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GEOMORPHOLOGY, STRATIGRAPHY, AND LUMINESCENCE AGE OF THE MESCALERO SANDS, SOUTHEASTERN NEW MEXICO

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Abstract.—The Mescalero sand sheet consists of two eolian sand members, a lower eolian sand unit with an OSL age of 90 to 75 ka, correlating with oxygen isotope stage 5A, and an upper eolian sand unit with an OSL age of 9 to 5 ka, deposited during the early Holocene. The sand sheet overlies the calcic Mescalero paleosol. It has a stage II-III carbonate morphology and may have formed before and during the Sangamonian and early Eowisconsinan. After deposition of the lower eolian sand unit, the argillic Berino paleosol developed on the stable sand sheet. The Berino paleosol is a non-calcic, clayey soil that formed during the Wisconsinan, a period of regionally wetter climate and sagebrush grassland vegetation. Also during the Wisconsinan, large springs and cienegas formed extensive fossiliferous deposits throughout the area of the sand sheet, especially adjacent the Ogallala escarpment where a higher glacial-age water table fed large springs. The early Holocene eolian sand unit overlies the spring deposits. The sand sheet was in a state of quasi-stability during the past 5000 yrs. The Loco Hills soil, a thin A horizon without B horizon development, formed throughout the area on all substrates: lower and upper eolian sand, alluvium, and colluvium. The radiocarbon age of the A horizon soil is younger than 500 yrs BP; the soil formed during a brief period of slightly moist climate and a stable desert shrub grassland vegetation. Within the past 120 yrs since American settlement of the area, Torrey mesquite expanded its range onto the sand sheet, and coppice dunes formed around the mesquite, especially in areas where the lower eolian sand is exposed at the surface. Parabolic dunes formed recently in areas of thicker upper eolian sand and are dominated by a dense cover of shinnery oak shrubs. The coppice and parabolic dunes overlie the Loco Hills soil. Transverse dunes occur in small patches of presently active eolian sand.

INTRODUCTION

The Mescalero Sands is a 25- to 30-mile wide sand sheet that occurs west of the High Plains escarpment and east of the Pecos River in southeastern New Mexico (Fig. 1). It was first named by Darton (1928). The sand sheet is notable for its large mesquite coppice dunes, and, in the center where sand is thick, shinnery oaks dominate the landscape and mantle small parabolic dunes (Peterson and Boyd, 1998). The Mescalero Sands occur at the northeastern edge of the Chihuahuan Desert; mean annual precipitation is about 13 to 14 in. and mean annual temperature is about 60 ºF at an elevation of about 3500 to 4000 ft. The sand sheet has not been previously investigated in any detail although various field workers mentioned it (Kelley, 1971; Hendrickson and Jones, 1952, Muhs and Holliday, 2001; Holliday, 2001), especially Bachman (1976) who made new observations on the geology of the sand sheet and associated paleosols. The present paper is a summary of recent studies (Hall, 2002a, 2002b; Altschul et al., 2005).

FIELDWORK

Fieldwork and mapping in the Mescalero Sands area were conducted in 2000, 2001, and 2003 by the senior author. The surficial geologic map was drawn at the scale of USGS topographic maps 1:24,000, aided by black-and-white stereo aerial photography at a scale about 1:52,000 and color infrared stereo aerial photography at a scale about 1:86,000 from the EROS data Center, Sioux Falls, SD. Landforms and landscape features in the field smaller than about 200 ft across were not mapped.

OSL ANALYSIS OF SAND SAMPLES

Sample preparation/dose-rate determination

Sample preparation and analysis were carried out under amber-light conditions in the UNL Luminescence Geochronology Laboratory (Goble et al., 2004; Rittenour et al., 2003, 2005). Samples were wet sieved to extract the 90–150 μm fraction, and then treated with 1 N HCl to remove carbonates. Quartz and feldspar grains were extracted by flotation using a 2.7 gm cm^{-3} sodium polytungstate solution, then treated for 75 minutes in 48% HF, followed by 30 minutes in 47% HCl. Reddish sands with heavy iron oxide coatings were given an additional treatment with CBD solution (sodium citrate, sodium bicarbonate, sodium dithionate). The sample was then resieved and the <90 μm fraction discarded to remove residual feldspar grains. The etched quartz grains were mounted on the innermost 2 mm of 1 cm aluminum disks using Silkospray.

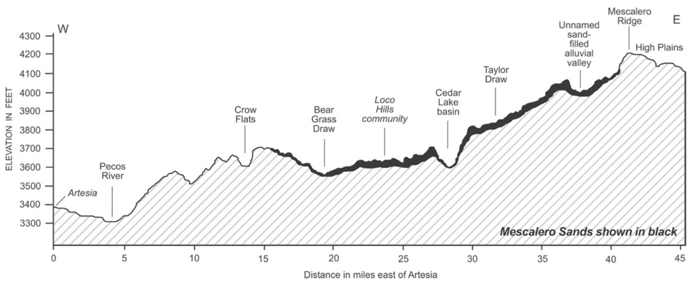


FIGURE 1. Topographic profile from Artesia to High Plains through Loco Hills community with location of Mescalero Sands shown in black.

Chemical analyses were carried out by Chemex Labs, Inc., Sparks, NV, using a combination of ICP-MS and ICP-AES. Dose-rates were calculated using the method of Aitken (1998) and Adamiec and Aitken (1998). The cosmic contribution to the dose-rate was determined using the techniques of Prescott and Hutton (1994).

Optical measurements

Optically stimulated luminescence measurements were carried out on a Daybreak Nuclear and Medical Systems reader equipped with green (λ = 514 nm) diodes operated at a power level on the sample of approximately 24.2 mW cm^{-2}, an EMI 9635Q photomultiplier, UG-11 filters, and an on-plate irradiator with a 100 mCi ^{90}Sr source delivering approximately 0.05 Gy/s. The Single Aliquot Regenerative Dose (SAR) technique of Murray and Wintle (2000, 2003) was used, with a preheat of 240ºC/10s, a cutheat of 160ºC/0s, based upon a preheat plateau test between 180 and 280ºC. Examination of the growth curves for the samples showed the samples to be well below saturation. Optical ages are based upon a minimum of 20 aliquots. Individual aliquots were monitored for low count-rate, poor quality fits (i.e. large error in the equivalent dose, D_e), poor recycling ratio, strong medium vs. fast component, and detectable feldspar. Aliquots deemed unacceptable based upon these criteria were discarded from the data set before averaging.

STRATIGRAPHY: EOLIAN SAND

Two eolian sand units form the Mescalero Sands, a lower unit that accumulated in the late Pleistocene and an upper unit that was deposited during the early Holocene (Fig. 2). The sand sheet has been largely stable during the past 5000 yrs although recent disturbance of the vegetation has exposed the sand to deflation, resulting in the formation of coppice, parabolic, and, in present-day patches of open sand, transverse dunes.

Lower eolian sand

The lower eolian sand unit represents the first episode of wind-transported sand accumulation in the Mescalero Sands area east of the Pecos River and west of the Ogallala Caprock escarpment. Before this unit was deposited, the sand sheet did not exist. The lower eolian sand is fine to medium to very fine quartz sand, subangular to subrounded, and well sorted. Its color is yellowish red to red (5YR 5/8, 2.5 YR 5/8), the redder color due to Bt horizon development of the Berino paleosol at the top of the sand unit. The sand lacks bedding, probably due to bioturbation. Close inspection of the sand shows numerous faint burrow fills between 10 and 20 mm diameter, similar in size and shape to burrows formed by cicada insect nymphs. The red sand rests directly on the eroded surface of the Mescalero paleosol as well as filling pipes and cavities within the Mescalero caliche. The lower eolian sand is greater than 3 m thick in some places but more commonly is no more than 40 to 60 cm thick. The sand unit is undergoing erosion today where not protected by coppice dunes or the overlying upper eolian sand

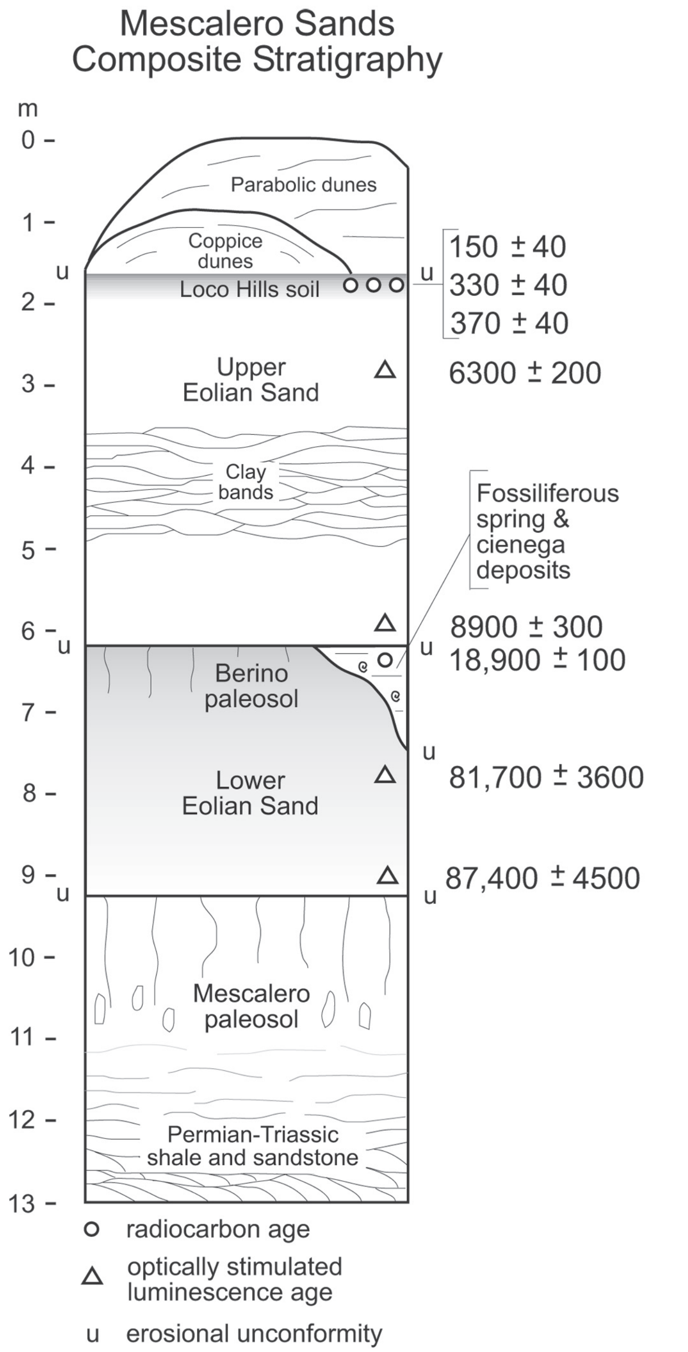


FIGURE 2. Composite stratigraphy of the Mescalero Sands, NE Eddy Co., New Mexico; no single locality exhibits all of these units and paleosols together.

unit. The Berino paleosol formed on the stabilized eroded surface of the lower eolian sand; it is discussed below.

Bachman (1976, p. 145) is the first to suggest that the Mescalero eolian sand originated from the Ogallala and not from Pecos River alluvium: "During wet intervals in the Pleistocene the sand was eroded from the Ogallala, and during arid intervals it was blown across the Mescalero plain." The chemistry of the Mescalero eolian sand differs from that of Pecos alluvium, further indicating that alluvium from the Pecos River is not the source of

TABLE 1. Selected sedimentology data from deposits in the Mescalero Sands area, northeastern Eddy Co., New Mexico; values are means with 1 sigma standard deviation; number of samples in parentheses; Wentworth scale.

Sample	Medium Sand %	Fine Sand %	Very Fine Sand %	Total Sand %	Silt %
Coppice dunes (4)	17.7 ± 2.7	67.2 ± 8.6	14.8 ± 6.0	93.5 ± 3.6	2.3 ± 1.4
Loco Hills soil (5)	19.1 ± 6.0	64.0 ± 10.0	16.2 ± 6.8	92.9 ± 6.4	3.2 ± 2.9
Holocene Alluvium (2)	9.6 ± 0.3	60.8 ± 1.3	29.0 ± 2.2	77.8 ± 6.3	12.5 ± 1.7
Upper Eolian Sand (5)	14.7 ± 1.8	68.0 ± 4.3	17.2 ± 5.1	95.6 ± 1.4	1.5 ± 0.7
Lower Eolian Sand (10)	21.0 ± 6.8	60.7 ± 5.5	17.4 ± 4.4	84.9 ± 9.4	3.9 ± 2.6
Ogallala Fm. (3)	11.9 ± 1.3	60.5 ± 3.2	25.5 ± 0.9	86.1 ± 3.7	11.2 ± 4.4

the sand sheet (Muhs and Holliday, 2001). Textures of the lower eolian sand and the sand in the Ogallala Formation show a close similarity (Table 1).

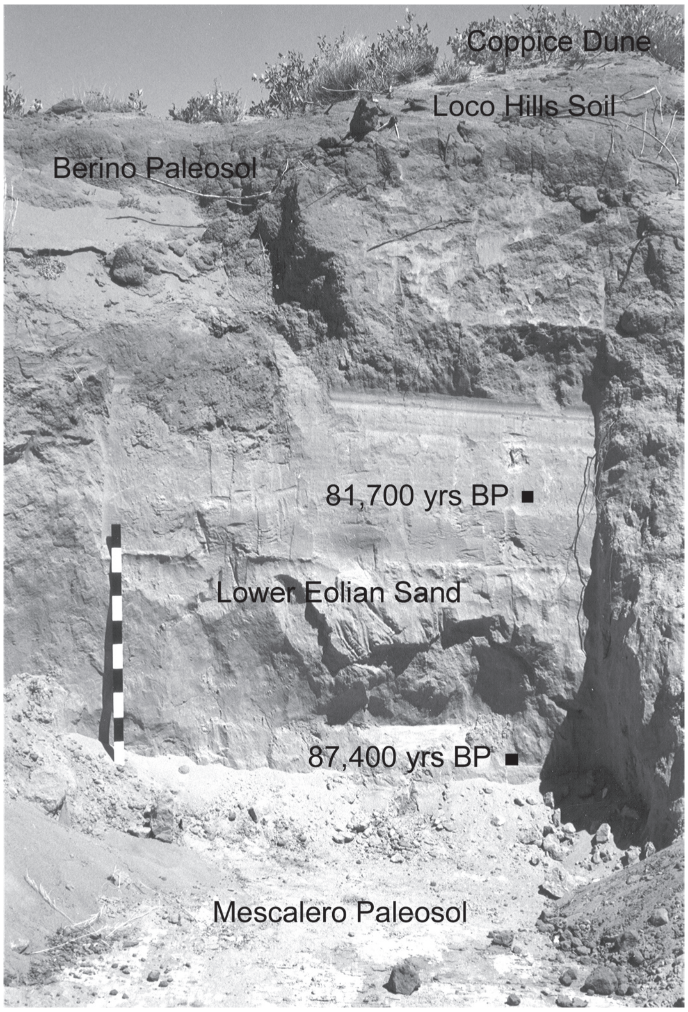


FIGURE 3. Lower eolian sand unit with Berino paleosol overlain by Loco Hills soil and historic coppice dune with Mescalero paleosol at base; locality from which OSL ages were obtained from the lower eolian sand (Table 2); Valley Gas Rd. sand pit, 0.8 mi. south of US Hwy. 82; loc. #1 in Hall (2002a) (E-C sec. 28, T17S, R29E); 1-m scale.

Luminescence age of the lower eolian sand

Optically stimulated luminescence (OSL) ages from a 310-cm thick section (E-C sec. 28, T17S, R29E) of the lower eolian sand unit are 81,700 ± 3600 yrs from 160 cm depth and 87,400 ± 4500 yrs from 280 cm depth, 30 cm above the base of the lower sand and its unconformity with the Mescalero paleosol (Table 2; Fig. 3). This especially thick exposure of the lower eolian sand is unusual in the region; only one other example of such a thick section was observed within the project area. Extrapolation of the OSL age values to the outcrop from which the samples were collected indicates that the 310 cm of eolian sand was deposited from 88,825 to 74,100 yrs B.P. during a period of 14,725 yrs. To be conservative, we conclude that the lower eolian sand accumulated between about 90 and 75 ka, a period of time that corresponds to oxygen isotope stage 5A (Fig. 4).

Upper eolian sand

The upper eolian sand unit is a fine to very fine quartz sand, reddish yellow (5YR 6/6), grains subrounded to rounded, well sorted, and noncalcareous. The sand unit is massive, lacking primary bedding, probably due to bioturbation. The sand has a thickness of 4 to 5 m in the central area of the sand sheet while at the margins the unit thins to less than 1 m in thickness. The sand unit does not contain a soil or paleosol although the much younger Loco Hills soil occurs at the top of the unit. The upper eolian sand rests unconformably on late Pleistocene spring and cienega deposits, described below.

Clay bands

Lamellae or clay bands occur in the middle of the thicker stratigraphic sections of the upper eolian sand. The clay bands occur in the interval of about 150 to 300 cm depth. Each band is about 5 mm thick and consists of sand that is slightly hardened by clays and iron oxides, giving the bands a slightly darker color than the surrounding sand. The bands contain about 6-7% clay compared with only 1-3% clay in the surrounding eolian sand. The bands are noncalcareous. The bands are discontinuous, no single one extending laterally more than about one meter. Clay bands are commonly visible in the thicker central portion of the sand sheet where recent deflation has exposed the upper eolian unit.

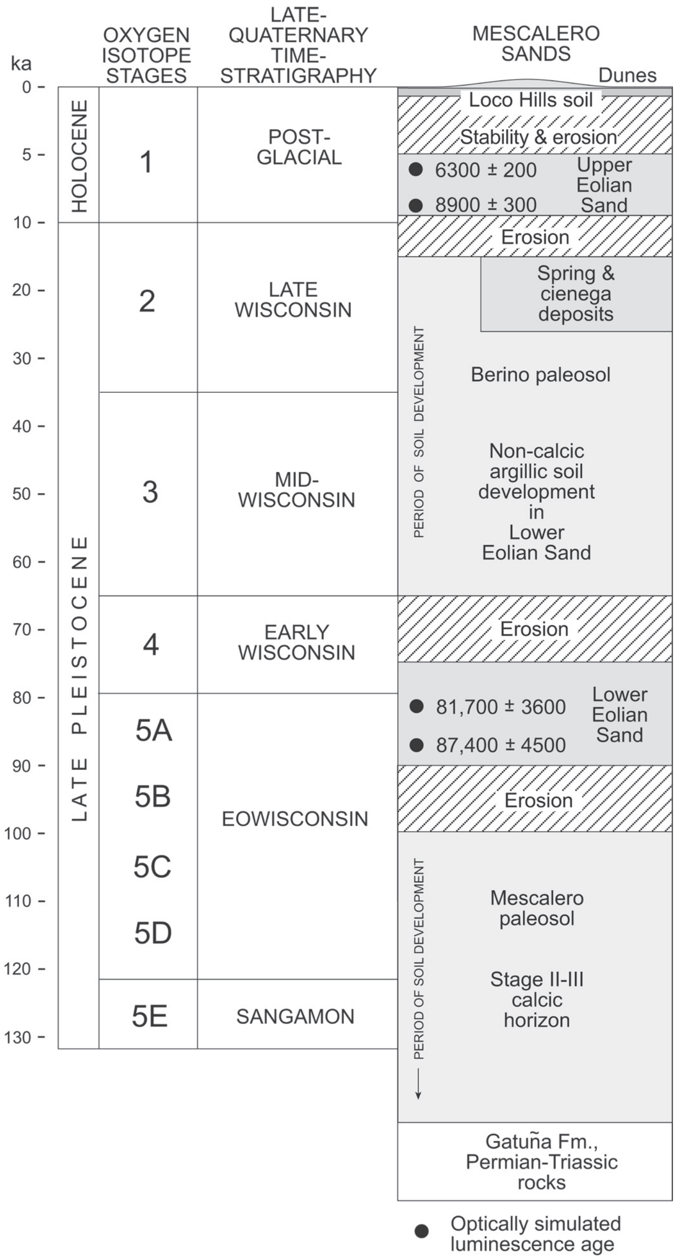


FIGURE 4. Late Quaternary time stratigraphy of the Mescalero Sands with OSL ages (Table 2); late-Quaternary time stratigraphy and oxygen isotope stages from Richmond and Fullerton (1986); change in scale at 10 ka; the age of the Mescalero paleosol may include a pre-Sangamonian period of development.

Clay bands in eolian sand have been reported before from the region (Gile, 1985; Holliday, 2001; Holliday and Rawling, 2006). Bands evidently form continuously through time with more band accumulation occurring in older sand deposits and less band accumulation in younger deposits. In the Mescalero Sands, organic acids from shinnery oak leaves, stems, and bark leach clay and iron from the eolian sand, translocating them downward where they accumulate in bands. The bands are secondary sedimentary features that, in the upper eolian sand unit, formed in the past 5000 years.

Luminescence age of the upper eolian sand

Two OSL ages were obtained from a 460-cm section (C sec. 1, T16S, R30E) in the upper eolian sand unit: 8900 ± 300 yrs BP at 455-cm depth, 5 cm above the base of the eolian sand and its contact with underlying spring deposits, and 6300 ± 200 yrs BP at 135 cm depth (Table 2) (Fig. 5). The extrapolated age of the upper sand outcrop is from 8940 to 5203 yrs BP, rounded to 9 ka to 5 ka.

STRATIGRAPHY: PALEOSOLS

Mescalero paleosol

The Mescalero paleosol was first named informally the Mescalero caliche by Bachman (1976). The Mescalero paleosol is a calcic soil that developed on the eroded surface of Permian and Triassic redbeds as well on the eroded top of the Gatuña formation (Miocene? to Middle Pleistocene) in southeastern New Mexico (Bachman, 1976; Powers and Holt, 1993). After its formation, the Mescalero paleosol was partly eroded and buried by eolian sand that comprises the Mescalero Sands. The calcic Mescalero paleosol everywhere underlies the Mescalero sand sheet although it is not related to the sand sheet, having formed before the eolian sand accumulated. Eolian sand was not observed beneath the paleosol in the study area.

The morphology of the Mescalero paleosol is somewhat variable across the region. Some of the observed variability may be explained by post-paleosol erosion and solution that removed some of its upper calcic horizon as well as any overlying Bt horizon. The paleosol is characterized by pipes measuring 30 cm to 15 m across at the top and extending as little as 1 m into and in other cases entirely through the calcic horizon. These soil pipes may be the same feature described by Gile et al. (1981, p. 74, 191). While Gile et al. (1981) regard pipes as forming contemporaneous with pedogenesis, the pipes in the Mescalero paleosol may have formed by post-paleosol dissolution. Thin coats of sec-

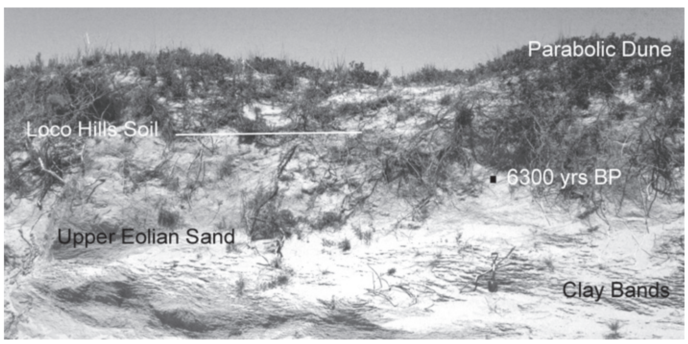


FIGURE 5. Upper eolian sand unit with Loco Hills soil and historic parabolic dune sand at top; locality from which OSL ages were obtained from upper eolian sand (Table 2); Booger Langston Rd. (Eddy Co. 256) 4.4 mi. E of Hagerman Cutoff; loc. #8 in Hall (2002a) (C sec. 1, T16S, R30 E); lower OSL age sample collected below clay bands; shovel scale at clay bands.

TABLE 2. Optically stimulated luminescence (OSL) ages from the Mescalero Sands, Eddy Co., New Mexico.

Sample #	Field Moisture (%)	K_2O (%)	Th (ppm)	U (ppm)	D_{cosmic} ($Gy \cdot a^{-1} \cdot 10^3$)	D_{total} ($Gy \cdot a^{-1} \cdot 10^3$)	Paleodose ($Gy \pm 1\sigma_s$)	Aliguots (n)	Age (ka $\pm 1\sigma$)
1	2.7	0.76	2.0	0.5	0.14	0.99 ± 0.02	86.16 ± 3.42	21	87.4 ± 4.5
2	2.5	0.71	2.2	0.6	0.14	0.99 ± 0.02	80.63 ± 2.49	21	81.7 ± 3.6
3	2.9	0.73	1.8	0.6	0.14	0.99 ± 0.02	8.79 ± 0.19	25	8.9 ± 0.3
4	2.7	0.59	1.0	0.4	0.14	0.76 ± 0.02	4.83 ± 0.11	23	6.3 ± 0.2

Sample 1 & 2: Lower Eolian Sand Unit, 280 cm & 160 cm depth, respectively (Fig. 3)
Sample 3 & 4: Upper Eolian Sand Unit, 455 cm & 135 cm depth, respectively (Fig. 5)

ondary carbonates encrust the pipe surfaces. The pipes are filled with red eolian sand, the lower eolian sand unit in this study. Small cavities 10 to 20 mm diameter occur in the caliche and are filled with red sand; the cavities may be molds of cicada insect burrows. The thickness of the preserved paleosol ranges from 30 to 140 cm.

The Mescalero Bt and Btk horizons above the calcic Bk horizon are partly preserved in a few rare localities. At the Square Lake Rd. soil pit (NE1/4 SW1/4 sec. 18, T16S, R31E), the red (2.5YR 4/6) noncalcareous Bt horizon clay content is 49.6%, and at the Valley Gas Rd. sand pit (E-C sec. 28, T17S, R29E), the red Btk horizon has 44% clay and 18% carbonates (Table 3). The Btk carbonates occur as a fine crystalline mass with an absence of nodules. More commonly, the Bt and Btk horizons are missing due to post-paleosol erosion. The rarely preserved Bt and Btk horizons of the Mescalero paleosol are not related to the overlying Berino paleosol.

The carbonate morphology of the Mescalero paleosol is moderately consistent across the area. The whole-sample carbonate content is about 50-70% compared with about 80-90% for the Ogallala Caprock (Table 3). The Bk carbonates of the soil fabric are finely crystalline and, while the calcic paleosol is laterally continuous and resistant to erosion, the degree of carbonate cementation is overall weak. The upper part of the calcic horizon can have weak discontinuous laminae and in many cases laminae are absent. Carbonate nodules are rare and when present are small, soft, and occur at the base. The stage of carbonate morphology falls within the stage II and III categories (Hawley, 1993; Birkeland, 1999, p. 356-358). While the occurrence of laminar structure, the meter-plus thickness, and the high amount of carbonate indicate stage III designation, the weak degree of cementation and near-absence of hard nodules, and the absence of or weak development of laminar structure indicate stage II. Bachman (1981) summarizes the calcic horizon of the Mescalero paleosol as having loose carbonate nodules in the lower half and massive carbonate in the upper half with occasional laminar structure in the upper 2-5 cm, also consistent with stage II or III carbonate morphology.

The age of the Mescalero paleosol is bracketed stratigraphically by (a) the age of the upper Gatuña Formation where the paleosol

TABLE 3. Carbonate and textural data from Mescalero Paleosol and Ogallala Caprock; numbers are percentages; Wentworth scale.

	Sand (mm)					Recalculated			
Sa□	v. coarse	coarse	medium	fine	very fine			<3.9µm	Whole-Soil Carbonates*
Mescalero Paleosol**									
#10, Bt	0	0.1	10.9	59.4	29.6	27.6	22.8	49.6	0
#1, Btk	0.5	0.8	11.4	53.2	34.2	35.5	20.6	43.9	17.9
#3, Bk	29.6	18.9	19.4	21.3	10.8	81.9	10.2	7.9	63.8
#4, Bk	33.2	18.7	15.0	21.1	12.0	79.0	10.6	10.3	63.5
#5, Bk	9.0	12.5	15.5	37.9	25.1	48.4	27.0	24.7	51.6
#9, Bk	8.1	12.8	17.9	36.0	25.2	23.2	54.5	22.3	55.3
Ishee, Bk	8.2	9.9	18.0	46.9	17.0	93.5	1.4	5.1	69.4
Ogallala Caprock, cm depth from top of caliche									
Bk, 85	11.2	18.7	18.9	25.6	25.6	64.3	21.5	14.2	89.5
Bk, 200	0.6	1.9	7.6	59.5	30.0	87.3	9.3	3.3	86.9
Bk, 270	0.9	14.8	10.7	17.4	56.3	44.2	40.8	15.0	80.6

*Chittick method
**Localities from Hall, 2002a
Analyses by Milwaukee Soil Laboratory, 6917 W. Oklahoma Ave., Milwaukee, Wisconsin 53219

occurs at the top and (b) the age of the eolian sand that overlies the paleosol. Bachman (1980) discovered a volcanic ash in the upper part of the Gatuña Formation that subsequently was identified as Lava Creek B, dated at 602 ka (Gansecki et al., 1998) or 639 ka (Lanphere et al., 2002). The lower eolian sand unit that covers the eroded surface of the Mescalero paleosol is dated by luminescence as no older than 90 ka (this study). Thus, the Mescalero paleosol formed sometime within the broad period from 639 to 90 ka although the actual period of soil development is shorter.

Berino paleosol

The Berino is a soil series of noncalcareous, red, sandy soils developed in eolian sand in eastern Eddy County and named in the USDA area soil report (Chugg and others, 1971). The Berino soil occurs throughout the study area. Bachman (1980, p. 44; 1984) is evidently the first to recognize it as a fossil soil that overlies the Mescalero paleosol; he suggested that the Berino might be the remnant Bt of the Mescalero, although the results from our study indicate that the Mescalero and Berino paleosols are unrelated.

The Berino paleosol occurs at the top of the lower eolian sand unit and is red to dark red (2.5YR 4/8, 3/6), giving the sand its characteristic red color. The paleosol is noncalcareous, as observed by Bachman (1981), and has about 15 to 20% clay. The paleosol has a weak ped structure about 15 to 20 cm diameter that can be seen on deflated surfaces. Paleosol thickness is generally no more than 50 to 70 cm and grades at depth to massive yellow sand with weak filamentous carbonates but lacking a discernible Bk horizon. Commonly, where the lower eolian sand unit has a thickness of 30 to 50 cm, the paleosol has formed in the entire thickness of the lower eolian sand and into sand wedges in pipes in the underlying calcic horizon of the Mescalero paleosol. The Berino paleosol is not a remnant Bt horizon of the Mescalero; instead, it formed more recently in time, as indicated by the luminescence age of the lower eolian sand. Also, a prominent erosional unconformity exists between the Mescalero paleosol and overlying Berino-bearing sand, and, at two localities the Berino paleosol is developed at the top of 3-m thick sections of eolian sand, separated stratigraphically as well as pedogenically from the underlying Mescalero paleosol (Fig. 3).

The lower eolian sand with the Berino paleosol at the top is dated by OSL between 90 to 75 ka. Thus, the Berino paleosol developed after 75 ka during the comparatively cool, wet climate of the Wisconsinan. Bachman (1981, p. 4) observed that the paleosol "began forming under more humid conditions than present." The environment of formation of the noncalcic argillic Berino paleosol is in sharp contrast to the semiarid environment of formation of the older calcic Mescalero paleosol.

Loco Hills soil

The Loco Hills soil is an A horizon 10 to 20 cm thick that occurs throughout the area on eolian sand, both lower and upper eolian sand units, and in young colluvium and alluvium (Fig. 6). The thin A horizon is distinctive by its grayish color that contrasts with lighter colored sand. The darker color is related to its organic matter content that ranges from 0.15 to 0.93%. The A horizon sand is massive and lacks secondary clays and carbonates, being too young to have B-horizon structure or chemistry. Three radiocarbon ages of organic matter from the soil range from 150 ± 40 to 370 ± 40 ^{14}C yr BP, and the calibrated calendar age (2-σ) ranges from AD 1440 to 1950 (Table 4). Thus the soil formed during the past 500 yrs. Soil development ended about 120 yrs ago in the 1880s due to alteration of rangeland and associated erosion accompanying the arrival of American settlers and livestock (Bogener, 2003; Chugg and others, 1971).

In most places the Loco Hills soil is absent due to historic erosion. It is commonly preserved and visible beneath historic coppice dunes in the area of eroded lower eolian sand. In these cases, the A horizon rests directly on the eroded Berino paleosol on the lower eolian sand unit. In many places, the A horizon is visible beneath parabolic dunes where exposed by erosion. Textural analysis shows that the sand matrix of the Loco Hills soil is a mixture of lower and upper eolian sand although more closely tied to the upper sand (Table 1). The Loco Hills soil is the only A horizon soil observed in the Mescalero Sands area.

The Loco Hills soil likely formed on a regional surface that was stabilized by dense desert shrub grasslands. A similar young A horizon soil has been observed in other areas of southern New Mexico (Swift, 1991) although it is largely absent from the landscape due to recent erosion. The paleoclimate at the time the Loco Hills soil formed during the past 500 years may have been a period of increasing regional moisture (Hall, 1984), a local manifestation of the climatic trend associated with the Little Ice Age.

Geochronology of the Mescalero and Berino paleosols

Bachman (1980, 1984) reports uranium-series ages from the upper and lower carbonates of the Mescalero paleosol and from the red sand (Berino paleosol) that overlies the paleosol. Three uranium ages from the Mescalero paleosol range from 410 to 510

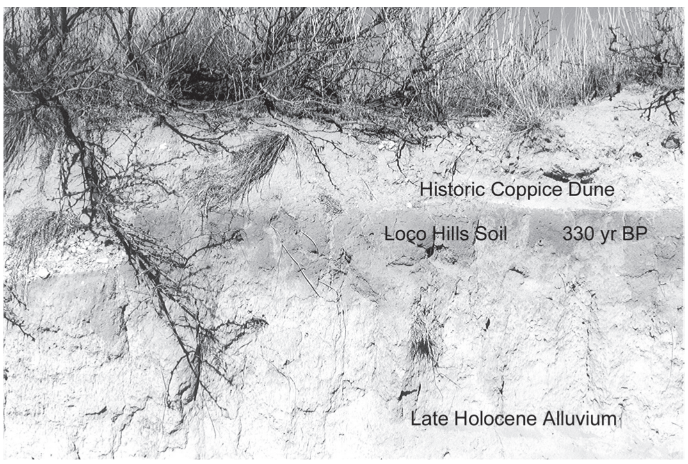


FIGURE 6. Late Holocene alluvium with Loco Hills soil dated 330 ± 40 ^{14}C yr BP (Table 4) ; 0.1 mi. S on Caprock Rd. (Eddy Co. 255) from jct. with Radio Rd. (Eddy Co. 254), right bank along small unnamed arroyo; loc. #12 in Hall (2002a).

TABLE 4. Radiocarbon ages from the Mescalero Sands, Eddy Co., New Mexico.

Lab No.	Material Dated	Measured Radiocarbon Age*	$\delta^{13}C$ ‰	Corrected Radiocarbon Age	2-Sigma Calibrated Age‡
Beta-160894	organic detritus[1]	240 ± 40	-17.0	370 ± 40	AD 1440-1640
Beta-159213	organic detritus[2]	90 ± 40	-21.6	150 ± 40	AD 1660-1950
Beta-156687	organic detritus[3]	300 ± 40	-23.2	330 ± 40	AD 1460-1650
Beta-156514	aragonitic snail shells	18,620 ± 100	-7.7	18,900 ± 100	21,080-19,910 BC

*AMS, Libby half-life
‡Stuiver and Reimer, 1993; Stuiver et al., 1998
[1]Loco Hills soil A horizon in mesquite coppice dunes, loc. #3 in Hall, 2002a
[2]Loco Hills soil A horizon in mesquite coppice dunes, loc. #13 in Hall, 2002a
[3]Loco Hills soil A horizon in alluvium (Fig. 6), loc. #12 in Hall, 2002a

ka, and a single uranium age from the overlying Berino paleosol is 350 ka.

OSL ages from the lower eolian sand indicate that the lower eolian sand accumulated about 90 to 75 ka. The Berino paleosol is developed at the top of the stratigraphic section; thus, the Berino paleosol formed after 75 ka, subsequent to the deposition of the lower eolian sand unit in which the Berino developed.

The OSL age of the Berino is approximately 20% that of the uranium-series age. If the same proportion were applied to uranium ages from the Mescalero paleosol, its age would be 82 to 102 ka, correlating to the Eowisconsin and overlapping the age of the lower eolian sand. The conversion also reduces the amount of time for the accumulation of the Mescalero carbonates from 100 ka to 20 ka, consistent with a stage II carbonate morphology. If the shorter time scale based on OSL is more accurate than the long time scale derived from uranium series, the Mescalero paleosol may have developed before and during the Sangamonian and early Eowisconsinan, between about 100 and 130 ka and perhaps earlier (Fig. 4). The dry paleoclimate of the interglacial-age is supportive of calcic soil development.

SAND DUNES

The Mescalero sand sheet has three areas of different dune types that are related to local plant communities, or in the case of the transverse dunes, absence of plant cover. All of the dunes overlie the Loco Hills soil and are historic in age, probably forming since the 1880s. Some of the dunes are still active today. In the mapped area of about 505 sq mi (Fig. 7), parabolic dunes occur in 55% and coppice dunes in 31% of the area (Fig. 8). The remainder of the mapped area (13%) is mostly denuded surfaces on Permian, Triassic, and Tertiary rocks with thin Holocene soils. Barchan and aklé dunes have been reported from the Mescalero Sands (Holliday, 2001) but were not observed in this study.

Coppice dunes

Coppice dunes, also called nebkhas or nabkhas, are small circular mounds of sand that form around the base of a shrub where decreased wind velocity has resulted in sand deposition. In the Mescalero Sands, most of the coppice dunes are formed around Torrey mesquite (*Prosopis glandulosa torreyana*) (formerly *P. "juliflora"* and *P. juliflora torreyana*) (Martin and Hutchins, 1980-81; Correll and Johnston, 1970). A few low coppice dunes west of the Mescalero Ridge escarpment formed around clumps of javelina bush (*Condalia ericoides*). Nearly all of the coppice dunes in the broad region of southern New Mexico and adjacent Texas or the northern Chihuahuan Desert, however, are associated with Torrey mesquite.

Most of the coppice dunes in the Mescalero Sands occur in areas dominated by the lower eolian sand unit (Fig. 9). A few patches of coppice dunes occur on the top of the upper eolian sand mixed in with parabolic dunes. Coppice dune height ranges from about 40 to 180 cm, averaging 100 cm above the pre-dune surface that, in most cases, is the Loco Hills soil. Dune diameter, measured at the base, ranges from about 3 to 9 m. When mesquites grow close together, coppice dunes merge forming a larger mass. The dunes consist of fine to very fine silty quartz sand. Dune sand is yellowish red to light yellowish brown (5YR 4/6, 10YR 6/4) and generally mimics the color of the local source sand that, in this case, is the red lower eolian sand. The dunes exhibit thin bedding that follows the curvature of the mounded sand around the mesquite. Thin crusts of silt and very fine sand are part of the bedding structure. The thin crusts form during rainfall events when silty particles are washed from mesquite leaves and stems and deposited as a drape of fine particles on the dune surface. The soft sand of young coppice dunes attracts burrowing animals, resulting in mixture of the sand and loss of primary bedding structures in most of the dunes.

In order for a coppice dune to form in the Mescalero Sands, a mesquite bush must be present. The appearance of coppice dunes on the sand sheet is related to the expansion of Torrey mesquite. While honey mesquite (*Prosopis glandulosa*) has been a component of the regional flora for at least 10,000 years (Van Devender, 1986), the range expansion and increase in abundance of Torrey mesquite is a recent biogeographical event in southern New Mexico as it was in south Texas (Johnston, 1963). In one study, the oldest Torrey mesquite stem from a coppice dune germinated ca. 1877, and 62% of the mesquite in a coppice dune field germinated in the period ca. 1931 to 1941 (Gadzia and Ludwig, 1983).

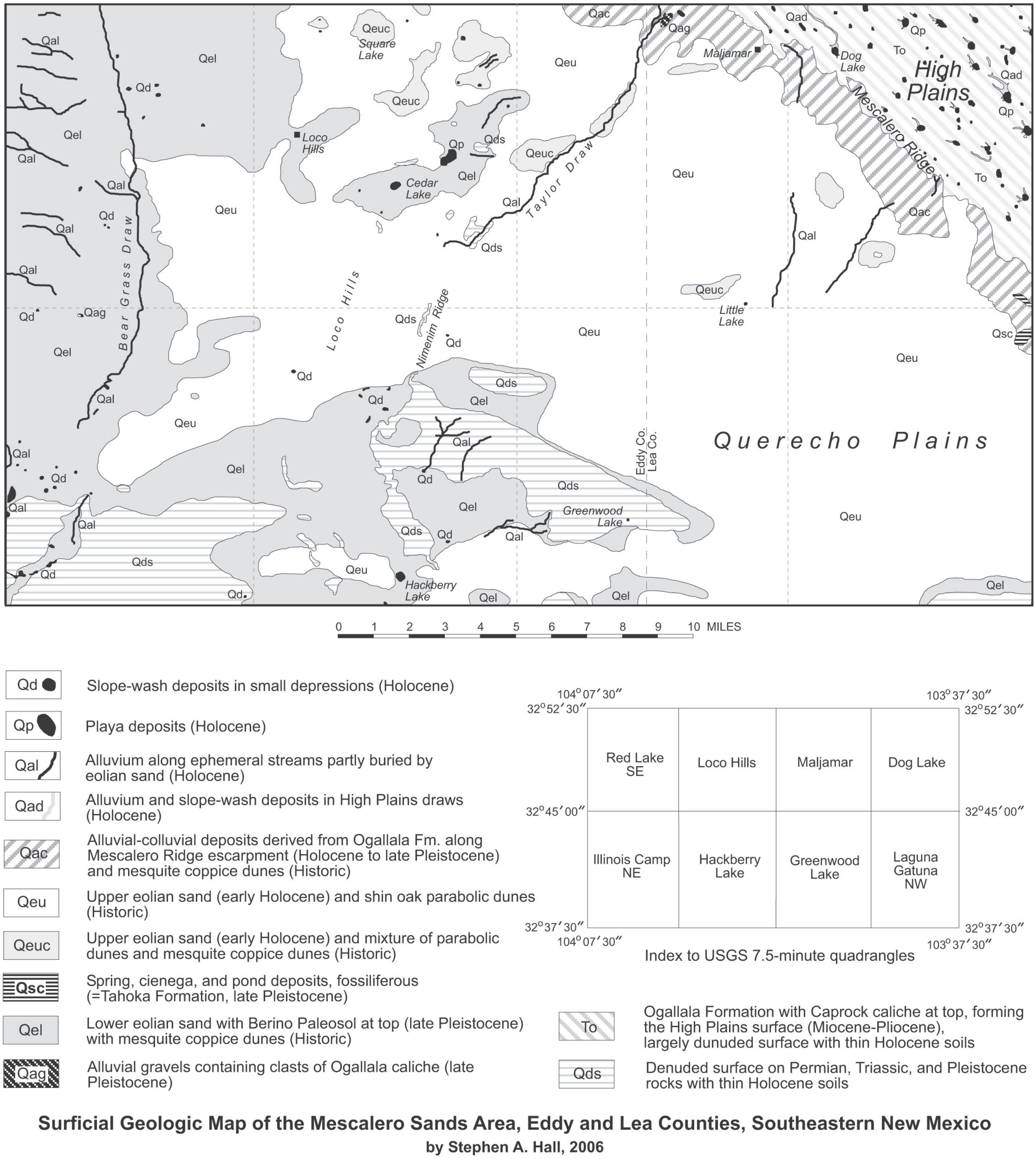


FIGURE 7. Surficial geologic map of the Mescalero Sands area, Eddy and Lea counties, southeastern New Mexico; small, low coppice dunes extend less than 1/2-mi. west of map edge; mapped by Hall in 2000, 2001, and 2003.

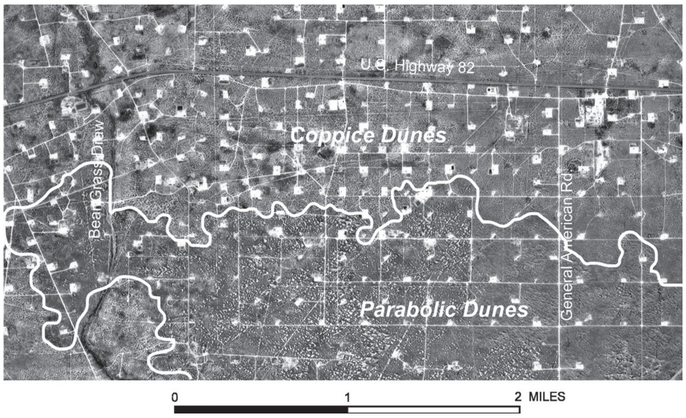


FIGURE 8. Aerial photograph west of Loco Hills community and east of Bear Grass Draw, Eddy Co., showing distribution of coppice and parabolic dunes; coppice dunes coincide with surface exposures of the lower eolian sand unit, and the parabolic dunes are formed on the surface of the thicker, younger upper eolian sand unit; coppice dunes are formed around Torrey mesquite shrubs (*Prosopis glandulosa torreyana*), and parabolic dunes are formed in areas of shinnery oak (*Quercus havardii*); both dune types occur on Loco Hills soils and are historic in age; white lines and squares on the aerial photograph are caliche roads and well pads.

Field notes from 19th century surveyors indicate the presence of broad areas in southern New Mexico without mesquite or coppice dunes prior to 1880 (Gile, 1975). Repeat baseline vegetation plots show a decrease in black grama desert grassland and increases in mesquite (Buffington and Herbel, 1965; York and Dick-Peddie, 1969; Hall, 1990a). Today, Torrey mesquite dominates broad sandy areas of southern New Mexico, and, where go mesquite, coppice dunes follow.

The coppice dunes, while currently dominating the landscape in many areas of southern New Mexico, are going through a 200-yr history of development, growth, and erosion (Fig. 10). In the western margins of the Mescalero Sands, coppice dunes are being eroded and lost. Erosion involves both deflation and slope processes. First, dunes form on the Loco Hills soil, and then as deflation continues, the soil is removed and the underlying red sand begins to be denuded and exposed. Within a few decades, the margins of the coppice dune are removed and the dune becomes isolated on a pedestal; the base of the eroded dune is too high for sand saltation and new sand does not reach the top of the dune. Deflation and sheet wash expose mesquite roots and its growth slows and eventually the shrub dies. Without the mesquite for growth and protection, the remainder of the dune is lost to erosion.

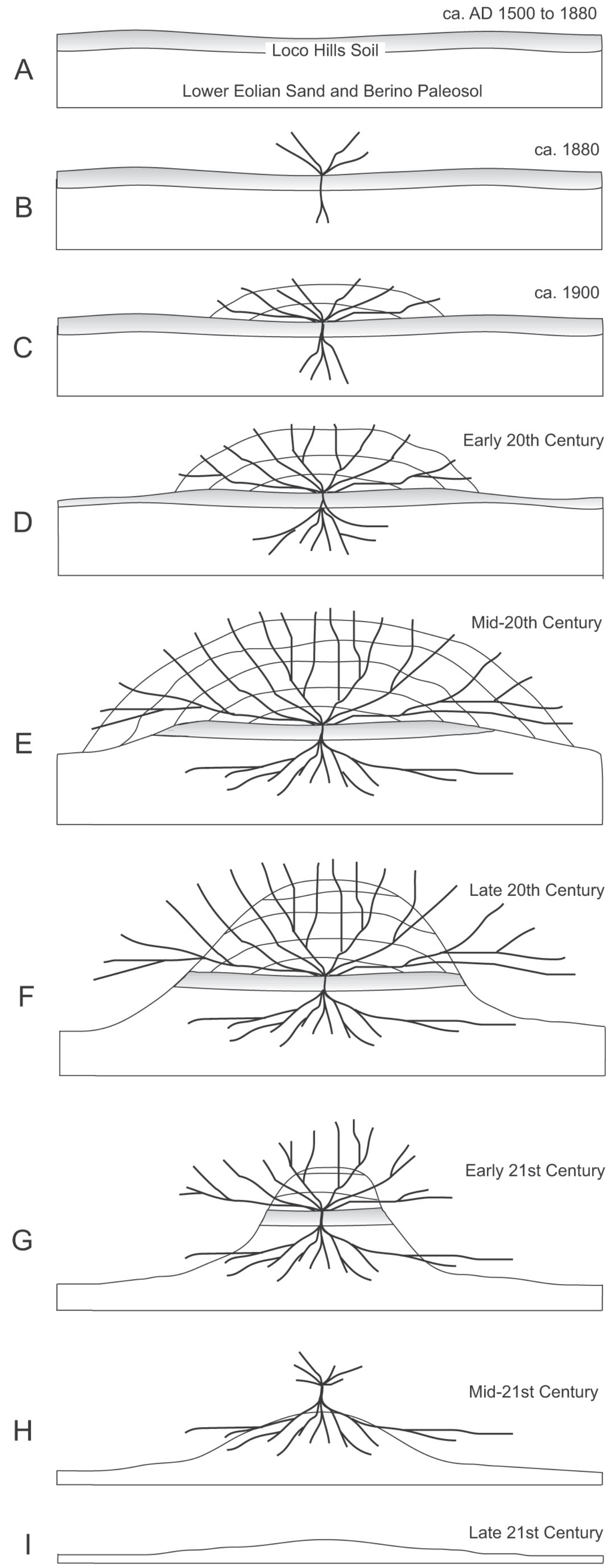
Parabolic dunes

Parabolic dunes cover most of the central part of the sand sheet where the upper eolian sand unit is thick and dominated by shinnery oak (*Quercus havardii*) vegetation (Qeu, Figs. 7, 11). The dunes are small and sub-circular, averaging about 23 m long, 20 m wide, and 3 m high measured vertically from the floor of the deflation basin or blowout to the down-wind crest. The dunes are oriented N70-90ºE, formed by west and west-southwest winds. Shinnery oak shrubs serve to both trap sand and protect the surface from deflation. In most areas, shinnery oaks, thick upper sand unit, and parabolic dunes occur together. However, in the southeastern portion of the study area, parabolic dunes have formed outside of the range of shinnery oak. In some places parabolic dunes are being deflated. Because of protection by clumps of shinnery oaks, the eroded rims of parabolic dunes form pedestals, mimicking coppice dunes (Fig. 12).

Transverse dunes

Several patches of active sand dunes with little or no vegetation, each generally less than 400 acres, occur in the east-central part of the Mescalero sand sheet study area northwest of Maljamar (Fig. 13). Transverse dunes characterize areas of present-day active sand movement. The transverse dunes and patches of active sand movement occur on the upper eolian sand unit where the sand is about 5 meters thick. The transverse dunes are oriented perpendicular to N45-65ºE, indicating wind direction from the west-southwest. A patch of stabilized transverse dunes occur north of E. Square Lake Road. The dunes are oriented N30ºW, indicating a more southerly wind direction at the time

FIGURE 9. Mesquite coppice dune on lower eolian sand; caliche pebbles on the eroded surface are derived from bioturbation through the lower sand into the calcic Mescalero paleosol that underlies the sand.



they formed (Fig. 13). All of the recent dunes are reworked sand within the areas of active sand, and none of the small transverse dune fields appear to have resulted from dune migration from other areas. However, the apparent in situ development of the transverse dunes may simply reflect the recentness of the dunes; with time, the dunes and areas of active sand could migrate. Shinnery oak parabolic dunes surround the areas of transverse dunes and are somewhat stable.

BIOTURBATION ON THE SAND SHEET

Small pebbles on the surface

The sand sheet surface contains small pebbles composed predominantly of caliche derived from the underlying Mescalero paleosol along with smaller numbers of siliciclastic pebbles (quartz, chert, quartzite, rhyolite) from the gravelly parent material in which the paleosol is formed. Large caliche clasts, such as fire-cracked rock associated with hearths, are generally related to prehistoric cultural activity, but numerous small caliche clasts are a result of burrowing activity of insects, ants, rodents, and carnivores. Generally, the size of the clasts brought to the surface during burrowing corresponds to the size of the burrower: small animals produce small rubble, and large animals throw out larger clasts. A study of ant activity on the sand sheet shows that 84 g of material per square meter is brought to the surface in one year, the pebbles (mostly caliche) ranging from approximately 3 to 6 mm diameter. If uniform, this equals 749 lbs per acre per year or 37 tons per acre per century (Whitford and others, 1986). Deflation of sand and sheet wash of pebbles from mounds of animal burrows results in a pavement of small caliche and silicic clasts on the eroded surface of the sand sheet (Fig. 9).

Cicada insect burrow fills in sand

The absence of bedding structures in the sand sheet may be due to burrowing activity of cicada insect nymphs (Homoptera: Cicadidae). Both lower and upper sand units show evidence of numerous cicada nymph burrow fills (Fig. 14). Cicada nymph burrow fills are cylindrical, about 10 to 20 mm in diameter, and

FIGURE 10. Development and erosion of coppice dunes during 200-yr period in SE New Mexico; A = Loco Hills soil development on desert shrub grassland; B = expansion of Torrey mesquite into grasslands after appearance of white settlers and livestock; C = landscape disturbance and beginning accumulation of wind-transported sand around the base of Torrey mesquite shrubs; D = continued eolian deposition and beginning deflation of Loco Hills soil; E = maximum growth of coppice dunes and continued deflation around dune margins; F = dune growth slows, and dune margins and areas between dunes are further deflated; G = dunes severely eroded and no longer accumulating new eolian sand; dune-mound geometry is erosional instead of depositional in origin; pre-dune substrate exposed; mesquite roots exposed and shrub is dying; H = erosional remnant of former coppice dune with dead mesquite; I = denuded surface formed in lower eolian sand and all traces of coppice dunes are gone; most of the coppice dunes in the Mescalero Sands are category E and F, although examples of C, D, G, and H are present.

FIGURE 11. Parabolic dunes SW of Loco Hills community; vegetation is dominated by shinnery oak (*Quercus havardii*) with sand sage (*Artemisia filafolia*) and yucca (*Yucca* sp.).

are characterized by crescent-shaped backfilling. Burrow fills are oriented in all directions. The calcic horizon of the Mescalero paleosol also exhibits cicada nymph burrow fills; some carbonate nodules are casts of burrows. Cicada nymph burrow fills are reported from sagebrush steppe-loess soils to 50 cm depth with maximum nymph burrowing activity concentrated at 27 to 33 cm depth where greater than 50% of the soil volume is disturbed (O'Geen et al., 2002). Cicada nymph burrowing activity in the Mescalero Sands during the late Pleistocene may be related in part to the dominance of sagebrush grassland vegetation (Hall, 2005).

Cicada nymph burrowing effects on OSL ages

Cicada nymphs dig through and back-fill sediment as they burrow. In theory, particle displacement should be only a few centimeters. Based on field observations of thinly layered archaeological sediments in the study area, burrow fills may contain sediment that has been displaced by 10 to 20 cm. While a bioturbation model is beyond the scope of this study, a 20-cm vertical interval of the lower and upper sand units corresponds to 950 and 162 yrs, respectively. Thus, the maximum effect of nymph burrowing and sediment mixing in a 20-cm interval may be broadly within the 1-σ variability of an OSL age. In a depositional environment such as the Mescalero sand sheet, the zone of nymph burrowing rises as the surface aggrades, resulting in abandoned fossil burrow fills preserved at depth (O'Geen and Busacca, 2001).

SPRING AND CIENEGA DEPOSITS

Several exposures of light olive gray calcareous sands occur along the eastern half of the sand sheet. These deposits represent former spring and cienega deposits when the water table was high during the Wisconsinan. The deposits are exposed in large blowouts and along some stream banks. At one locality, spring-cienega deposits are 5 m thick and are exposed over a distance

FIGURE 12. Eroded parabolic dunes partly protected by shinnery oaks near Square Lake; erosional features mimic coppice dunes.

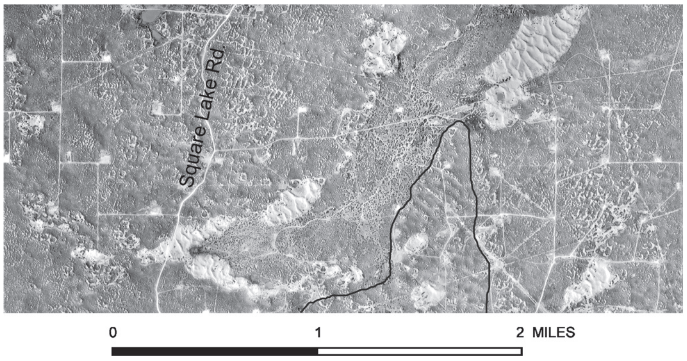


FIGURE 13. Transverse dunes NW of Maljamar, E of Square Lake Rd., in areas of active open sand without vegetation; small area of stabilized transverse dunes outlined.

of one-half mile across the landscape (Fig. 15). The upper eolian sand overlies and is unconformable with the spring deposits. Many of the deposits contain mammalian bone fragments and shells of aquatic and land snails. Aragonitic shells from one locality yielded a radiocarbon age of 18,900 ± 100 ^{14}C yrs BP (Table 4), indicating full-glacial age and correlation with the lacustrine Tahoka Formation on the High Plains (Hall, 2001). Bachman (1981) reported similar fossiliferous spring-cienega deposits at Nash Draw south of the study area.

A small collection of shells from a Mescalero Sands spring deposit is dominated by *Pupilla muscorum*, a land snail that today occurs at 8000 to 10,800 ft elevation on Sierra Blanca (Dillon and

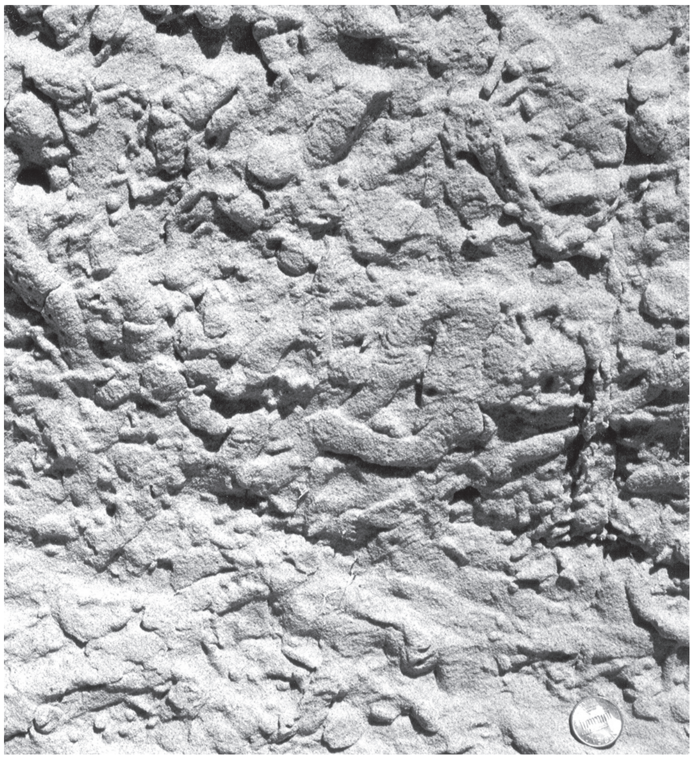


FIGURE 14. Bioturbation of upper eolian sand unit by cicada insect nymphs; about 25 cm across; US cent for scale lower right.

Metcalf, 1997), 4000 ft higher than these late Pleistocene faunal localities. Other Pleistocene molluscan faunas are reported from Nash Draw (Ashbaugh and Metcalf, 1986). In all cases, the fossil molluscan assemblages indicate a late Pleistocene climate that was cooler and wetter than that of today.

PLAYAS AND SMALL DEPRESSIONS

Numerous playa basins occur on the High Plains, many with small in-flowing drainages. Other playas and small depressions without drainages occur on the sand sheet west of the Mescalero Ridge escarpment, such as Cedar Lake, Hackberry Lake, Greenwood Lake, and Little Lake. More than 40 additional small shallow depressions occur in the mapped area (Qd, Fig. 7), most about 90 to 150 m diameter and associated with the sand sheet, many in the area of the lower eolian sand. Field inspection and color infrared aerial photography indicate that the small depressions hold water for brief periods of time and contain sediments that have washed in from within the margins of the small basins. The origin of the small basins is uncertain. Numerous other areas of closed topographic contour lines occur on the sand sheet, but they do not hold water and are too young to contain a sedimentary record.

CORRELATION OF MESCALERO SANDS EOLIAN RECORD

The sequence of eolian sand deposition in the Mescalero Sands area occurred in two episodes: the lower eolian sand unit was deposited 90 to 75 ka and correlates with oxygen isotope stage 5A, and the upper eolian sand unit was deposited 9 to 5 ka during the early Holocene. During the past 5000 yrs the sand sheet has been quasi-stable: no new sand accumulated and no old sand lost, yet soil development did not occur on the surface of the sand sheet until a period of stability during the past 500 ^{14}C yrs when the Loco Hills soil formed. Between about 5000 and 500 yrs ago, the surface of the sand sheet was in a continual state of flux although without significant eolian deposition or erosion and without soil development.

The Mescalero Sands sequence of two periods of eolian sand deposition following calcic paleosol development seems to correspond to the eolian-paleosol sequence in the Tularosa Basin of south-central New Mexico (Blair and others, 1990). However, the Tularosa Basin sequence is not directly dated; the age of the sand is assumed to be the age of associated archaeology. We believe that the archaeological sites are intrusive and post-date the age of the eolian sand. The geochronology of eolian sand sequences from the southern High Plains is also based largely on associated archaeology. Numerous study sites, however, indicate that in general the sand sheets on the southern High Plains accumulated after 4000 yrs BP during the late Holocene (Holliday, 2001), although some eolian sand accumulated locally in draws during the mid-Holocene (Holliday, 1989a). The early Holocene eolian sand deposition in the Mescalero Sands evidently does not have a strong parallel on the southern High Plains. Holocene eolian sand deposition in the Chaco dune field in northwestern New Mexico occurred between 6000 and 2000 ^{14}C yrs ago (Hall, 1990b) and seems to be out of phase as well with the Mescalero Sands. The luminescence age of the lower eolian sand unit in the Mescalero Sands is beyond the present range of radiocarbon dating and, accordingly, there is a general absence of directly dated stratigraphic sequences pre-40 ka in the region. Two thermoluminescence (TL) ages (118 and 28.6 ka) from the Blackwater Draw Formation on the southern High Plains bracket the age of the lower eolian sand unit (Holliday, 1989b). However, from a variety of evidence, the TL ages may be too young and the Blackwater Draw Formation likely pre-dates the Mescalero sand sheet.

Correlation of eolian sand sequences requires independent direct age control. At the Mescalero Sands, OSL analysis provided a geochronology that would not otherwise have been possible to obtain from associated archaeology or radiocarbon dating.

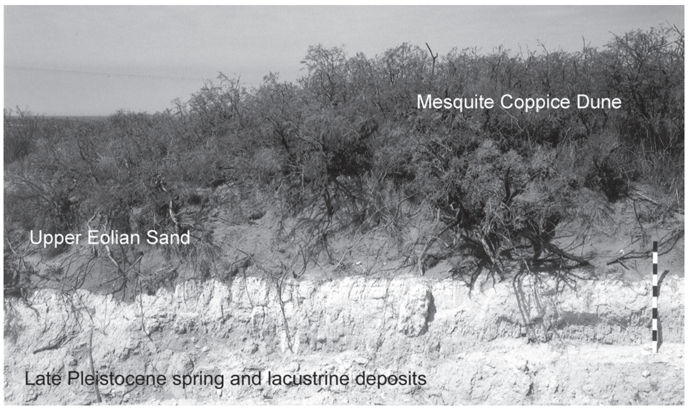


FIGURE 15. Late Pleistocene spring and cienega deposits, composite section about 5 m thick (loc. #11, Hall, 2002a; SW1/4 SW1/4 sec. 3, T16 S, R31E); contains fossil shells of aquatic and land snails and mammalian bone fragments; snail fauna from upper part of this exposure dominated by *Pupilla muscorum*; 1-m scale.

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Fields in New Mexico and Wyoming (Ingbar et al., 2005). We thank Eric Ingbar, Gnomon, Inc., and Jeffrey Altschul and Lynne Sebastian, SRI Foundation, for encouragement and support. We thank Glenna Dean for identifying Torrey mesquite for us. We also thank David Love and John Montgomery for numerous helpful comments on the manuscript.

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