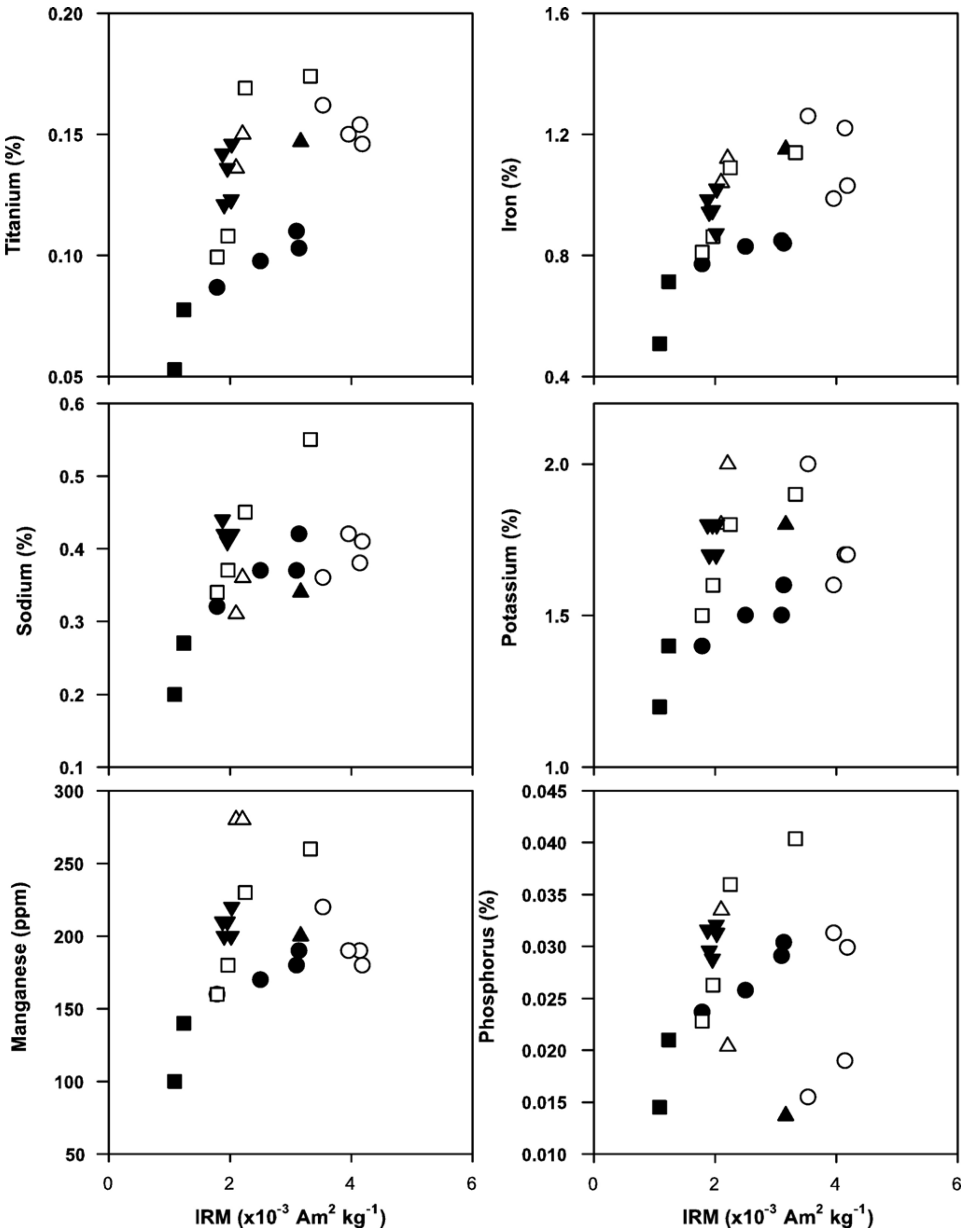

Fig. 11. Isothermal remanent magnetization (IRM) plotted against selected elements, dune-crest hole 8U-11. Symbols as indicated for depth intervals in Fig. 7.

5.2. Causes of variations in properties

We considered three principal causes for the observed spatial and temporal changes in physical and chemical properties, including dust content and soil-nutrient concentrations: (1) changes in the positions of landforms while surfaces were active; (2) enhanced accumulation of eolian dust on stable surfaces; and (3) variations in the amount and composition of dust.

First, changes in the position of geomorphic settings would have produced large textural changes, because each setting has a partly separate range of sediment transport and depositional energy (e.g., Bagnold, 1941, pp. 96–106, 189–191). Dune sediments are strongly sorted by winds, with resultant grain size-distributions that depend on numerous factors, including shear stress and source materials (see Lancaster, 1995, pp. 105–121; Lancaster et al., 2002). The overall effect, nevertheless, is to concentrate coarse particles and deplete the fine fraction (Bagnold, 1941, p. 98; Pye and Tsoar, 1990, pp. 66–68), some of it originally introduced as far-traveled dust, some of it from local bedrock sources, and some of it internally produced. Despite initially uniform dust fall across the landscape, the dune-swale setting (similar to, but much smaller than, dry, sandy interdune areas in dune fields) preferentially collects relatively fine sediment (e.g., Ahlbrandt, 1979). Such finer sediment may accumulate as a result of (1) retention of infiltrated dust in relatively more protected, low-energy sites between dune crests, (2) more efficient trapping of fines by denser vegetation in the swales, and (3) perhaps by runoff moving fines over surfaces covered by biologic soil crust (Yair, 1990; Verrecchia et al., 1995; Kidron and Yair, 1997; Shachak and Lovett, 1998). Spatial shifts in geomorphic setting at any one place through time likely would have had dominant control on the upward change in texture and related properties as the small depositional basin filled. For example, large variations in sediment properties in dune-crest hole 9U-22 are consistent with a recent (late Holocene?) shift from a silt-rich setting near the edge of the basin to the modern dune-crest environment. As another example, the overall increase in silt in the swale holes (8U-10 and 00U-27) may partly reflect a change from a dominantly sand-sheet setting to the modern dune-swale setting. Such changes in depositional settings might be expressed by differences in internal sedimentary structures, but this possibility could not be addressed by examination of the disaggregated auger-hole samples.

Differences in wind energies and resultant degrees of sorting in different geomorphic settings may contribute to compositional variations with depth. In the dune-swale setting, magnetite is strongly correlated with silt and with the abundance of many elements. The poor or absent correspondence of magnetite and silt in dune-crest settings, in contrast, likely reflects different sorting behavior of materials of varying size and density in response to higher and (or) more variable winds associated with dunes.

Second, periods of landscape stability exposed surfaces to relatively greater inputs of eolian dust during soil formation, as sand movement diminished. We attribute the higher IRM values in paleosols to relatively higher amounts of eolian magnetite. Evidence for pedogenic development of highly magnetic Fe oxide minerals is lacking: FDMS values (a measure of pedogenic magnetite or maghemite) are very low (nearly all are less than 3%) and show no consistent relation to soils (Goldstein et al., 2005). Moreover, the observed abundance of large titaniferous magnetite particles in the paleosols is qualitatively sufficient to account for high IRM values. Increasing amounts of dust in younger sediments may be partly related to the time span of land-surface exposure. Holocene and late Pleistocene surfaces would have acquired more dust, relative to older surfaces, if stable for longer time spans under conditions of constant dust flux. The higher degree of pedogenesis in the youngest paleosol (Reheis et al., 2005) suggests a longer exposure of this soil surface compared with older soil surfaces and (or) a period of wetter climate.

A third possible cause for variations in sediment properties involves changes in dust inputs, including more or less dust from common sources or perhaps changes in sources. To test for the possibility of changes in dust flux, we analyzed chemical and textural data from dated deposits in the two soil pits. In this analysis, eolian inputs in paleosols were considered to be additions of silt, clay, calcite, and salt above the respective average amounts in adjacent sand units that were relatively unaffected by pedogenesis in soil pits in dune-crest (VP-1) and dune-swale (VP-2) settings (Table 1). In the dune-crest setting, dust flux during the late Pleistocene (21.8 g/m^2/year) is estimated to be higher than during the Holocene (16.5 g/m^2/year). In the dune-swale setting, dust flux during the early to middle Holocene (34.7 g/m^2/year) is estimated to be almost twice that of the late Holocene (19.3 g/m^2/year). In each set of comparisons, the rates of eolian additions in the past are much greater than the rate of modern dust fall at the study site (10.4 g/m^2/year; Reheis, 2003) (Table 1).

Changes in dust sources are suggested by shifts in mineralogic and chemical compositions that are clearly defined in dune-swale sediment. The most distinctive

Table 1
Comparison of calculated pedogenic accumulation rates and modern dust deposition rates in Virginia Park

Site and setting	Interval age (years)[a]	Silt additions			Clay additions			$CaCO_3$ additions			Salt additions			Total additions		
		Ped[b]	SR[c]	DR[d]	Ped[b]	SR[c]	DR[d]	Ped[b]	SR[c]	DR[d]	Ped[b]	SR[c]	DR[d]	Ped[b]	SR[c]	DR[d]
VP-1																
Dune-crest surface soil	8600	9.0	10.5	7.4	2.7	3.1	2.0	2.3	2.7	0.8	0.1	0.2	1.0	14.2	16.5	10.4
Dune-crest buried soil	5200	6.5	12.5	7.4	1.5	2.9	2.0	3.2	6.2	0.8	0.1	0.1	1.0	11.3	21.8	10.4
VP-2																
Dune-swale surface soil	4200	3.8	9.0	7.4	2.4	5.7	2.0	1.8	4.3	0.8	0.2	0.4	1.0	8.1	19.3	10.4
Dune-swale buried soil	3500	3.7	10.6	7.4	4.2	12.1	2.0	4.1	11.8	0.8	0.1	0.2	1.0	12.2	34.7	10.4

[a] Approximate time span that soil was exposed at surface. For example, in VP-1 the surface soil is equal to OSL1 (8.6 ka) and the first buried soil is equal to OSL2 − OSL1 = 13.8 − 8.6 ka = 5.2 ky.

[b] Ped, pedogenic in (g/cm^2/soil column). Profile weights (g/cm^2/soil column) were calculated as follows: Weight percentages of silt, clay, $CaCO_3$, and soluble salt in each horizon of a soil are multiplied by the bulk density of the less-than-2 mm fraction and by horizon thickness. These amounts are then subtracted from amounts estimated to have been present in the parent material (method of Machette, 1986), and the net values are summed for the soil profile. Bulk density for each soil horizon was estimated from particle size and organic matter content using techniques of Rawls (1983). Parent material values were assumed to be the same as the least altered eolian sand in auger holes in the study area, and varied with landscape setting: sediment deposited in dune swales was assumed to contain more silt and less sand than sediment on dune crests.

[c] SR, soil rate in (g/m^2/year).

[d] DR, dust rate in (g/m^2/year). Values are average rates from 1998 to 2003 at dust trap site in Virginia Park. Dust silt and clay values include $CaCO_3$ fraction, and, thus, total dust addition is the sum of silt, clay, and salt contents.

changes occur between 1.5 and 1 m depth, corresponding to about 15–10 ka. Dust deposited after this time is enriched in magnetite relative to older dust, as indicated by the sharp change in slope in the plot of IRM against silt in Figs. 4 and 5. Comparison of maximum IRM and silt values within the two paleosols in swale holes 8U-10 and 00U-27 to respective minimum values in the intervening sand unit shows that dust infiltrating the upper paleosol was more enriched in magnetite relative to silt in the lower paleosol. In swale hole 8U-10, magnetite increases by a factor of 3.3 and silt by 1.4, and in 00U-27 by 4.1 and 2.3, respectively. The lower paleosol in hole 8U-10 is enriched in magnetite by only 1.1× and silt by 1.3×. In the lower paleosol of hole 00U-27, magnetite is enriched by 1.5× and silt by 1.6×. Younger dust is also enriched in magnetite with respect to hematite compared with older dust as shown in depth plots of *S* parameter (Figs. 2 and 3) and in plots of IRM vs. HIRM (Figs. 4 and 5). Comparable relations are found between magnetite abundance and chemically immobile Ti, as well as some potential plant nutrients (Na, K, Mn, Fe, and Zn) (Fig. 6).

Further evidence for shifts in dust composition is indicated by changes in concentration-independent elemental ratios. Sediment above 120 cm in swale hole 8U-10 is characterized by relatively high amounts of magnetite and high Ti/Fe values, and sediment below 120 cm by low amounts of magnetite and low Ti/Fe values (Fig. 4). The two populations of samples provide direct support for changes in dust sources, because of the common relation of Ti with magnetite and the petrographic observations of titaniferous minerals in close association with many of the magnetite grains. Because As and Sb are also associated with Fe–Ti oxide minerals such as magnetite and ilmenite (Onishi and Sandell, 1955; Onishi, 1969a,b), values of As/Sb might reveal changes in dust sources for Fe–Ti oxide minerals. In swale hole 8U-10, As/Sb values remain nearly constant in sediment deeper than 120 cm (Fig. 2). Above this depth, however, As/Sb values decrease systematically. The two populations of As/Sb values (below and above 120 cm) are significantly different ($p<0.05$), suggesting different sources for the Fe–Ti oxides in these deposits. As another example, the plot of Al/Fe vs. IRM indicates systematically decreasing Al/Fe in the sediments as magnetite inputs increased (below 1.3-m depth) and nearly constant Al/Fe in younger sediment (Fig. 4). The changes in Al/Fe do not appear to reflect diagenetic or pedogenic alteration patterns, because relations among Fe, magnetite, and chemically immobile Ti (Fig. 6) do not indicate significant mobility of Fe and Al in this setting.

Sediment-property variations imply a later change in dust compositions that may also reflect changing dust sources. The upper 40–50 cm of sediment in the swale sites, corresponding to about the last 4–5 ky, is lower in amounts of magnetite, hematite, and many elements compared to sediment below (to depths of ~1 m) (Figs. 4–6). Amounts of hematite fall close to those of sediment that represent pre-15 ka accumulation (Figs. 4 and 5). This shift indicates increasing contributions from hematite-rich dust sources after about 4–5 ka, suggesting increasing contributions of dust from the Colorado Plateau, which hosts widespread hematite-bearing sedimentary rocks (redbeds).

5.3. Dust sources and their changing conditions

Little is known about the sources for dust now found in surficial deposits in this part of the Colorado Plateau. Modern dust sources include nearby surfaces, especially those that are periodically grazed by domestic livestock and that are acutely vulnerable to wind erosion during times of drought (Reynolds et al., 2003b). Some of the locally derived, modern dust emitted from the region surrounding the study site was originally introduced into the region as far-traveled dust (Neff et al., 2005). Other dust sources on the Colorado Plateau that periodically may affect our study area are known from back-trajectory analysis of air masses responsible for contemporary dust fall onto the San Juan Mountains in southwestern Colorado (T. Painter, 2004, personal communication) and from our direct observations. Dust sources from beyond the Colorado Plateau, such as the Mojave Desert, have been documented on the basis of satellite images (Chavez et al., 2002; Reynolds et al., 2003a). Dust from central China also falls on the Colorado Plateau (Husar et al., 2001), but these events are rare in modern times, and thus such sources likely have not contributed greatly to the surficial deposits.

The changes in dust flux during the late Pleistocene and early Holocene suggest that past dust-source areas were at times larger than modern sources or that wind erosion from some common sources could be periodically severe. Chemical results described above indicate that late Pleistocene and early Holocene dust deposited on the central Colorado Plateau differed from both older and younger dust and thereby imply that dust sources have changed over time. A possible explanation for larger dust-source areas during this time period involves the formation of dry lakes (playas) that resulted from desiccation of large pluvial lakes in western North America. The large lake basins filled and dried many times during Pleistocene time, filling mostly recently at times bracketing the Last Glacial Maximum (LGM, about 21 000 years BP). Inundated areas included large parts of the western Basin and Range Province (Lake Lahontan and many others), the Bonneville Basin (Lake Bonneville), and the Mojave Desert (the Owens–China–Searles–Panamint and the Manix–Mojave lakes systems) (e.g., Morrison, 1964; Currey and Oviatt, 1985; Thompson et al., 1986, 1990; Benson et al., 1990; Negrini, 2002). These lakes covered about 106 000 km^2 at their combined maximal extents. Although latitudinal climatic effects apparently led to different timing of high stands (ranging from about 24 000 to 15 000 years BP; see Enzel et al., 2003), major drying and contraction of some of these large lakes was underway between about 17 000 and 14 000 years

BP (Benson et al., 1990; Adams and Wesnousky, 1998; Enzel et al., 2003). The Bonneville basin experienced catastrophic draw down with the collapse of its natural sill at about 17 400 years BP (about 14 500 ^{14}C years; Currey and Burr, 1988), and its continued drying is attributed to regional aridification (Currey and Oviatt, 1985; Benson et al., 1990). Significant regional desiccation was widespread by about 9500 years BP. With respect to the current study, an important effect of lowered lake levels was to expose large areas of fine-grained sediment to the atmosphere (e.g., Morrison, 1991; Benson et al., 1992) and to potential wind deflation. Numerous studies have attributed increased dust accumulation and soil development on surfaces to increases in playa development in the region during Pleistocene-to-Holocene aridification (Wells et al., 1985; Machette, 1985; McFadden et al., 1986; Wells et al., 1987; Reheis et al., 1989; Chadwick and Davis, 1990; Reheis et al., 1995).

5.4. Influence of surficial deposits on modern ecosystem dynamics

The physical development of the landscape that resulted in strong subsurface variations in textural and chemical properties may influence modern ecosystem dynamics in several ways. First, geomorphic processes, periods of stability, and dust inputs have together produced variations in amounts of potential plant nutrients, within the rooting depths of many plant species (depths to ~1 m). On this basis alone, some plants today may be utilizing nutrients that have been introduced and distributed across a changing landscape over the past several thousands of years. The ecological importance of dust is underscored by observations that many essential plant nutrients are concentrated in the fine fraction of soil particles (Caravaca et al., 1999; Neff et al., 2005). We examined this possibility for our setting using P as an example. In swale hole 8U-10, dust inputs have increased P, as shown by generally corresponding increases in P and magnetite abundance (IRM values), which is a proxy for dust (Fig. 6). Both P and IRM in bulk soil at Virginia Park are much higher than P and IRM for the Cedar Mesa Sandstone in the region (Reynolds et al., 2006). As plants tap into subsurface paleosols in these environments, they may be able to access P concentrations enhanced by dust inputs. As a crude indicator of plant-available P, we determined water-soluble P in near-surface samples from Virginia Park and found that it was associated with magnetite abundance (IRM values in Fig. 12). Because magnetite represents dust in these surficial deposits, this result strongly suggests that dust has delivered at least some plant-available P to this ecosystem. Interestingly, similar subsurface nutrient reserves may provide an important source of essential nutrients to plants in disturbed soils at other settings where wind erosion has reduced soil nutrient contents within about 30 cm of the surface (e.g., Neff et al., 2005). Further work is needed to determine whether plants access nutrients from these deeper soil settings.

The subsurface distribution of particle sizes also influences modern ecologic processes with respect to water availability. Within only the upper meter in Virginia Park, silt contents vary from less than 10% to more than 60% depending on modern and past geomorphic settings in an overall sand-dominated substrate. Such variations translate into large landscape-scale differences in soil-moisture capacity, with consequences for water storage and availability during periods of drought. In mesic environments, finer textured soils generally hold higher amounts of water. In desert environments, however, sandy soils may actually contain more subsurface water compared with siltier substrates because of the inverse texture effect, in which dry sand at the surface contributes to trapping subsurface water (Noy-Meir, 1973). Although this overall effect of texture on water-holding capacity has been documented,

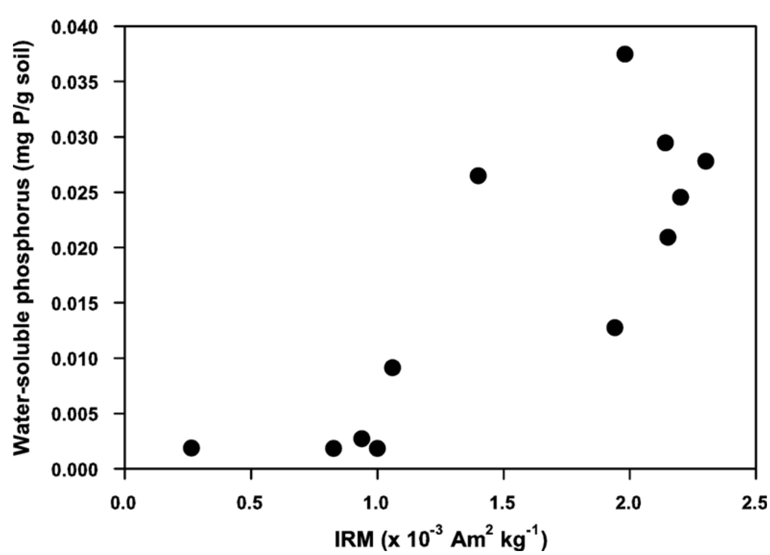

Fig. 12. Water-soluble phosphorus plotted against isothermal remanent magnetization (IRM; a proxy for dust) in shallow (0–10-cm depth) sediment collected from transect (Fig. 1) in the study area.

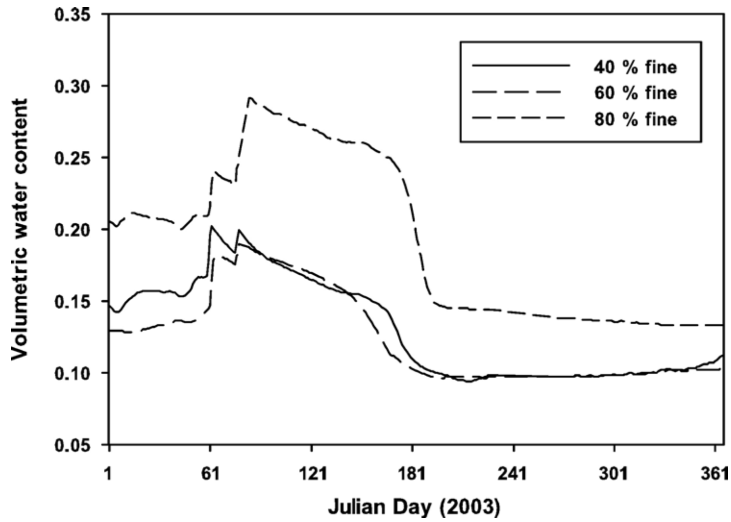

Fig. 13. Volumetric water content in 60-cm-deep soil layers of varying texture (fine=silt+clay fraction) in the study area near dune-crest hole 9U-22. The similarity between the 40% and 60% fine-fraction measurements results from higher subsurface water-holding content in coarse textured deserts soils (Noy-Meir, 1973).

much less is known about how vertical variation in texture, and specifically the presence of fine-textured paleosols, influences plant access to reserves of subsurface water. Given the strong influence of texture on water availability in this dryland setting (Fig. 13), the subsurface variation in soil texture is a potentially important control on available plant water and a topic that deserves further exploration.

6. Conclusions

In light of the importance of recently deposited atmospheric dust to the modern ecosystem of the study area, with respect to soil-nutrient load and texture at shallow depth (Neff et al., 2005; Reynolds et al., 2006), a primary objective of this study was to examine the distribution of older dust as revealed in the physical and chemical properties of the deeper substrate. The presence of older dust in this setting can be detected by measurement of eolian magnetite using isothermal remanent magnetization (IRM). This finding is based on (1) correlation of IRM to Ti (and other elements typically associated with magnetite, such as V); (2) petrographic observations of silt-sized particles of detrital (Ti)magnetite; and (3) the absence of magnetite in local bedrock.

Variations in dust abundance in Virginia Park substrates have been controlled partly by depositional energy in dominantly active sand-dune and sand-sheet settings, with higher amounts of dust accumulation in relatively low-energy dune-swale settings. Dust concentrations increase overall from bottom to top (including late Pleistocene and Holocene sediments) in dune-swale and dune-crest auger holes. Such increases may also be related to increased stability of late Pleistocene–Holocene land surfaces, which would have acquired and retained more dust relative to dynamic sand surfaces. Dust abundance is greatest in Holocene paleosols. Analysis of soil components suggests that increased dust flux further contributed to relatively high dust contents in late Pleistocene–Holocene sediments.

Increased dust emission from shrinking lakes during the late Pleistocene to the early and middle Holocene may explain the combination of high dust flux and changes in dust composition. The dating control on surficial deposits in Virginia Park is much coarser than the chronology of playa formation in western North America. Nevertheless, the timing of compositional changes in dust in Virginia Park substrates is consistent with the timing of desiccation of western pluvial lakes. The possible association between increased dust inputs to the Colorado Plateau and shrinkage of these lakes may be tested by future chemical or isotopic studies for dust-source attribution. If corroborated, the association would demonstrate how paleoclimatic and paleoenvironmental changes in a region might influence the development of landscapes in distant regions. An excellent example of landscape development linked to far distant dust emission is provided by Muhs et al. (in press) who document the dominant role of North African dust in soil development on Caribbean islands.

The distribution of eolian dust in the surficial deposits of Virginia Park is important to modern ecosystem dynamics for several reasons. First, some plants today tap into nutrients that were deposited as dust as long ago as about 12–15 ky (to ∼1-m depth in some settings) and then re-deposited by physical sorting. Studies of plant foliar chemistry along transects indicate that plants are sensitive to some dust-borne nutrients in this and similar settings (Neff et al., in press). Moreover, the performance of some plants, such as the invasive annual grass *B. tectorum*, apparently involves complex interactions related to soil texture and chemical composition that are partly structured by the amount of eolian dust (Miller et al., in press). Finally, eolian dust adds fine-grained sediment to substrates. In dryland substrates such as those at our study site, these additions can be significant through their influences on water infiltration, retention, and evaporative loss (e.g., McDonald, 1994; McDonald et al., 1996).

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