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Sedimentology (1999) **46,** 505–515

Aeolian system sediment state: theory and Mojave Desert Kelso dune field example

GARY KOCUREK* and NICHOLAS LANCASTER†
**Department of Geological Sciences, University of Texas, Austin, TX 78712, USA (E-mail: garyk@mail.utexas.edu)*
†Quaternary Sciences Center, Desert Research Institute, Reno, NV 89506, USA (E-mail: nick@dri.edu)

ABSTRACT

The sediment state of aeolian dune fields and sand seas at a basinal scale is defined by the separate components of sediment supply, sediment availability and the transport capacity of the wind. The sediment supply for aeolian systems is the sediment that contemporaneously or at some later point serves as the source material for the aeolian system. Numerous factors impact the susceptibility of grains on a surface to transport, but these are cumulatively manifested by the actual transport rate, which serves as a proxy for sediment availability. Transport capacity is the potential sediment transport rate of the wind. Because the three aspects of sediment state can be given as a volumetric rate, they are directly comparable. Plotted simultaneously against time, the generated curves define nine possible classes of sediment state. Sediment supply that is stored occurs because it is transport or availability limited, or generated at a rate greater than the potential or actual transport rates respectively. Contemporaneous or lagged influx to an aeolian system may be limited by sediment availability, but cannot exceed the transport capacity of the wind. For the Kelso dune field in the Mojave Desert of California, a variety of stratigraphic and geomorphic evidence is used to approximate the sediment state of the system. The sediment supply was generated during the latest Pleistocene and earliest Holocene during humid periods of enhanced discharge by the Mojave River to form the Lake Mojave fan delta or terminal fan, and has been calculated over time from the sedimentation rate and the frequency of floods. Estimation of transport capacity over time was based upon modern wind data, with an allowance for greater winds during the Pleistocene based upon climatic models. Sediment availability was approximated by calculation of a modern dune mobility index, with variation over time based upon climatic inferences. While quantifying the Kelso or any natural system is subject to numerous uncertainties, the sediment state approach reflects the temporal and spatial disjointed nature of accumulations at Kelso, as well as illuminating questions for future research.

Keywords Aeolian sand sea, aeolian sediment transport, Kelso dune field.

INTRODUCTION

Aeolian dune fields or sand seas form given a surface of sand and winds sufficient for transport. This simplistic statement, however, belies numerous complex issues central to any understanding of aeolian systems, including why dunes form, the derivation of dune sand, substrate controls on dune formation, the range of grain sizes that the wind can transport and the transport capacity of the wind. The origin of dunes has been explored through fundamentally different routes – as products of boundary-layer fluid dynamics (e.g. Hunt & Simpson, 1982; McLean

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& Smith, 1986; Nelson & Smith, 1989) and as self-organizing complex systems in which the details of the flow are not important (Werner, 1995). Whereas the general grain size range for different modes of aeolian transport are well known, the effects of grain size on dune morphology, size and spacing remain controversial, and the complex interactions of grains, substrate and airflow continue to present challenging problems (e.g. reviews in Lancaster, 1995; Kocurek, 1996).

In the broad consideration of aeolian systems in a basinal or stratigraphic context, however, given a range of grain sizes suitable for wind transport and that dunes form, it is the generation of a sediment supply, the availability of this sediment to the wind and the transport capacity of the wind that are paramount. For example, it is important to understand under what climatic, eustatic and tectonic regimes quantities of sand originate that are sufficient for sand sea construction, whether the sediment supply was generated contemporaneously or lagged over time with respect to sand sea construction, and over what time spans sand seas are developed and removed.

Unfortunately, terms such as 'sand supply', 'availability', 'sand abundance' and 'transport capacity' have been used loosely, thereby diminishing their utility (see Rubin, 1984). In large measure, these ambiguities arise from the difficulties in defining and quantifying measures of the components of aeolian sediments precisely. The thesis of this paper is that, to the degree necessary for aeolian systems at the basinal scale, the terms of sediment supply, sediment availability and transport capacity of the wind are separate issues that together define the sediment state of an aeolian system. Considered over time, these factors portray the aeolian system at a given time, as well as the system history in terms of its sediments. Through an example, the Kelso dune field in the Mojave Desert of SE California, this treatment not only reveals aspects of an aeolian system that are not otherwise clear, but also raises critical questions that might not otherwise be addressed.

SEDIMENT SUPPLY, AVAILABILITY AND TRANSPORT CAPACITY

Aeolian sediment supply is taken here as the sediment of a suitable grain size that serves as the source material for an aeolian system contemporaneously or at some later point in time. These sediments can be derived through primary deflation of strata, as with wind erosion of lacustrine gypsum (e.g. White Sands dune field, New Mexico; McKee, 1966) or marine carbonates (e.g. Arabian Gulf area; Glennie *et al.*, 1994). The aeolian sediment supply in these cases was generated by the accumulation of these 'chemical' sediments. In contrast, the bulk of grains necessary to form terrigenous dune fields and sand seas is only rarely derived through primary deflation of rock, but rather is derived secondarily from fluvial/alluvial, coastal or lacustrine systems. The generation of an aeolian sediment supply, as defined here, is the accumulation of these fluvial/alluvial, lacustrine and coastal sediments, which may subsequently be deflated to source an aeolian system. The location of the sediment supply with respect to the aeolian system can be either external (e.g. deflated alluvial systems sourcing dunes downwind) or internal (e.g. cannibalization of sediment by negatively climbing dunes or deflation from interdune areas).

Sediment availability is generally taken as the susceptibility of surface grains to entrainment by the wind. In the obvious case, the chemical sediments described above are not available for wind transport as long as the surface is flooded. For less extreme examples, it has long been recognized that a variety of factors inhibit sediment entrainment by the wind. Sediment that is perfectly available, or for which the maximum flux is achieved most readily for a given wind, consists of grains that are spherical, well sorted, dry and loose. Transport varies for a given wind by grain size, shape and sorting (Williams, 1964; Willetts *et al.*, 1982). Availability can be restricted by a raised threshold value caused by moisture (e.g. Hotta *et al.*, 1984) and surface binding or cementation (e.g. Nickling & Ecclestone, 1981; Nickling, 1984). Roughness elements such as pebbles or vegetation restrict sediment availability by reducing the surface wind energy (e.g. Ash & Wasson, 1983; Wasson & Nanninga, 1986; Stockton & Gillette, 1990). Numerous attempts have been made to quantify winds necessary for transport given, directly, the degree of vegetation and, indirectly, precipitation/evaporation ratios that support vegetation (e.g. Talbot, 1984; Wasson, 1984; Muhs & Maat, 1993), with a general characterization based upon indices derived from climatic data (Lancaster, 1988).

The transport capacity of the wind is its sediment-carrying capacity. Beginning with Bagnold (1941), numerous theoretical/empirical equations have been developed to describe sand transport rates (see review in Sarre, 1989). In general, the basis for these equations is that transport varies as a cubic function of friction velocity (u_*), although it is increasingly recognized that turbulence and other factors play very significant roles (Lancaster *et al.*, 1996). As a general statement, a given wind has a potential transport capacity, which is realized in a matter of seconds over a surface of perfectly available sand (Anderson & Haff, 1991). Given lesser availability, longer time spans are needed before the actual transport of the wind reaches its potential, or becomes saturated, during which time it must be at least potentially erosional, and the flow is unsaturated (Kocurek & Havholm, 1993).

Consideration of the separate issues of sediment supply, sediment availability and transport capacity of the wind to define the sediment state of an aeolian system is reasonable only as long as these components are equated. The generation of a sediment supply can be readily considered as a volumetric rate. The transport capacity of the wind is the potential transport rate, q_p, which can also be given as a volumetric rate in terms of potential sediment delivery to the aeolian system. Sediment availability is more difficult to quantify, but may be considered as the dimensionless percentage of a surface at a given time that is covered by grains that the wind can entrain. Such a calculation, even beyond its inherent difficulties, may not reflect the actual sediment flux to the aeolian system because of torturous transport paths and the aerodynamic configuration of the surface. The manifestation of sediment availability, however, is the actual transport rate, q_a, to the aeolian system, with the ratio q_a/q_p defining the sediment saturation level of the flow (see also Fig. 2 in Kocurek & Havholm, 1993). Here, therefore, q_a is used as a proxy for sediment availability, with the difference between q_a and q_p inferred to be caused by the sediment availability. The actual transport rate may also be limited or fall to zero because of the waning of the sediment supply, which then simply reflects a decreasing percentage of the surface covered by grains that the wind can entrain. In following this overall scheme, sediment supply, the actual transport rate, used as a proxy for sediment availability, and the potential transport rate, used as a measure of the transport capacity of the wind, all share common units and are directly comparable.

MODELS FOR AEOLIAN SYSTEM SEDIMENT STATES

The simultaneous plotting against time of sediment supply, sediment availability and transport capacity of the wind, or their proxies as discussed above, yields nine potential sediment states in which the volumetric rates can be compared and, assuming a constant time scale, volumes of sediment can be measured by cross-sectional area (Fig. 1). Generated sediment supply can either serve as contemporaneous influx (CI) to an aeolian system or be stored (S), with the actual transport curve (i.e. availability) in Fig. 1 separating influx from any stored sediment. Stored sediment can then be removed from storage later to serve as lagged influx (LI), and an aeolian system could be sourced simultaneously by both contemporaneous and lagged influx (CLI). These four designations define the major clans of the sediment states in Fig. 1.

Sediment that is stored at a given time must be so because it is availability limited (S_{AL}) or transport limited (S_{TL}), while the total volume of stored sediment could contain components of both availability- and transport-limited storage (S_{TAL}; Fig. 1a). Availability-limited stored sediment occurs where $q_a < q_p$, because surface factors limit the ability of the wind to entrain sediment. Transport-limited stored sediment occurs where $q_a = q_p$ and implies that the sediment supply is generated at a rate greater than the wind can transport it, and that availability is not a limiting factor. Stored sediment that contains both availability- and transport-limited components describes the case in which availability limits sediment entrainment by the wind but, even without this factor, winds are insufficient to transport sediment from the site of sediment supply at the rate at which it is generated.

Contemporaneous influx to an aeolian system arises from the sediment supply that is not stored (Fig. 1a). This influx must at least be transport limited (CI_{TL}), because influx cannot exceed the transport capacity of the wind, and with fully saturated flow $q_a = q_p$. Where $q_a < q_p$ (unsaturated flow) because of availability, q_a is the availability-limited contemporaneous influx (CI_{AL}) to the aeolian system. In the case of availability-limited contemporaneous influx in which q_a is limited by the volume of sediment supply, the q_a curve must follow the sediment supply curve (e.g. bottom portion of Fig. 1a).

Lagged influx to an aeolian system occurs with deflation of sediment that has been previously

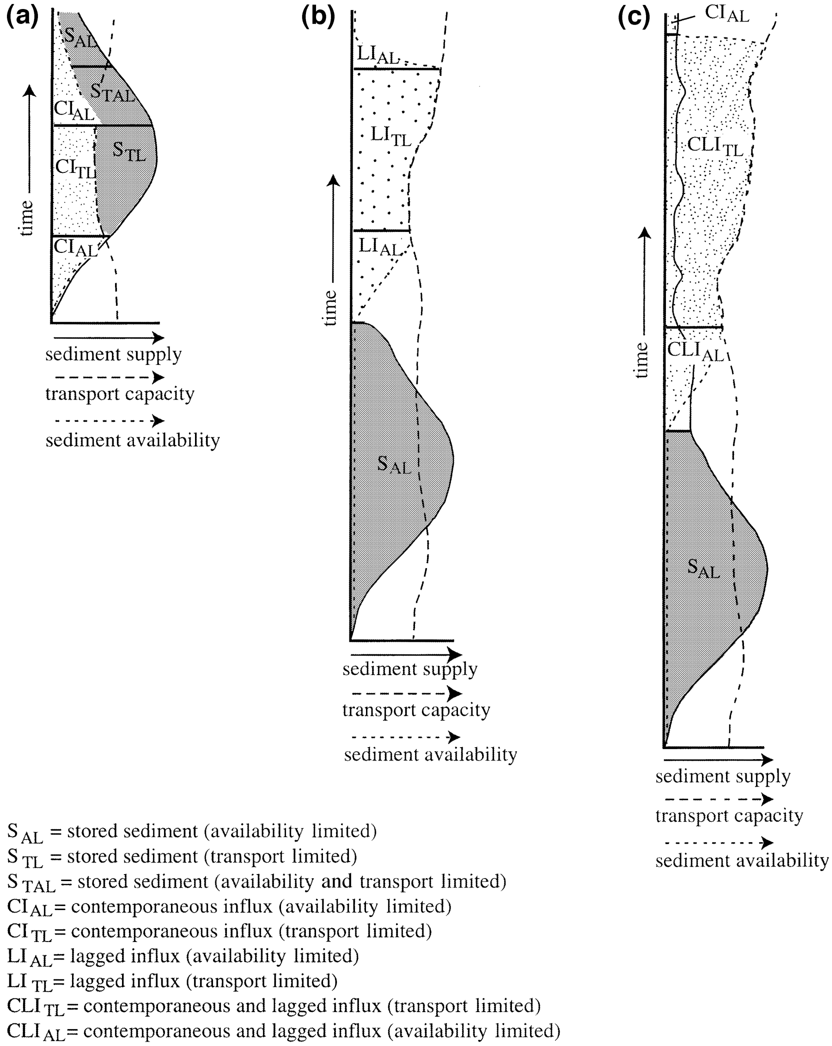

Fig. 1. Definition diagram for classes of sediment state determined by the plotting of sediment supply, sediment availability and transport capacity of the wind against time. (a) Aeolian construction contemporaneous with the generation of the sediment supply. (b) Aeolian construction separated in time from an earlier period when the sediment supply was generated. (c) Aeolian construction sourced by both a contemporaneous sediment supply and erosion of previously stored sediment.

stored for any reason. Lagged transport-limited influx (LI_{TL} in Fig. 1b) occurs with wind deflation of stored sediment in saturated flow conditions ($q_a = q_p$). Availability-limited lagged influx (LI_{AL} in Fig. 1b) is influx to an aeolian system from stored sediment in which the flow is unsaturated ($q_a < q_p$) because of sediment availability. As seen in the upper portion of Fig. 1b, as the volume of stored sediment nears exhaustion, fully saturated flow conditions yield to unsaturated flow that is availability limited because q_a decreases with the falling percentage of the surface covered by grains that may be entrained. Seen as a whole, therefore, states of lagged influx parallel those of contemporaneous influx but with the important distinction that influx to the aeolian system does not occur contemporaneously with the generation of the sediment supply.

Sediment states that describe sediment influx to the aeolian system that is both contemporaneous and lagged occur where the influx is derived both from contemporaneous sediment supply and from previously stored sediment. For this mixed influx, the definitions of transport-limited influx (CLI_{TL}) and availability-limited influx (CLI_{AL} in Fig. 1c) are the same as used for contemporaneous and lagged influx above. Note in the uppermost portion of Fig. 1c that, as the volume of stored sediment is exhausted, the q_a curve falls to parallel the sediment supply curve and, from that point, constitutes contemporaneous influx that is availability limited, as in Fig. 1a. Before that point, while influx may have been derived preferentially from either the stored or the contemporaneous sediment supply, for the practical purposes of sourcing the aeolian system, the two are not distinguished here.

The possible sediment states described above limit, but do not dictate, the conditions of the aeolian system beyond its sediment state.

Constructional periods of bedform growth or accumulation of strata in which influx is necessarily greater than outflux, with the balance stored within growing bedforms or their accumulation (i.e. a positive sediment budget of Kocurek & Havholm, 1993), can occur as long as there is influx to the system. However, influx does not necessarily mean that accumulation or bedform growth occurs as, depending upon other conditions and the aeolian system type, the sediment budget could be neutral (i.e. influx equals outflux), producing a bypassing condition, or negative (i.e. outflux is greater than influx), resulting in a period of dune destruction (see Kocurek & Havholm, 1993). Aeolian system destructional conditions also occur where the sediment supply has been exhausted or is not available for transport. Stabilization of dunes occurs as sediment availability approaches zero, at which point sediment within the dunes is stored.

EXAMPLE – KELSO DUNES, MOJAVE DESERT, CALIFORNIA

System configuration and history

Owing to the confined nature of the system, as well as a relative abundance of geomorphic, stratigraphic, palaeohydrologic and palaeoclimatic data, the Kelso system in the east-central Mojave Desert of California is one of only a few systems in which the sediment state can be presently approached not only in a conceptual manner, but also crudely quantified. The overall system occurs within interconnected intermountain basins that house fluvial, lacustrine and aeolian environments (Fig. 2). It is the spatial and temporal limits of these environments, as well as their interactions from the Late Pleistocene to the present as a function of climate, that give rise to the sediment state of the system. Although the Kelso system is one of the best known, the number of assumptions and gross approximations that must be made in developing this example serves also to illustrate the difficulties in quantifying any natural system.

While sediment contributions occur with drainage from the bounding uplifts, following Sharp (1966), the Mojave River is considered the principal sediment source for the system. Originating in the granitic San Bernardino Mountains and flowing north, then east over a tectonically active terrain to empty into the Mojave River Sink, the Mojave River has a large potential, tectonic-induced sediment supply, with discharge as a function of climate being the sediment-limiting factor. Presently, after heavy winter rainfall, the Mojave flows east through Afton Canyon into the Mojave Sink containing Soda and Silver Playas, as well as into the adjacent Cronese Basin (Enzel *et al.*, 1992; Fig. 2). This current drainage configuration is believed to have existed since about 16·5 ka BP, when Afton Canyon was incised, terminating Lake Mannix immediately to the west of Afton Canyon and

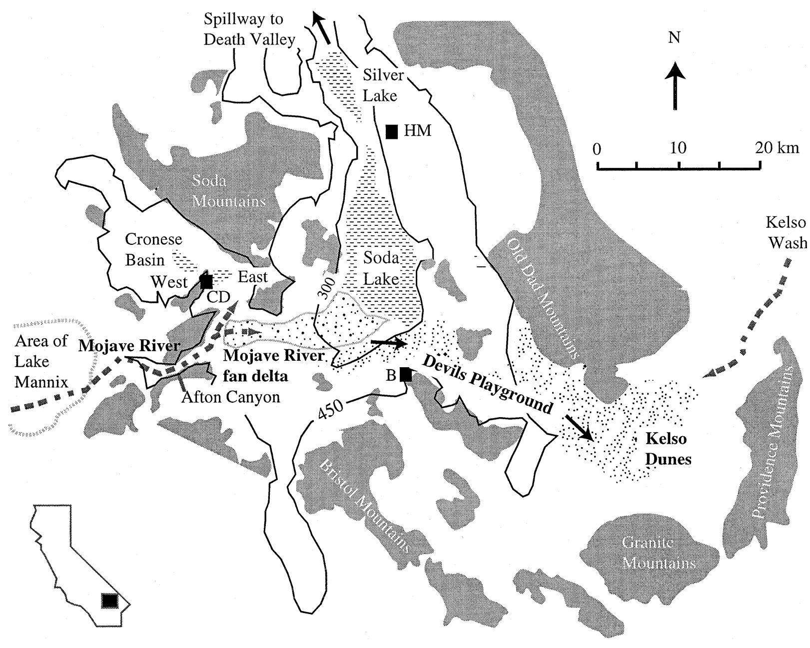

Fig. 2. Kelso dune field region in the Mojave Desert of south-eastern California. Aeolian transport is from the Mojave River fan delta through the Devil's Playground to the Kelso dunes area. The maximum stand of Lake Mojave was 287 m or just below the 300 m contour line. HM, Hanks Mountain sand ramp; CD, Cat dune complex; B, Balch.

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within the Mojave Valley (Meek, 1989; Brown *et al.*, 1990). The sediment depocentre has varied from a shallow lake that extended over the areas of Soda and Silver Playas (Late Pleistocene and Early Holocene Lake Mojave; Brown *et al.*, 1990), in which the Mojave River terminated as a fan delta, to drier periods when the termination of the Mojave River can best be described as a terminal fan. During highstands, Lake Mojave was confined by a sill at the northern end of present-day Silver Lake, with overflow to Death Valley via the Amargosa River (Fig. 2). The Mojave Sink today is characterized by a deflated gravel lag and small coppice and crescentic dunes.

Because of loss of flow confinement upon exiting Afton Canyon, sand and coarser sediment is deposited largely on the fan delta or on the terminal fan, with lake floor sediments consisting of silts and clays that are not of direct interest with respect to the downwind dune systems. Aeolian transport within the system begins with deflation of lacustrine and fan sediments under winds from the west and west-north-west, with infrequent winds from the south-east (Sharp, 1966), as measured from wind data recorded at Daggett Station 100 km west of the area. Subsequent aeolian transport occurs through the Devil's Playground, a 10-km-wide corridor between the Old Dad and the Bristol Mountains (Fig. 2). Currently, the western part of the Devil's Playground contains active crescentic dunes up to 5 m in height, while the eastern portion is marked by vegetation-stabilized sand sheets. The primary area of accumulation is within the Kelso dune field, which rests upon the piedmont slopes of the Granite and Providence Mountains and is bounded to the north, east and south by prominent uplands (Fig. 2). Active dunes, covering about 40 km^2, are surrounded to the west, north and east by low, vegetation-stabilized dunes. A prominent aspect of the dune field is the juxtaposition of dunes of distinctly different morphological type, size, spacing and alignment, with geomorphic and stratigraphic relationships showing that the entire complex consists of stacked and shingled separate dune fields, each representing an episode of sediment input or reworking of existing dunes (Lancaster, 1993). Secondary aeolian accumulations comprise the many sand ramps and dunes that mantle the slopes of the Old Dad and Bristol Mountains (Lancaster & Tchakerian, 1996).

Geomorphic and stratigraphic relations, together with luminescence and radiocarbon ages for aeolian, fan and lacustrine units (all given here as radiocarbon years), have enabled the principal events in the Kelso area to be recognized (Fig. 3a). From a series of luminescence dates for aeolian deposits in the Kelso system (Wintle *et al.*, 1994; Clarke *et al.*, 1996a,b; Rendell & Sheffer, 1996), distinct periods of aeolian activity can be recognized. The earliest such period (phase I in Fig. 3a) spans the time from 26 ka BP (or earlier) to 15–13·2 ka BP and comprises the Cat dune complex, the upper part of the sand ramp at Balch, the oldest sand sheets in the eastern part of the Kelso dunes and the Hanks Mountain sand ramp (see Fig. 2 for locations). The continuity of this period of aeolian construction is unknown, but a highstand of Lake Mojave (Lake Mojave I in Fig. 3a) occurred between 18 and 16 ka BP (Brown *et al.*, 1990). Aeolian phase I was terminated by the onset of geomorphic stability and soil formation on dunes and sand ramps, coincident with a second highstand of Lake Mojave (Lake Mojave II in Fig. 3a), which persisted from 13·7 to 11·4 ka BP (Brown *et al.*, 1990). The next major period of aeolian accumulation (phase II in Fig. 3a) started about 11·5 ka BP and continued until 4 ka BP. Phase II accumulation can be subdivided into two parts: phase IIa extended from 11·5 to 7 ka BP and comprises the bulk of the sand ramps at the West Cronese Basin, Balch and the Old Dad Mountains; phase IIb continued to about 4 ka BP in the Old Dad Mountains, West Cronese and at Kelso dunes. Phase II was also terminated by a period of geomorphic stability and soil formation that occurred during a period of increased regional precipitation and cooler temperatures, with a highstand of Lake Mojave at 3·9 ka BP (Wintle *et al.*, 1994). Phase III aeolian accumulation is found only at West Cronese and Kelso and spans the period from 2 to 1·5 ka BP. Likewise, phases IV and V are restricted to these localities and span the intervals 0·8–0·4 ka BP (Wintle *et al.*, 1994) and 0·25–0·15 ka BP (Clarke *et al.*, 1996a) respectively (Fig. 3a). A highstand of Lake Mojave is recognized at 0·39 ka BP (Enzel *et al.*, 1992) near the termination of aeolian phase IV.

Sediment supply

The sediment supply for the Kelso aeolian system was generated by the accumulation of sediment on the Mojave River fan delta or terminal fan and at a rate determined by Mojave River sediment influx of sand-sized sediment. While Mojave River influx over time is not known, sedimentation rates on the fan provide an estimation. Using data from Brown (1989), the mean Holocene fan sedimentation rate was 2 m 1000 years^{-1}, which

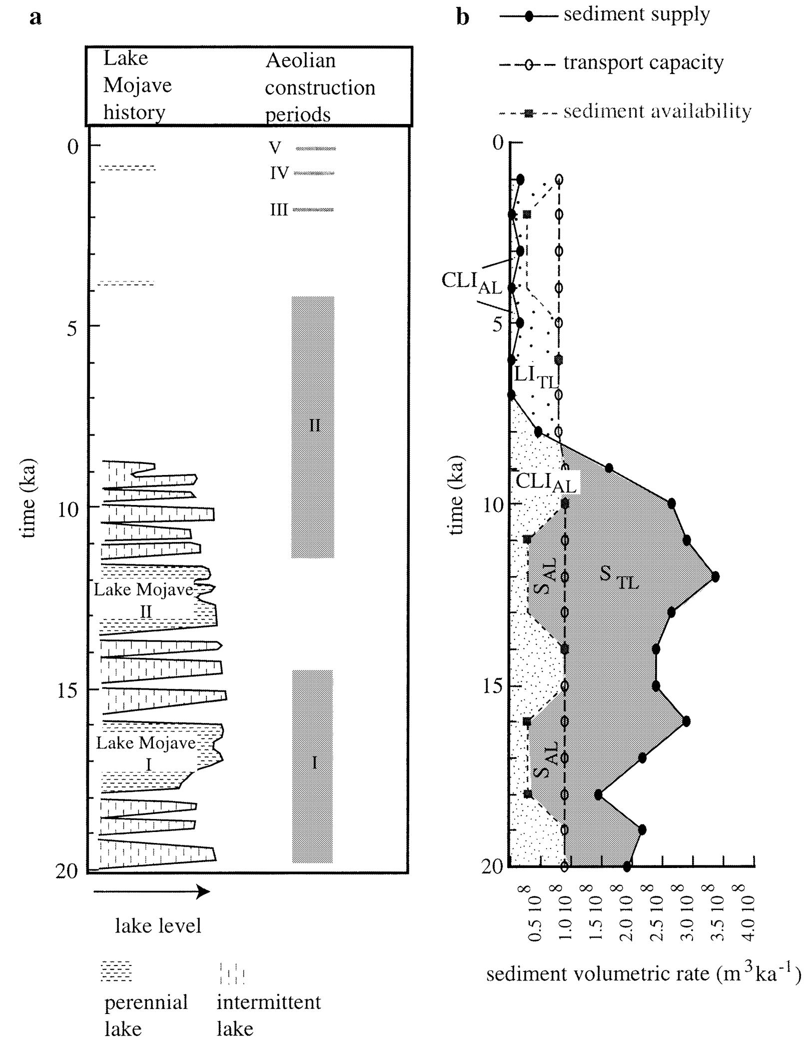

Fig. 3. (a) History of Lake Mojave and aeolian constructional periods determined from stratigraphic and geomorphic evidence, as discussed in the text. Radiocarbon ages from Lake Mojave are from Brown (1989) and Brown *et al.* (1990). Luminescence ages for aeolian accumulations are from data in Rendell & Sheffer (1996), Wintle *et al.* (1994) and Clarke *et al.* (1996a,b), and these have been converted to radiocarbon years to facilitate comparison, using the CALIB v3·0 program (Stuiver & Reimer, 1993). (b) Sediment state diagram for the Kelso system. Symbols are the same as in Fig. 1 and in the text.

was also adopted for Pleistocene rates for lack of more definitive data. Variation from this mean production rate over time can be approximated from a series of flood events interpreted by Brown (1989) to be represented by 1- to 3-cm-thick silty micaceous layers in dated sediment cores from Silver Lake. The frequency of these flood events varied with time, reaching a maximum of 14 per 1000 years between 13 and 12 ka BP, and was used as an index for the variation of sediment supply over the past 20 ka. The sediment supply curve in Fig. 3b was derived by multiplying the mean fan sedimentation rate by the normalized number of flood events per 1000 years. This calculation yields a mean Holocene sediment supply rate of 11×10^6 m^3 1000 $years^{-1}$, whereas that for the Pleistocene was $23{\cdot}8 \times 10^6$ m^3 1000 $years^{-1}$.

Because the overall Kelso system is closed with respect to sand, the entire sediment supply from the time of accumulation until the present must reside either as stored sediment within the terminal fan accumulation or within the aeolian features and their accumulations. Of the total calculated volume of $2{\cdot}94 \times 10^9$ m^3 of generated sediment supply since 20 ka BP (as represented by cross-sectional area in Fig. 3b), $1{\cdot}17 \times 10^9$ m^3 have been deflated and incorporated into aeolian accumulations and bedforms. This compares with the 1×10^9 m^3 of sediment estimated to be contained within the Kelso dune field (Lancaster, 1993), with the remainder making up the sand ramps and other aeolian bedforms in the Devil's Playground. The remaining $1{\cdot}77 \times 10^9$ m^3 of the sediment supply still resides as stored sediment within the 125 km^2 area of the terminal fan accumulation. This is equivalent to an average thickness of sediment of 14 m for the Mojave fan, which compares well with measured fan sediment thickness of 12–25 m (Brown, 1989).

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As seen in Fig. 3b, peaks of generation of the sediment supply are coincident with highstands of perennial Lake Mojave (i.e. Lake Mojave I and II), while an overall period of sediment supply generation characterized the late Pleistocene and earliest Holocene when varying stands of Lake Mojave existed. After 8·7 ka BP, when final desiccation of Lake Mojave occurred, additions to the sediment supply were minimal. For the Mojave region as a whole, the record of alluvial fan aggradation shows a major episode of fan aggradation that began at about 16·3 ka BP and persisted until 8·4 ka BP (Wells & McFadden, 1987; Bull, 1991; Harvey & Wells, 1994). It is likely that, with a finer resolution of the sediment supply curve in Fig. 3b, it would mirror more closely the Lake Mojave history, because lake stand, fluvial discharge and sediment supply co-varied as a function of climate. At a yet finer scale, however, the generation of sediment supply might be expected to vary with phase of climatic cycle, nature of discharge, vegetation and other factors.

Sediment transport capacity

In order to estimate the sediment transport capacity for the Kelso system over time, it is necessary to approximate the potential transport rate over the area where the sediment supply occurs. Only the net westerly winds across this area of the Mojave fan funnelled through the Devil's Playground into the Kelso area are of significance here. Winds from other directions, while important for aeolian activity and bedform construction, do not directly transport sand from the area of sediment supply to the zone of aeolian accumulation.

Using only the net westerly components of modern sand-transporting winds as measured at the Daggett Station and the method of Hsu (1971), in which the sediment transport rate is proportional to $u_{10}m^3$ (where u_{10} is wind speed measured at 10 m above the ground), a modern volumetric transport rate of 7·86 m^3 m^{-1} $year^{-1}$ was calculated. This transport rate per unit width was multiplied by the width (perpendicular to flow) of the area of sediment supply (10 km) to yield a modern volumetric rate of transport of 78 600 m^3 $year^{-1}$. Because no quantified data exist for earlier Holocene winds, this value was used in Fig. 3b for the entire Holocene. For late Pleistocene winds, we used a 14% increase in sediment transport capacity over the Holocene value based upon Joussaume's (1989) comparison of modern and Pleistocene GCM simulations of global dust transport. The 14% increase in transport capacity is probably a minimum figure for the Mojave. Figure 3b therefore portrays a constant transport capacity for the late Pleistocene and for the Holocene, with the latter reduced by 14% from the former.

Estimations of sediment transport capacity are a clear weak link in the determination of the sediment state of a system. Unlike wind tunnel quantifications of sediment transport, no appropriate method exists to determine potential sand transport from wind data confidently on a regional scale. Any simple derivation of transport from wind data at a given site assumes a similar wind regime, topography and surface roughness. Moreover, for the Kelso example, wind data are obtained from a source 100 km from the area. Extrapolating modern estimations of potential transport, themselves not an accurate measure, back in time are done here as only a most crude estimation, given the lack of strong criteria upon which relative strengths of wind energy may be based.

Sediment availability

In order to estimate sediment availability through time for the Kelso system, an approximation of variation in substrate conditions through time must be made, so that differences between the potential and the actual transport rates can be gauged. For this example, sediment availability is assumed to decrease during cooler and/or wetter climatic periods during which the water table rises and vegetative cover is increased. Conversely, increases in sediment availability occur during warmer and/or drier climatic periods. Estimates of sediment availability therefore rely upon inferences (i.e. proxies) of past climatic conditions. As shown in Fig. 3a, stands of Lake Mojave provide one set of proxy data for climatic conditions, in which highstands indicate relatively wet periods and vice versa. An additional set of proxy data is from the aeolian accumulations, in which periods of aeolian activity and periods of stabilization (represented by palaeosols), directly reflect sediment availability (Fig. 3a).

The sediment availability curve in Fig. 3b mirrors a 'dune mobility index' from Lancaster (1988) over time. Beginning with the modern data from Daggett Station for the period 1973–91, a modern mean mobility index of 621 was calculated from the ratio W/P′, where W is the percentage of time the wind is above threshold velocity, and P′ is P/Etp, the effective precipitation, where P is precipitation and Etp is potential evapotranspiration. For Fig. 3b, a range through time is assumed for the mobility index of ± one standard deviation, with lower values assigned to cooler/wetter periods and higher values assigned to warmer/drier periods, compared with the present. Because these values do not reflect changes in wind energy, which affect the actual transport rate, the normalized mobility index was then multiplied by the potential transport capacity. The sediment availability curve in Fig. 3b therefore reflects both inferred changes in wind energy over time as well as the degree of sediment mobility to yield an interpretative actual sediment transport rate.

While the dune mobility index is widely used as a measure of sediment mobility (e.g. Muhs & Maat, 1993; Bullard *et al.*, 1997), the sediment availability curve in Fig. 3b is also linked with the temporal variation in wind energy, for which numerous uncertainties exist, as discussed above. The degree of variation assigned for sediment availability by climate is an estimation, with interpretation of the palaeoclimate itself limited by the coarse resolution of the proxy data. Even for modern settings, the variation in sediment transport as a function of vegetation type and cover is not well known. Moreover, the present calculation of sediment availability does not take into account surface stability produced through armouring by coarser grains, a high water table or other effects besides vegetation as a function of effective precipitation. Any gross estimation of sediment mobility at the temporal scale presented here also neglects seasonal variations in wind, vegetation, water table and other variables.

System sediment state

The Kelso sediment state shown in Fig. 3b, especially when compared with the history of the system in Fig. 3a, both clarifies the system dynamics and raises questions that may direct future research. While the assumptions and possible errors in this analysis have been emphasized, the conceptual rigour imposed by the sediment configuration approach does create a relatively robust model, such that the overall Kelso sediment state portrayed here is reasonable, and errors exist mostly in terms of absolute values.

No aeolian system of dunes can exist without a sediment supply and, for the Kelso system, all evidence indicates that its generation occurred during the latest Pleistocene and earliest Holocene when sediment delivery by the Mojave River exceeded both the potential and actual aeolian transport rates, in spite of evidence for greater wind strength and the existence of contemporaneous aeolian construction (phase I). Higher river discharge, higher lake and groundwater levels and greater vegetation cover than at present all contributed to the formation of this large volume of stored sediment, and all are a function of a regionally wetter climate. Subsequent periods of aeolian construction (phases II–V) have largely been sourced through the deflation of this stored sediment, transported as lagged influx during arid periods. Figure 3b envisions that most of phase II aeolian construction occurred with influx rates limited only by the transport capacity of the wind. Phase II was also a period of increased dust flux in the region, in which the fine-grained components of the sediment supply were deflated from lakes and playas and accumulated in dust mantles on alluvial fans and lava flows (Wells & McFadden, 1987). Later, lesser periods of aeolian construction were probably availability limited because of vegetation. While sediment supply through most of the Holocene has remained at a minimal level, with the minor exception of short-lived stands of Lake Mojave, a comparison of cross-sectional areas in Fig. 3b shows that significant volumes of stored sediment supply remain.

Figure 3b also raises questions that cannot be addressed with the current set of data. Variation in the sediment supply and availability curves suggest that the designation of phase I of aeolian construction as a homogeneous period is oversimplified, and that future research may reveal a far more disjointed aeolian record, as well as identifying the conditions under which aeolian construction occurred. Did aeolian influx occur even during relative lake highstands, or was it confined to lowstands and periods of maximum deflation? While times of geomorphic stability coincide with relative highstands of Lake Mojave, the present calculations that give rise to the sediment availability curve suggest that some level of aeolian influx continued. If correct, then was stabilization solely the result of a more humid climate, or in part the result of a less mobile substrate because of a reduced flux of wind-blown sand? In contrast to phase I, the onset of phase II of aeolian activity was initiated by regional desiccation, and Fig. 3b suggests that this later phase represents a largely continuous period of aeolian activity. Overall, therefore, while the stratigraphic and geomorphic record at Kelso has already been shown to be complex, a portrayal of its sediment state indicates that it is probably even more spatially and temporally disjointed.

CONCLUSIONS

The thesis of this paper is that the conceptual framework of sediment state for an aeolian system provides a relatively rigorous way of thinking about the sediment component of aeolian systems at a basinal scale. Considering simultaneously the separate issues of sediment supply, the availability of this sediment and the potential of the wind to carry the sand from the site of supply to the area of aeolian system construction not only portrays the sediment aspect of the system as a diagram, but also forces a more critical thinking about modern and ancient aeolian systems in terms of their dynamics, interactions with adjacent environments and reactions to external forcing factors, such as climate, sea level and tectonism.

As with the Kelso example, quantification of a natural system is difficult. Based upon geological and geomorphic evidence, however, a qualitative approach to sediment state will be satisfying in many cases (see Fig. 4 in Kocurek, 1998, which is a sediment state diagram for the Sahara region since the last glacial maximum). As apparent from our Kelso example, the timing and volume of the creation of the sediment supply may be more obtainable than other components of the sediment state. Because of principles of sediment conservation, the generated sediment supply must always be somewhere. Its identification is easiest in closed basins, such as that of the Kelso dune field, and more difficult with open systems, such as the Sahara, where aeolian sediment may be carried into the Atlantic, or with some ancient systems, where the origin of the sands is unknown. For sediment transport capacity, the variation in past wind strength is commonly poorly known on relevant time scales, but it should be possible to derive regional estimates of past winds from the record of dust particle size (e.g. Prospero *et al.*, 1981) or from GCM output. Changes in sediment availability may be approached using changes in vegetation cover and type as a proxy for past precipitation, while evidence for water table level, encrusted or stabilized surfaces provide yet other measures of substrate conditions.

As also apparent from the Kelso example, the sediment state approach emphasizes the time scales over which the components of the sediment state may vary. Overall periods of major sediment supply will commonly reflect tectonic, eustatic or climatic events that operate over longer time spans than do climatic cycles that commonly control sediment availability. Given perfectly available sand, it is likely that, in most places, the transport capacity of the wind is at least adequate to pace the generation of the sediment supply, so that sediment availability will be the control on aeolian construction.

ACKNOWLEDGEMENTS

We appreciate the constructive comments by Brian Jones and Ian Corbett in reviewing this paper. This work was funded through the US National Science Foundation (Grant no. EAR-9217803).

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Manuscript received 30 May 1997;
revision accepted 3 August 1998.

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