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Short Paper

New optically stimulated luminescence ages provide evidence of MIS3 and MIS2 eolian activity on Black Mesa, northeastern Arizona, USA

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ABSTRACT

Eolian deposition on the semiarid southern Colorado Plateau has been attributed to episodic aridity during the Quaternary Period. However, OSL ages from three topographically controlled (e.g. falling) dunes on Black Mesa in northeastern Arizona indicate that eolian sediments there were deposited in deep tributary valleys as early as 35–30 ka, with most sand deposited before 20 ka. In contrast, the oldest OSL ages for sand sheets fall within the Pleistocene-Holocene climatic transition (~12–8 ka). Thus most eolian sediment accumulated on Black Mesa under climatic conditions that were in general cooler, moister, and more variable than today, not more arid, pointing to a considerable increase in sediment supply.

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Introduction

The Black Mesa region of northeastern Arizona, USA (Fig. 1) has been a focus of many geomorphic investigations, partly due to the excellent archaeological record of human occupation. Several studies have examined the timing and scope of landscape change in the alluvial record (e.g. Karlstrom and Karlstrom, 1986; McFadden and McAuliffe, 1997; Karlstrom, 2005), but it was Hack (1941) who first noted the geomorphic significance of the widespread eolian deposits and developed a still widely used model that links dune form to sediment supply, wind speed, and vegetation cover. Through alluvial and eolian stratigraphic characterization, Hack (1942) estimated that relict dunes in the most arid, low-elevation areas were deposited during the mid Holocene, but lacking precise age control, the climatic significance of the dunes was not well established. Later estimates of the maximum age of eolian deposits on the nearby Moenkopi Plateau range from 100 ka (Breed and Breed, 1979) to as much as 2.4 Ma (Billingsley, 1987). Only a few numerical ages have been obtained from linear dune crests, dates that Stokes and Breed (1993) conclude demonstrate significant remobilization during the Holocene on the Moenkopi Plateau.

This study provides the first optically stimulated luminescence (OSL) ages for morphodynamically stable eolian deposits (falling dunes) in the Black Mesa region, which is located in one of the largest, yet relatively unstudied, North American dune fields. The ages reported in this study establish an eolian chronology very different from the eolian chronology reported above, in part because we have dated eolian deposits that due to their landscape position were not reactivated. The volume and age of these immobile deposits suggests that glacial-age paleoenvironmental conditions controlling eolian sediment supply and availability (e.g. Kocurek and Lancaster, 1999) were much different from present. Our work supports a growing body of research suggesting that a large proportion of eolian deposits may initially accumulate under cool and moist (e.g. Rendell and Sheffer, 1996; Clarke and Rendell, 1998; Reheis et al., 2005), but highly variable climatic conditions (e.g. Broecker, 2000; Overpeck and Cole, 2006) that characterize glacial-age climate in the southwestern US (e.g. Anderson et al., 2000; Pigati et al., 2009; Wagner et al., 2010).

Study area and methods

Black Mesa is a topographically inverted Cretaceous structural basin ringed by relatively flat lying sedimentary rocks of the Triassic Chinle Supergroup and Jurassic Glen Canyon and San Rafael Groups, capped by resistant Cretaceous Mesa Verde Group sandstones, which form cliffs up to 300 m high along the Hopi Mesas and valley walls of the major drainages (Fig. 1). Highest elevations in this region (up to 2500 m) are cool and moist with an estimated mean annual precipitation (MAP) of 300–350 mm (WRCC, 2009) and dominant forest cover of *Pseudotsuga menziesii* (Douglas-fir) and *Pinus ponderosa* (ponderosa pine). Lowest elevations along the Little Colorado River (roughly 1300 m) are more arid (mean annual temperature is 12.1°C and MAP is 165 mm at Leupp,

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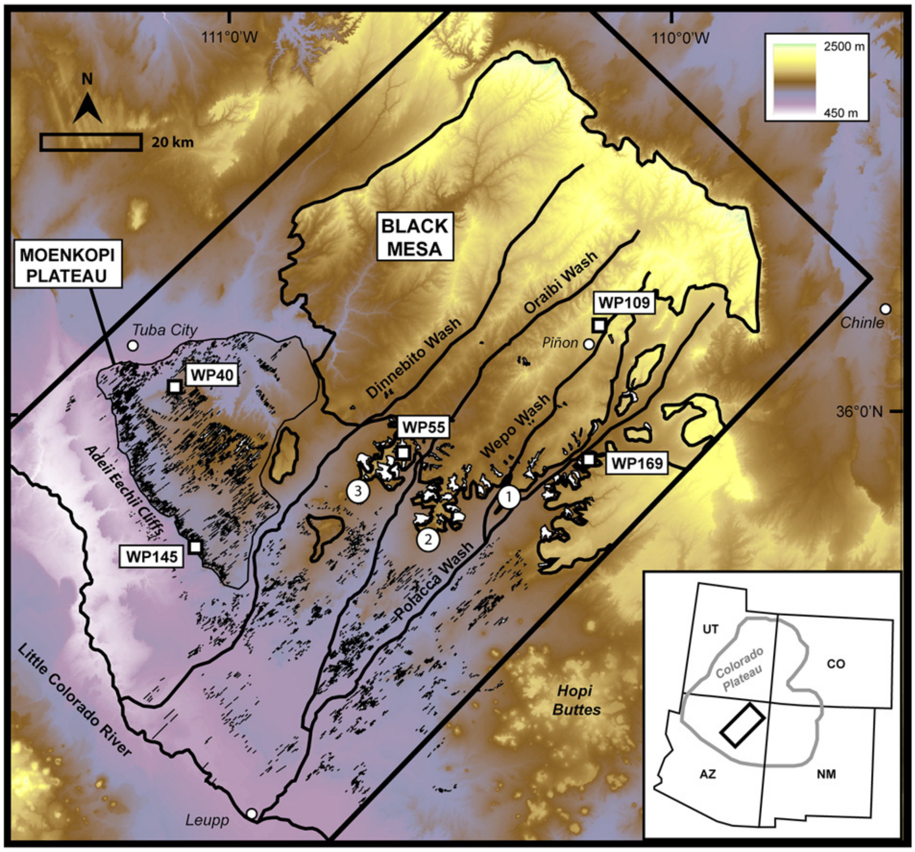

Figure 1. The study area is located in northeastern Arizona (AZ), in the Four Corners region of the southwestern USA. Linear dunes are shown as thin black lines that trend to the northeast. Falling dunes, shown as white polygons, are associated with canyons in the Cretaceous Mesa Verde Group sandstones, these rocks are outlined using a thick black line. The Hopi Mesas (First Mesa, Second Mesa, and Third Mesa) are numbered.

AZ; WRCC, 2009). Linear dunes that form parallel to the dominant wind direction are the primary eolian landforms southwest of the Hopi Mesas (Fig. 1), whereas climbing and falling dunes dominate downwind of the Hopi Mesas in deep tributary canyons. Falling dunes are most extensive where local relief is greatest near the Hopi Mesas, in some cases eolian deposits fill entire tributary basins. These deposits decrease in volume towards the northeast, where they are expressed as falling dunes. All eolian landforms were mapped by the authors using landsat imagery and 1-m digital orthophoto quadrangles (DOQs) in a GIS and were subsequently field checked (see online supplement for photos of active and stable linear dunes along the Adeii Eechii Cliffs on the Moenkopi Plateau and a falling dune to the northeast of Oraibi, AZ on Third Mesa).

Eolian deposits were characterized using conventional soil stratigraphic techniques (e.g. Birkeland, 1999) applied to hand-dug soil-pits and natural exposures. Optically stimulated luminescence (OSL) age estimates on quartz sand were used to measure the last exposure of eolian sediment to sunlight. In this project, OSL ages are determined using the single-aliquot regeneration approach (SAR) for sand grains. The preferred component for SAR dating is the "fast" component (e.g. Murray and Wintle, 2000; Wintle and Murray, 2006), a signal usually released in the first 0.8 s of typical blue diode stimulation. A dating precision of ~10% can be attained routinely with multigrain SAR quartz methods (e.g. Murray and Olley, 2002) when applied to eolian sand. With SAR, each aliquot yields a distinct equivalent dose (De) value and age estimate. Quartz-rich fractions were prepared by first destroying any carbonates and organic material by use of 4 N hydrochloric acid and 35% hydrogen peroxide, respectively. Heavy liquid was employed to concentrate quartz–feldpar mixtures before treatment with 48% hydrofluoric acid for dissolution of remaining feldspars (e.g. Mahan and Brown, 2006). Representative multigrain portions of each sample were then tested for the possible presence of residual feldspar by running an IRSL "wash." No samples showed any sign of feldspar contamination (see online supplement for additional details regarding OSL methods).

Results and discussion

South of the Moenkopi Plateau, dunes are largely active, but on the Moenkopi Plateau and other mesa top sites they are dominantly stable. Sites WP145 and WP40 (Figs. 1 and 2) provide good examples of the stratigraphy and soil profile development in eolian deposits of exposed and windy (high transport-capacity) mesa top landscape positions. Linear dune or sand sheet sediments are typically 1–3 m thick and deposited directly on bedrock. Soils associated with stable eolian landforms exhibit Btk soil horizons and stage II carbonate morphology (Fig. 2), which for this location imply late Pleistocene to early Holocene stabilization (e.g. Machette, 1985; Wells et al., 1990). OSL ages from eolian parent material (Fig. 2 and Table 1) indicate that the oldest eolian deposits on this surface date to the Pleistocene-Holocene climatic transition (ca. 12–8 ka; E-7 and E-19).

The southernmost sand ramp, consisting primarily of eolian sediments interbedded with thin colluvial and alluvial deposits (Lancaster and Tchakerian, 1996), was partially exposed in a meander bend in an arroyo and cleared by hand to a depth of roughly 8 m from the surface. Only one weakly developed soil profile (Bw) was observed in this section (Fig. 2). An OSL age from the middle of the exposure (17 ± 1 ka; E-3) yields a late-glacial depositional age. Sand ramp deposits were not sampled to their base because of the thick accumulation of colluvium (~2–3 m) shed from the exposure, which covers the underlying deposits.

At Echo Canyon (WP169), falling dune stratigraphy shows that the deposits are largely of eolian origin and the entire section contains four buried soils (Fig. 2). The uppermost weak Bw horizon formed in

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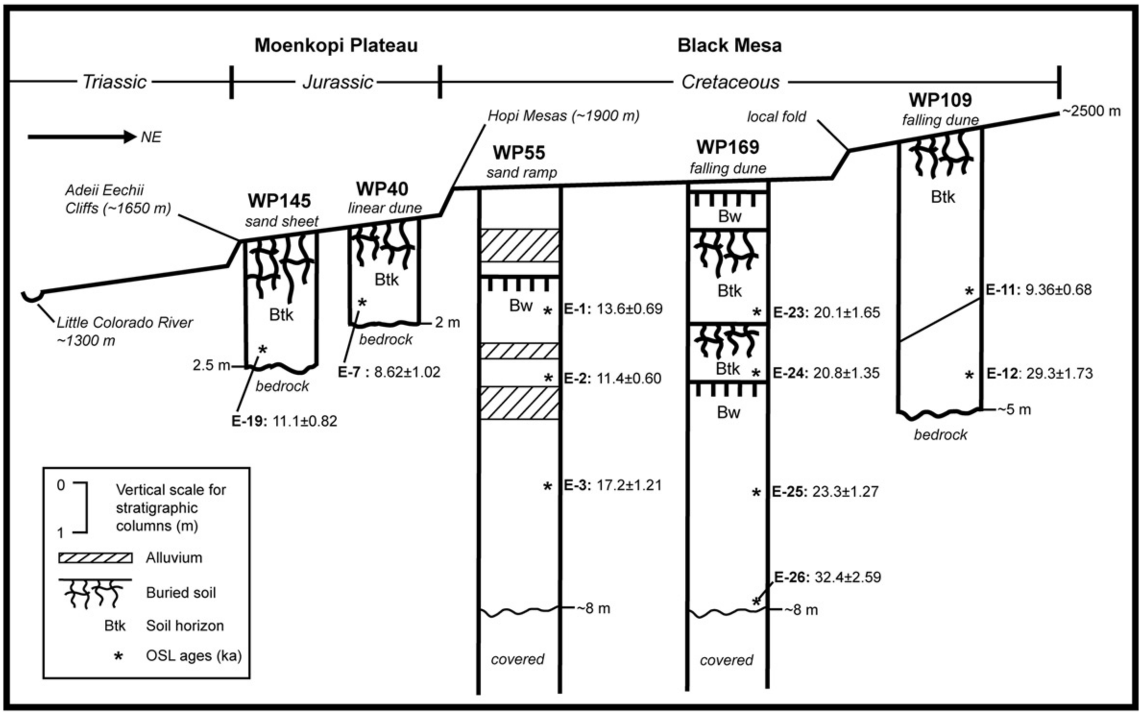

Figure 2. This schematic cross-section shows the distribution of lithology, topography, eolian and soil stratigraphy, and OSL ages of eolian units as well as geographic features mentioned in the text. The two stratigraphic columns on the left were described in one linear dune and one sand sheet on the Moenkopi Plateau, the three columns to the right depict stratigraphy in one sand ramp and two falling dunes on Black Mesa. Alluvium is indicated by the hatched pattern; all other units in columns are eolian. Colluvium described in the upper 20 cm of WP169 is shown above the weak buried soil profile (Bw). The simplified topographic profile has ~20× vertical exaggeration. Scale for stratigraphic columns located in legend. See Figure 1 for site locations. The OSL age inversion in WP55 is likely caused by greater water-holding capacity of the fine-grained eolian unit sampled by E-2; increased moisture dampens OSL signal accumulation.

eolian parent material that contains rare thin gravel lenses, and this profile is capped with ~20 cm of colluvium. Weak soil profile development in the upper meter suggests late Holocene deposition. Below this unit, OSL ages show that the largest volume of sand in this falling dune was deposited ca. 32-20 ka (E-23, E-24, E-25, E-26, Table 1; Fig. 2).

Table 1
Moenkopi Plateau and Black Mesa area dunes: sample locations, dosimetry, dose rates, equivalent doses, and age estimates. The main SAR parameters included use of the 40-s blue-diode wash step of Murray and Wintle (2000) at the same temperature as the preheat temperature. Signals in the multigrain SAR experiments were recorded with automated Riso Model DA15 OSL-reader systems, also using an EMI 9235Q PMT, and blue light-emitting diode (LED) stimulation. An aliquot consists of 200-300 grains on a single metal disk. Several quality-control criteria were employed to reject OSL signals and resultant SAR De values. Data rejection criteria were similar to those in common practice (e.g. Wintle and Murray, 2006). We accepted data having "recycle" ratios within 20% of 1.0, "recuperation" ratios (e.g. Aitken, 1998) within 2% of zero when recuperation was >20% of the normalized "natural" signal (Lx/Tx ratio), and test-dose signal errors were <15%. We forced dose-response curves through the origin.

Sample number	Depth (m)	Water content (%)[a]	K (%)[b]	Th (ppm)[b]	U (ppm)[b]	Cosmic dose additions (Gy/ka)[c]	Total dose rate (Gy/ka)	Equivalent dose (Gy)	n[d]	Age (ka)[e]
WP145: sand sheet near Gold Springs, Adeii Eechii Cliffs, Moenkopi Plateau										
E-19	1.7	3 (37)	1.61 ± 0.11	3.21 ± 0.23	1.43 ± 0.23	0.23 ± 0.02	2.35 ± 0.11	26.0 ± 1.53	15 (24)	11.1 ± 0.82
WP40: linear dune crest north of the Hollow Place, Moenkopi Plateau										
E-7	1.4	2 (20)	0.61 ± 0.01	1.56 ± 0.06	0.58 ± 0.06	0.25 ± 0.02	1.10 ± 0.03	9.50 ± 1.04	34 (40)	8.62 ± 1.02
WP55: sand ramp northeast of Oraibi, Black Mesa										
E-1	2.3	1 (22)	1.33 ± 0.01	2.19 ± 0.12	0.64 ± 0.06	0.21 ± 0.01	1.85 ± 0.05	25.2 ± 1.10	17 (30)	13.6 ± 0.69
E-2	4.1	8 (31)	1.97 ± 0.02	6.71 ± 0.23	1.88 ± 0.13	0.18 ± 0.01	2.97 ± 0.07	33.7 ± 1.68	23 (35)	11.4 ± 0.60
E-3	6.1	2 (21)	1.42 ± 0.01	2.46 ± 0.10	0.67 ± 0.04	0.14 ± 0.01	1.88 ± 0.04	32.4 ± 2.10	22 (38)	17.2 ± 1.21
WP169: falling dune in Echo Canyon, Black Mesa										
E-23	2.4	2 (27)	1.88 ± 0.04	4.16 ± 0.27	1.15 ± 0.11	0.22 ± 0.02	2.62 ± 0.09	52.7 ± 3.95	20 (20)	20.1 ± 1.65
E-24	3.2	2 (31)	1.98 ± 0.06	3.94 ± 0.21	1.19 ± 0.09	0.20 ± 0.01	2.70 ± 0.07	56.0 ± 3.29	25 (27)	20.8 ± 1.35
E-25	4.5	2 (29)	1.90 ± 0.02	3.60 ± 0.26	1.10 ± 0.09	0.17 ± 0.01	2.54 ± 0.08	59.2 ± 2.60	10 (10)	23.3 ± 1.27
E-26	8.0	5 (30)	1.88 ± 0.05	4.09 ± 0.23	1.21 ± 0.09	0.11 ± 0.01	2.23 ± 0.06	72.2 ± 5.42	28 (30)	32.4 ± 2.59
WP109: falling dune in Wepo Wash Canyon, Black Mesa										
E-11	3.2	2 (26)	1.88 ± 0.07	4.14 ± 0.18	1.09 ± 0.07	0.20 ± 0.01	2.60 ± 0.07	24.3 ± 1.62	41 (50)	9.36 ± 0.68
E-12	4.0	3 (44)	2.37 ± 0.06	5.66 ± 0.22	1.40 ± 0.08	0.18 ± 0.01	3.20 ± 0.07	93.8 ± 4.68	13 (20)	29.3 ± 1.73

[a] Field moisture, with figures in parentheses indicating the complete sample saturation (%). Ages calculated using 10% of saturation values: soils are aridisols and PE is usually greater than P throughout the year, except E-26, which was below water table.
[b] Analyses obtained using laboratory Gamma Spectrometry (high resolution Ge detector).
[c] Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994). See text for details.
[d] Number of replicated equivalent dose (De) estimates used to calculate the mean. Figures in parentheses indicate total number of measurements made including failed runs.
[e] Dose rate and age for fine-grained (125–180 μm) quartz sand. Linear + exponential fit used to estimate equivalent dose data, errors to one sigma.

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The northernmost observed falling dune on Black Mesa, near Piñon, AZ (WP109), is dissected by an arroyo to its contact with bedrock. A well-developed soil (Btk horizon, stage II carbonate morphology) has formed in the upper meter of the deposit, which yielded an OSL age of 9 ± 0.7 ka (E-11). An erosional unconformity at 3.5 m separates the uppermost eolian unit from an underlying, slightly finer-grained eolian deposit with an estimated age of 29 ± 2 ka (E-12; Fig. 2 and Table 1).

Given the strong relationship between linear dune trends and transport direction (Fryberger and Dean, 1979), the observed northeast-trend of the linear dunes is consistent with deposition of falling dunes on north- and northeast-facing slopes of tributary canyon walls. Wind speed drops significantly in tributary basins promoting sediment trapping and protecting deposits from subsequent deflation. Our OSL ages from these topographically controlled dunes are evidence that eolian sediments were available, transported to, and deposited in topographic traps from 35 to 9 ka. When filled with sands of high infiltration capacity, tributary basins have been unable to generate sufficient discharge to remove dune sediments, even under full-glacial conditions. Therefore falling dunes are stable landforms that provide a long record of late-Pleistocene to early-Holocene eolian sediment transport and deposition on Black Mesa.

In contrast, the 12–8 ka OSL ages for mesa-top deposits record the stabilization of migrating eolian deposits (e.g. Chase, 2009), not the initial emplacement of sand. We infer that the majority of sand comprising sand sheets on mesa tops was delivered to these locations while sand was being emplaced as falling dunes, but were stabilized due to increased dust flux and consequently rapid soil formation (Reheis et al., 2005) at the Pleistocene–Holocene transition. Because of their exposed landscape position, linear dunes and sand sheets are prone to eolian reactivation; however, these stabilized landforms exhibited only local reactivation during the Holocene.

The observed distribution and ages of eolian deposits strongly imply that eolian sediment transport capacity, availability, and supply were high in the Black Mesa region during glacial times with climatic conditions significantly windier (e.g. COHMAP, 1988) and cooler and wetter than Holocene or modern conditions (e.g. Weng and Jackson, 1999; Anderson et al., 2000; Pigati et al., 2009). We infer that the extreme, abrupt climatic variability that characterizes glacial climate (e.g. Broecker, 2000; Overpeck and Cole, 2006) may have been responsible for increased variability of stream flow, resulting in formation of wide braided floodplains and increased sediment supply for the eolian system (e.g. Muhs and Holliday, 1995) from the Little Colorado River as well as the major southwest-trending washes. Therefore, we suggest that the dominant control on topographically-controlled dune deposition during the last glacial period is increased sediment supply, not aridity.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.yqres.2010.12.002.

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