Stratigraphy and geochronology of upper Quaternary eolian sand on the Southern High Plains of Texas and New Mexico, United States

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ABSTRACT

Eolian sand in dune fields and sand sheets cover >10 000 km² (~10%) of the Southern High Plains of northwestern Texas and eastern New Mexico. These deposits are concentrated in three west-east–trending belts of dunes (the Muleshoe, Lea-Yoakum, and Andrews dune fields, from north to south) that appear to be eastern extensions of the Mescalero-Monahans dune system in the Pecos River valley, and in the Seminole sand sheet, a discontinuous accumulation of sheet sands between the Lea-Yoakum and Monahans-Andrews dunes. The most common landforms are parabolic dunes associated with blowouts, coppice dunes, and sand sheets, all typical of sandy, vegetated, semiarid landscapes, barchan dunes, in keeping with a relatively limited sand supply and an underlying surface that is relatively hard (Blackwater Draw Formation, Pleistocene), and fence-row dunes, historic dunes formed along field boundaries. These eolian deposits accumulated episodically in the late Pleistocene and Holocene and provide clues to the history of regional drought and aridity. The earliest phase of sedimentation occurred when sheet sands were deposited between 11 000 and 8000 ^{14}C yr B.P., probably in several phases, based on archaeological data, as a result of episodic drought beginning between 11 000 and 10 000 yr B.P. Eolian deposits dating between 8000 and 3000 yr B.P. are rare, although eolian sediment 8000–4500 ^{14}C yr B.P. is ubiquitous in the draws that cross the region, and paleoenvironmental indicators show that the region was subjected to aridity throughout middle Holocene time. The middle Holocene deposits most likely were remobilized in late Holocene time. Most of the deposits and landforms of the dune fields and sand sheets are late Holocene, dating before 4000 ^{14}C yr B.P. and mostly before 1500 ^{14}C yr B.P. The Muleshoe and Lea-Yoakum dunes and the Seminole sand sheet underwent substantial eastward expansion in late Holocene time. Buried soils and radiocarbon ages show that the eolian sand accumulated in several stages, probably in response to cyclic drought. The Muleshoe dunes accumulated after ca. 1300 cal yr B.P. (ca. 1400 ^{14}C yr B.P.), after ca. 750–670 cal yr B.P. (ca. 850–750 ^{14}C yr B.P.), just after ca. 500 cal yr B.P. (ca. 450 ^{14}C yr B.P.), and during the nineteenth and twentieth centuries. The Lea-Yoakum dunes were active after ca. 3400 cal yr B.P. (ca. 3200 ^{14}C yr B.P.) and historically. The Seminole sand sheet was active ca. 430–330 cal yr B.P. (ca. 360 ^{14}C yr B.P.) and in the twentieth century. The Andrews dunes were subjected to at least two phases of eolian sedimentation after ca. 2320 cal yr B.P. (ca. 2320 ^{14}C yr B.P.). Comparisons with eolian chronologies from other regions on the Great Plains suggest that dune mobilization was a regional phenomenon after ca. 2300 cal yr B.P. (ca. 2300 ^{14}C yr B.P.); after ca. 1500–1400 cal yr B.P. (ca. 1650–1550 ^{14}C yr B.P.); after ca. 700 cal yr B.P. (ca. 800 ^{14}C yr B.P.); between 500 and 300 cal yr B.P. (ca. 450–300 ^{14}C yr B.P.); and in the nineteenth century. The climatic fluctuations responsible for mobilizing the dunes probably were relatively minor, yet the landscape impacts were substantial, resulting in widespread wind erosion and dune construction.

Keywords: dunes, lamellae, New Mexico, Southern High Plains, Texas.

INTRODUCTION

The Southern High Plains of northwestern Texas and eastern New Mexico is a semiarid region known to be affected by drought and wind erosion. Wind erosion is a particularly persistent problem in this dry region, documented to some degree in all years of the historic record (e.g., Fryrear and Randel, 1972; Kimberlin et al., 1977). New data show that wind erosion and eolian sedimentation occurred periodically in the region during late Quaternary time and that these processes were likely the result of episodic drought and in some cases prolonged aridity (Holliday, 1989a, 1995a, 1995b, 1997a, 1997b, 2000a). Given this geologic record and the paleoclimatic implications for the Southern High Plains, and predictions based on the results of most climate models used in studies of greenhouse warming (e.g., Schneider, 1989; Smith and Tirpak, 1990; Woodhouse and Overpeck, 1998), a reasonable assumption can be made that these phenomena will continue to be a severe problem in the region.

A more complete assessment of the effects of future drought on the High Plains landscape requires a better understanding of the history and impact of past climatic extremes. Preferred long-term, high-resolution records such as tree rings and speleothems are not available for most parts of the Great Plains. Moreover, environmental conditions on the Southern High Plains inhibit preservation of extensive or long-term paleontological or paleobotanical records. The eolian record, although far from ideal, appears to be the most complete late Quaternary, regionally traceable indicator of the geomorphic response to climatic extremes, especially periods of prolonged drought. Eolian sediments and associated soils are the most obvious and most extensive products of the past 30 k.y. and more of eolian activity in

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the region. Moreover, the dunes in particular are believed to be very sensitive to the effects of drought and desertification (Forman et al., 1992, 1995; Muhs and Maat, 1993; Muhs et al., 1997a).

In order to better understand the history of wind erosion and eolian sedimentation in the Southern High Plains, I conducted a systematic investigation of the dune fields and sand sheets of the region (largely 1992–1996) that cover ~10% of the surface. The work focused on (1) the eolian record as an indicator of the late Quaternary paleoenvironments, complementing systematic studies of the draws (Holliday, 1995a) and lunettes (Holliday, 1997a), and (2) the geomorphic evolution of the dunes, in particular clues concerning the sensitivity of the sands for remobilization. This paper presents the results of that research. For a concurrent study of the source areas of the dunes based on mineralogy and geochemistry, see Muhs and Holliday (2001).

SETTING AND BACKGROUND

The Southern High Plains, or Llano Estacado (''stockaded plains''), is a broad plateau covering ~130 000 km^2 (Fig. 1). It is an almost featureless plain, historically a prairie of perennial short grass (Blair, 1950). Altitudes range from 1700 m in the northwest to 750 m in the southeast. The plateau is underlain by Paleozoic, Mesozoic, and Cenozoic sediments and sedimentary rocks (Gustavson and Finley, 1985; Gustavson et al., 1990). Extensive Cenozoic deposits compose most of the exposed sections and surficial deposits. The bulk of the Cenozoic deposits are Miocene–Pliocene eolian and alluvial sediments of the Ogallala Formation (Gustavson, 1996; Reeves and Reeves, 1996). The upper Ogallala Formation has a thick, highly resistant pedogenic calcrete, the caprock caliche, a prominent ledge-forming unit near the top of the escarpments bordering the plateau. The Blackwater Draw Formation is the principal surficial deposit of the Southern High Plains, and blankets the Ogallala Formation (Reeves, 1976). This unit consists of early to late Pleistocene eolian deposits and buried soils (Holliday, 1989a, 1990; Gustavson, 1996; Gustavson and Holliday, 1999).

Slight topographic relief on the surface of the Southern High Plains is provided by thousands of small lake basins (playas), dry valleys (draws), and dunes (Reeves, 1972; Hawley et al., 1976; Holliday, 1995a, 1995b, 1997b) (Fig. 1). Dune fields are extensive on the Southern High Plains, occupying ~5800 km^2, and lunettes occur on the east or southeast sides of some playas. The dune fields and lunettes have different origins and stratigraphic records. The focus of this paper is the areally more extensive dune fields. The lunettes were described elsewhere (Holliday, 1997a). The lunettes and dune fields mantle the Blackwater Draw Formation and, where the Blackwater Draw Formation was deflated or never deposited, the Ogallala Formation (Holliday, 1995b, 1997a). Sedimentation in the draws, playas, and lunettes began in late Pleistocene time, and the valleys and lake basins filled with a variety of deposits (Haynes, 1975; Reeves, 1991; Holliday, 1995a; Holliday et al., 1996).

Most of the eolian sand of the Southern High Plains is found in three west-east–trending dune fields associated with reentrant valleys in the western escarpment (Fig. 1). From north to south, these sands are in the Muleshoe dunes (or sandhills); the informally termed Lea-Yoakum dunes (or Bledsoe dunes); and the informally termed Andrews dunes. An extensive belt of dunes is located in the Pecos Valley adjacent to the western escarpment of the High Plains (Fig. 1), called the Mescalero dunes in New Mexico and the Monahans dunes in Texas.

Smaller, isolated dune fields and sand sheets are also scattered across the southern and southwestern Southern High Plains. A few of these areas were investigated in this study (Fig. 1), including the Crosby dunes on the eastern edge of the Llano Estacado, the Scharbauer dunes near Midland, Texas, and a sand sheet draped across the landscape around Red Lake (a saline playa). Some work also focused on the discontinuous sand sheets and isolated sand dunes composing the so-called Seminole sand sheet (Fig. 1), scattered across ~7000 km^2.

Prior to 1992 there were no systematic studies of the dune systems and sand sheets on the Southern High Plains, although there were several investigations of individual dune fields. Melton's (1940) classic study of dune morphology included a chronology of dune-field evolution and changes in wind direction spanning the past 15 k.y., although no stratigraphic or other geochronologic data were presented. Reeves (1965) modified Melton's chronology of prevailing winds, based on studies of large lunettes associated with playas and on a few numerical ages. In other geomorphic studies, McCauley et al. (1981) showed that significant local dune deflation and dune movement can result from an individual and localized wind storm. Carlisle and Marrs (1982) used Landsat imagery to confirm previous interpretations (Green, 1951, 1961; Hawley et al., 1976) that the dune fields were constructed by westerly winds funneled through reentrants of the western escarpment.

In the Muleshoe dunes, several phases of late Quaternary dune construction were identified by Green (1951) and Gile (1979, 1981, 1985), but they had very limited age control. Gile (1979) also showed that soil morphology could be a useful tool for stratigraphic correlation throughout the dune field. Haynes (1975, 1995) and I (Holliday, 1995a) produced the only numerical age control for the Muleshoe dunes, indicating that the sediment accumulated episodically from the early to late Holocene.

In the Monahans dunes, a complex record of Pleistocene and Holocene eolian sedimentation was recognized by Huffington and Albritton (1941) and Green (1961). They correlated the deposits using vertebrate faunas, but otherwise had no means for refining the geochronology. East of the Monahans dunes, archaeological stratigraphy, paleontology, and soils were used to reconstruct the eolian record at the Midland archaeological site in the Scharbauer dunes (Wendorf et al., 1955; Wendorf and Krieger, 1959). Recent geoarchaeological research in the area refined the chronology at the Midland site and also showed that there were at least two local phases of eolian sedimentation in the Holocene (Hofman et al., 1990; Holliday and Meltzer, 1996; Holliday, 1997b).

The only data bearing on the age of the Lea-Yoakum dunes were available from several localities in New Mexico, where sand dunes formed over archaeological features that are dated as ca. 10 ka (Sellards, 1955; Holliday, 1997b). The dunes in the local area are therefore Holocene features.

The research prior to 1991 indicated that the dune fields are largely of Holocene age and that within the Holocene there were several episodes of eolian sedimentation and dune construction. The limited data suggested that much of the dune activity occurred between 9000 and 4500 yr B.P. (Holliday, 1989b), when the bulk of the eolian sediment in the draws accumulated (Holliday, 1995a, 1995b). Limited data also suggested that significant eolian sedimentation occurred in the late Holocene, similar in timing to records reported from the central Great Plains (Forman and Maat, 1990; Madole, 1995; Muhs et al., 1996, 1997a, 1997b). The research reported herein tests these hypotheses.

METHODS

Stratigraphic correlations are based on pedologic characteristics, radiocarbon dating, and archaeological data. Of particular pedogenic and soil-stratigraphic significance are clay bands or clay lamellae, thin (a few millimeters) horizons of pedogenic clay first described in the region by Gile (1979) and common in sandy soils of the world (e.g., Dijkerman et al., 1967; Larsen and Schuldenrein, 1990; Rawling, 2000). The number and thickness of clay bands appear to increase with age, but only limited age control was reported by Gile (1979).

Data were derived from field investigations of natural and artificial exposures, and from laboratory analyses of selected sections. I studied 48 localities. Most public roads through the dunes also were driven and many other exposures were examined informally as a means of assessing the extent and character of the eolian deposits. Mapping of the dune fields was based on field examination, air photos, and soil surveys. All sections were described (GSA Data Repository[1]) and samples from approximately half of the sites were subjected to a variety of laboratory analyses for sedimentologic and pedologic characterization (GSA Data Repository; see footnote 1), although the field characteristics and descriptions were the most informative kinds of data (e.g., Holliday, 1985a, 1985b, 1985c, 1985d, 1985e). Generalized descriptions of the principal stratigraphic units are presented in Table 1.

Most radiocarbon ages were determined by the University of Arizona radiocarbon laboratories (both the conventional lab A and the AMS [accelerator mass spectrometry] lab AA) (Table 2). Five ages (from the Clovis site and Red Lake) were determined as part of research by other investigators (Table 2). Most radiocarbon ages were determined on samples collected from the upper 5 cm of buried A horizons because preferred materials such as charcoal or wood are very rare on the Llano Estacado. Studies in the region and elsewhere on the Great Plains show that soils can yield reliable results and that samples collected from the top of a buried A horizon can provide a maximum age for overlying sediments (Holliday et al., 1983, 1985; Haas et al., 1986; Holliday, 1995a; Martin and Johnson, 1995). Radiocarbon ages on A horizons from weakly developed soils (A-C profiles) also provide a minimum age for their parent materials. The work reported herein and elsewhere for the Great Plains (Muhs et al., 1997a) shows that such soils form within less than a few hundred years. Organic-rich palustrine sediments, sampled in a few sections, also usually yield reasonable, approximate ages of deposition, but sometimes provide only minimum ages (Holliday et al., 1983, 1985; Haas et al., 1986; see also Holliday, 1995a).

Both humate (NaOH-soluble) and residue (NaOH-insoluble) fractions were extracted and dated. For (1) samples or horizons with several radiocarbon ages, (2) situations where ages appear reversed, or (3) where two ages are available from a single sample (both residue and humate fractions), the oldest age is considered the closest approximation of the true age because younger contaminants are more commonly and more easily introduced into buried soils. Contamination with dead carbon from groundwater, precipitated in calcium carbonate, is the only known, common means of yielding falsely old ages in the region. Calcium carbonate is removed during processing of samples, however. One radiocarbon age was determined on bone collagen using AMS following procedures described by Stafford et al. (1991).

All ages are based on a radiocarbon half-life of 5568 yr and are corrected for $\delta^{13}C$ fractionation. Most of the discussion of dating is based on uncalibrated radiocarbon ages (^{14}C yr B.P.) because (1) calibrations would confuse comparisons with other dated sequences from the region and surrounding areas, few of which are calibrated; (2) calibrations often require correction (especially the more recently published calibrations), rendering published, calibrated ages inaccurate (e.g., Stuiver and Pearson 1992; Stuiver, 1993); and (3) many of the radiocarbon ages from the draws and from archaeological sites are in the range of only tentative calibrations ($>$10 000 ^{14}C yr B.P.) (Becker, 1993; Stuiver, 1993). Late Holocene radiocarbon ages were calibrated (cal yr B.P.) following Stuiver and Reimer (1993) to facilitate some regional comparisons (Table 3). Stratigraphic correlation and dating of dune deposits also was based on archaeological data. The dune fields are rich in archaeological debris, but the dunes present special problems of interpretation due to their potential for deflation and mixing (e.g., Pearce, 1938; Fritz and Fritz, 1940; Green, 1961; Polyak and Williams, 1986; Holliday, 1997b). As a result, archaeological material was used for dating and correlation only where it was found in place or where reasonable stratigraphic inferences could be made. Regionally, the best known and best documented in situ artifacts are from the Paleoindian period, which is the time of the earliest known human occupation of the region, 11 500–8000 ^{14}C yr B.P. (Holliday, 1997b). Several well-dated and distinctive artifact types aid in dating and correlation: (1) the Clovis type (11 500–10 900 ^{14}C yr B.P.); (2) the Folsom and Midland types (ca. 10 900–10 000 ^{14}C yr B.P.); (3) the Plainview type (ca. 10 500–9500 ^{14}C yr B.P.); (4) the Milnesand and Agate basin types, probably dating the same as Plainview; (5) the Hell Gap type (ca. 10 000–9000 ^{14}C yr B.P.); and (6) the Firstview type (ca. 9400–8300 ^{14}C yr B.P.) (Holliday, 2000b).

STRATIGRAPHY

In the following discussion, the stratigraphy of each of the three main dune systems (Muleshoe dunes, Lea-Yoakum dunes, and the Monahans-Andrews dunes) is presented, followed by brief discussions of the other, smaller dune systems investigated. The stratigraphy is discussed from oldest to youngest, and the strata are grouped into age categories: late Pleistocene ($>$10 000 ^{14}C yr B.P.), early Holocene (10 000–7500 ^{14}C yr B.P.), middle Holocene (7500–4500 ^{14}C yr B.P.), and late Holocene (4500–0 ^{14}C yr B.P.).

Muleshoe Dunes

The Muleshoe dune field is a west-east–trending belt of sand consisting of a series of individual dune fields separated by areas that are either sand free or are covered by sand sheets (see Fig. 6 of Muhs and Holliday,

[1]GSA Data Repository item 2001012, Field methods, field descriptions, and laboratory data for selected dune and sand sheet sections, is available on the Web at http://www.geosociety.org/pubs/ft2001.htm. Requests may also be sent to Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301; e-mail: E-mail: editing@geosociety.org.

Figure 1. The Southern High Plains showing the locations of dune fields and sand sheets discussed in the text and selected physiographic features and cities. Also shown are the approximate eastern limit of the Muleshoe dunes, Lea-Yoakum dunes, and the Seminole sand sheet in early Holocene time (heavy curved line) and the locations of several miscellaneous study sites (EM—E&M; F—Flower Grove; M—Midland site in the Scharbauer dunes; RL—Red Lake). Inset shows the location of the Southern High Plains in Texas and New Mexico.

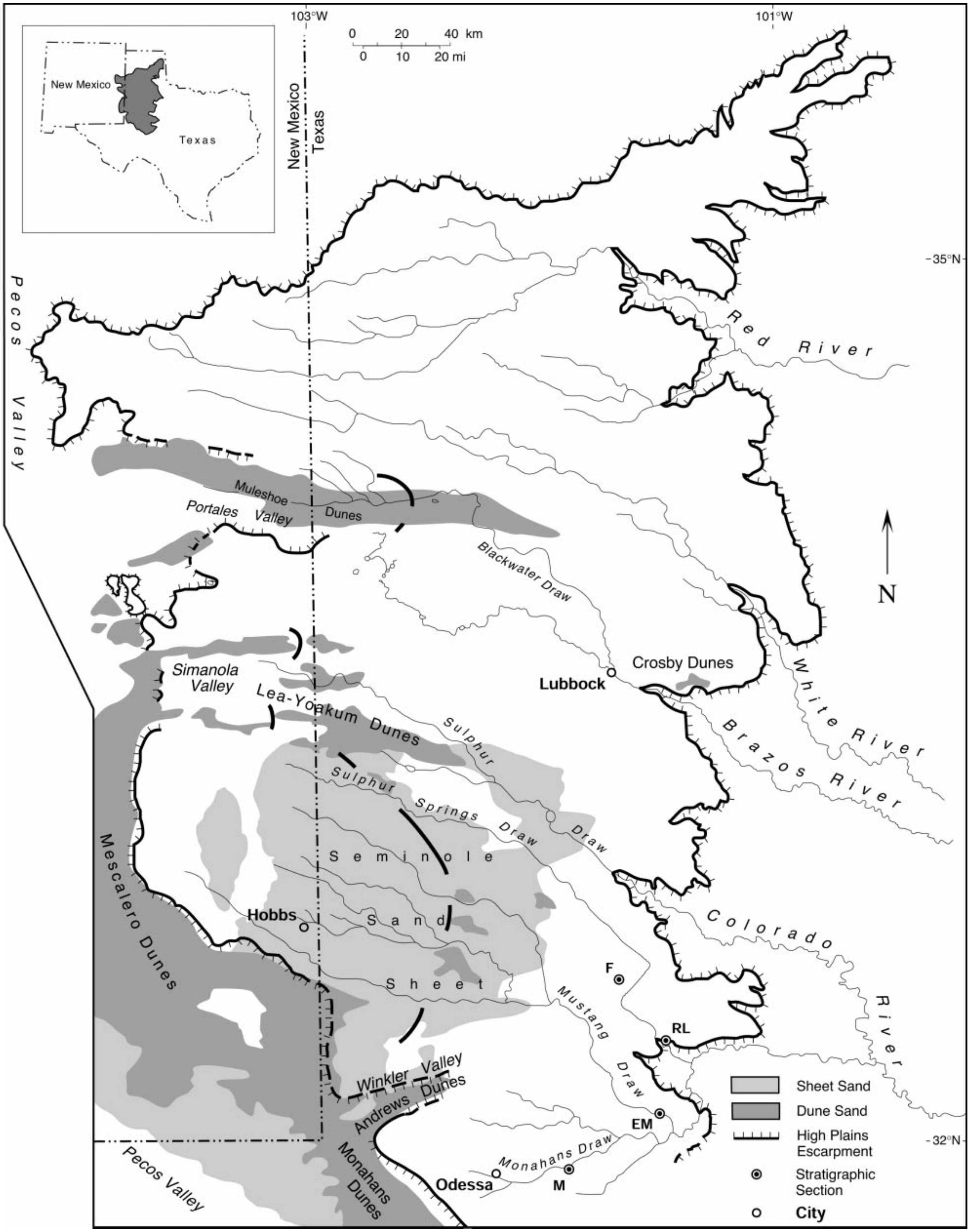
103°W
101°W
0 20 40 km
0 10 20 mi
New Mexico
Texas
New Mexico
Texas
35°N
32°N
Pecos Valley
Red River
Muleshoe
Dunes
Portales Valley
Blackwater Draw
N
Crosby Dunes
Lubbock
White River
Simanola Valley
Lea-Yoakum Dunes
Sulphur Draw
Brazos River
Sulphur Springs Draw
Seminole Sand Sheet
Mescalero Dunes
Hobbs
Colorado River
F
Mustang Draw
RL
Winkler Valley
Andrews Dunes
Monahans Dunes
EM
Monahans Draw
Odessa
M
Pecos Valley
Sheet Sand
Dune Sand
High Plains Escarpment
Stratigraphic Section
City

TABLE 1. GENERALIZED DESCRIPTIONS OF PRINCIPAL EOLIAN STRATIGRAPHIC UNITS

Andrews dunes*

Active dune sand (twentieth century)

Unit IX, loose fine sand, 100–400 cm thick, 10YR 6/6, 7/4, 7.5YR 6/6; low-angle planar cross-bedding; localized destruction of bedding by roots and burrows, otherwise no postdepositional alteration.

A or Ab horizon, ~40 cm thick; fine sand, 10YR 5/3, 5/4; very weak subangular blocky structure.

C or Cb horizon, 100–200 cm thick; loose fine sand, 10YR 6/3, 6/4, 7/2.

Late Pleistocene–early Holocene sand

Unit VIII, Btb horizon with clay bands, 30–100 cm thick; loamy sand, 10YR 6/4, 7/4 matrix with clay bands (number and thickness varies), 10YR 6/6.

Unit VIIb, Btb (argillic) or Bwb horizon, 30–100 cm thick; loamy sand, 7.5YR 5/4, 6/6; weak to moderate subangular blocky structure; thin patchy clay films on Btb peds.

Late Pleistocene sand and marl

Unit V, sandy marl, 10–15 cm thick; 10YR 8/1, 7.5YR 8/2; massive.

Unit IV, sand, 10–50 cm thick; 2.5Y 7/4, 5Y 8/2, 10YR 8/2, 7.5YR 7/4; massive.

Unit III, sandy marl, 10–20 cm thick; 10YR 8/2; massive.

Blackwater Draw Formation (Unit I)

Btb, Btkb, and Btgb horizons, sandy loam to sandy clay loam; 7.5YR 5/6, 6/6, 10YR 6/6, 7/2, 5Y 7/3; moderate to strong prismatic and moderate to strong subangular blocky structure; thick continuous clay films on ped faces.

Lea-Yoakum dunes

Active dune sand (twentieth century)

Loose fine sand, 100–300 cm thick, 10YR 6/4, 7.5YR 5/6, 6/4, 7/6; low-angle planar cross-bedding; localized destruction of bedding by roots and burrows, otherwise no postdepositional alteration.

Late Holocene sand

Fine sand; A or Ab horizon, 20–50 cm thick; 10YR 6/3, 7.5YR 6/4; massive to very weak subangular blocky structure.

Fine sand, C or Cb horizon, 50–100 cm thick; 10YR 5/4, 6/4; loose to very weak subangular blocky structure.

Late Pleistocene–early Holocene sand

Btb horizon (clay bands), 20–100 cm thick; loamy sand; 10YR 6/4, 7.5YR 5/6 matrix with 1–12 clay bands (thickness varies), 7.5YR 5/6, 5YR 4/6.

Btb horizon (argillic), 20–100 cm thick; loamy sand to sandy loam; 5YR 4/6, 5/6; weak to strong subangular blocky structure; continuous to patchy clay films on ped faces.

Blackwater Draw Formation

Btb, Btkb, and Btgb horizons, sandy loam to sandy clay; 2.5YR 4/6, 5YR 4/6, 5/6, 7.5YR 5/6, 10YR 6/4, 8/2, 7/3; moderate to strong prismatic and moderate to strong subangular blocky structure; thick continuous clay films on ped faces.

Muleshoe dunes

Active dune sand (twentieth century)

Loose fine sand, 50–300 cm thick; 10YR 6/3, 6/6; low-angle planar cross-bedding; localized destruction of bedding by roots and burrows, otherwise no postdepositional alteration.

Late Holocene sand (multiple layers common)

Fine sand; A or Ab horizon, 5–20 cm thick (locally as thick as 100 cm); 10YR 4/4, 5/3, 5/4, 6/4, 6/6; very weak subangular blocky structure.

Fine sand, C or Cb horizon, 100–300 cm thick; 10YR 5/4, 6/4, 6/6, 7/4, 7/6, 7.5YR 7/8; loose to very weak subangular blocky structure; low-angle planar cross-bedding preserved locally; up to 12 clay bands, 1–5 mm thick, 10YR 5/6, 6/8, 7.5YR 4/6 common.

Early to middle Holocene sand

Sand to loamy sand, Ab horizon (typically missing), 20–50 cm thick; 10YR 5/4, 6/4, 7.5YR 5/4, 6/4; weak subangular blocky structure.

Bt horizon (clay bands), 50–100 cm thick; loamy sand; 10YR 7/4 matrix with thin patchy clay films and ~12 clay bands, 2–5 mm thick, 10YR 5/6, 7.5YR 5/6.

Bt horizon (argillic), 50–100 cm thick; loamy sand to sandy loam; 7.5YR 5/4, 5/6; weak to moderate subangular blocky structure; thin discontinuous clay films on ped faces.

Late Pleistocene–early Holocene sand

Btb horizon (clay bands), 100–200 cm thick; sand, loamy sand; 10YR 7/3, 5YR 5/4, 6/5 matrix with up to 12 clay bands (thickness varies) 7.5YR 5/6, 5YR 4/6.

Btb horizon (argillic), 20–100 cm thick; loamy sand to sandy loam; 7.5YR 4/4, 5/4, 5YR 4/6, 5/6; weak to strong subangular blocky structure; continuous to patchy clay films on ped faces.

Note: Descriptions apply to the Andrews, Lea-Yoakum, and Muleshoe dunes only; all colors are dry Munsell.
*''Unit'' designations follow Green (1961).

2001). The Muleshoe dunes are in and downwind of the Portales Valley, a reentrant in the western High Plains escarpment (Figs. 1 and 2). The dunes also follow Blackwater Draw, a narrow, dry valley that heads within the Portales Valley and flows east-southeast to become a tributary of the Brazos River (Holliday, 1995a) (Figs. 1 and 2). The dune belt is situated north of Blackwater Draw or straddles it in New Mexico. In Texas it occurs along the south side of the draw, except where the drainage makes a sharp southward turn and the dunes cross the draw (Fig. 2). Reaches of Blackwater Draw that roughly parallel the prevailing westerly wind flow are dune free, but reaches that extend perpendicular to the wind flow are filled with eolian sand. Where the draw generally extends parallel to wind flow it may help funnel the winds, increase velocity and sand-transport energy, and thereby keep the drainage sand free.

The Muleshoe dunes overlie several substrata. In most areas, however, the sand overlies the Blackwater Draw Formation (Table 1; Fig. 3). The formation is heavily modified by pedogenesis (Table 1). In the portion of the Muleshoe dunes investigated by Gile (1979, 1981, 1985), soils of his Bailey, Curry, Hale, and Roosevelt geomorphic surfaces are equivalents to the soils formed in the Blackwater Draw Formation and other regional surficial deposits now included in the formation.

The oldest post-Blackwater Draw Formation eolian strata in the Muleshoe dune field comprise late Pleistocene to earliest Holocene sheet sand (LPEH in Fig. 3) in the western half of the area. Along the south margin of upper Blackwater Draw the sheet is a clean, white sand 1–2 m thick, stabilized by a well-developed soil with an A-Bt-C profile (b1 at Burns site and b2 at Car Body site; Figs. 2 and 3; Table 1). Archaeological materials recovered from these sands date them to between 11 500 and 9500 ^{14}C yr B.P. (Holliday, 1997b) (Fig. 3). The white sand probably was deflated from Paleoindian-age alluvial and spring sands reported in the draw (Haynes and Agogino, 1966; Haynes, 1975, 1995; Holliday, 1995b).

The upland equivalent to the white eolian sand includes both a sheet sand ~1 m thick and dunes to 3 m thick (LPEH in Fig. 3). These deposits contain a soil that varies in degree of development depending on whether it

TABLE 2. RADIOCARBON AGES FROM DUNE SANDS AND SHEET SANDS, SOUTHERN HIGH PLAINS

Dune field Site	Section	Age (^{14}C yr B.P.)	Sample number	Strat/soil horizon	δ^{13}C*	Comments
Andrews dunes						
Bedford Ranch		2125 ± 90	A-7432	VIII		Hearth; residue; unreliable
		2340 ± 40	A-7432.1	VIII	–22.5	Hearth; humates, AMS
Lea-Yoakum dunes						
Elida	93-2	3215 +355/–340	A-7435.1	ABtb1		Humates; Holiday et al. (1996)
	93-2	3475 ± 100	A-7436	2Btb1		Residue; Holliday et al. (1996)
	93-2	4720 +325/–315	A-7437	2Btb1		Residue; Holliday et al. (1996)
Lewis	Pit	6130 ± 165	A-6905	ABtb2		Residue
Muleshoe dunes						
Cage Pit	Borrow Pit	1940 ± 110	A-6906	ABtb2		Residue; unreliable
		2015 +110/–115	A-7441	ABtb2		Residue; unreliable
		3000 +140/–135	A-7441.1	ABtb2		Humates; unreliable
Cage West	93-1	14 275 +585/–545	A-7442	Btb4		Residue
		9710 ± 60	A-7442.1	Btb4		Humates, AMS; unreliable
	93-4	5140 ± 50	A-7443	Ab3		Residue, AMS; unreliable
		5160 ± 70	A-7443.1	Ab3	–23.1	Humates, AMS; unreliable
Tobosa Ranch	Roadcut	450 ± 30	A-6913	Ab1	–17.0	Residue; Holliday (1997a)
	Roadcut	755 ± 35	A-6912	Ab2	–17.8	Residue; Holliday (1997a)
	Castle	850 ± 60[†]	CAMS-16006	Cb2		Bone, AMS; Holliday (1997a)
	Roadcut	14 940 ± 240[§]	A-6914	Akb4	–13.0	Residue; Holliday (1997a)
Clovis	Southeast Bank	1480 ± 160	A-7861	G1, Ab2top	–20.5	Residue
		1480 ± 60	A-7861.1	G1, Ab2top	–20.5	Humates, AMS
		1835 +105/–100	A-7862	G1, Ab2mid		Residue; unreliable
		3890 ± 60	A-7862.1	G1, Ab2mid	–16.3	Humates, AMS
		2110 ± 80	A-7863	G1, Ab2base		Residue; unreliable
		1780 ± 50	A-7863.1	G1, Ab2base		Humates, AMS; unreliable
	South Bank[#]	680 ± 80	Y-2360	Unit G2		Stuiver, 1969; Haynes (1995)**
		910 ± 100	Y-2490	Unit G2		Haynes (1995)**
		4855 ± 90	SI-4585	Unit G1		Residue; Holliday (1985e)
	Northwest Bank[#]	2500 ± 60	AA-7094	Unit G1?		Residue, AMS; Haynes (1995)
		3800 ± 60	AA-7095	Unit G1?		Humates, AMS; Haynes (1995)
Plant X Draw	93-6	4360 ± 145	A-7444	3		Residue; unreliable
		6990 ± 70	A-7444.1	2		Humates, AMS; unreliable
	93-7	720 +195/–190	A-7445	Ab2	–16.1	Residue
		305 +145/–140	A-7445.1	Ab2		Humates, AMS; unreliable
Plant X Upland	93-1	4120 +210/–205	A-7446	Ab4	–27.0	Residue
		2140 +245/–240	A-7446.1	Ab4		Humates, AMS; unreliable
		2650 +175/–170	A-7447	A1b5		Residue; unreliable
		3195 +185/–180	A-7447.1	A1b5		Humates, AMS; unreliable
		6240 +260/–265	A-7448	ABtb5	–16.4	Residue
		5110 +395/–380	A-7448.1	ABtb5		Humates, AMS; unreliable
	93-2	7125 +190/–185	A-7449	ABkb5	–22.5	Residue
		6340 ± 50	A-7449.1	ABkb5		Humates, AMS; unreliable
	93-3	295 +95/–90	A-7450	Ab2		Residue; unreliable
		645 +150/–145	A-7450.1	Ab2	–15.7	Humates, AMS
	94–1	7330 +245/–235	A-7873	ABkb5		Residue
Rabbit Road	Southwest	7630 +485/–460	A-7871	Ab4	–22.0	Residue
		6320 ± 60	A-7871.1	Ab4		Humates, AMS; unreliable
	Northeast	Modern	A-7872	Ab1		Residue; unreliable
Miscellaneous localities						
Red Lake	41MT39	1680 ± 65	Beta-59873 ETH-10069	Qes		Charcoal, AMS; Frederick (1993)
		1810 ± 70	Beta-61789 CAMS-6033	Qes		Charcoal, AMS; Frederick (1993)
	93-1	8470 +220/–215	A-7433	BAtb2	–11.3	Residue
		6100 ± 60	A-7433.1	BAtb2		Humates, AMS; unreliable
		8640 ± 160	A-7434	Ab2	–10.4	Residue
		6620 ± 20	A-7434.1	Ab2		Humates, AMS; unreliable
	Lunette	10 050 ± 170	Beta 59874			Frederick (1993)
Terry County	41TY113	355 ± 60	ETH-16538	Sand sheet		Charcoal, AMS; Johnson et al. (1997)
Auxiliary Field	41TY115	7715 ± 60	A-9270	2Btb1	–27.0	Residue; Holliday (1997c)

Note: Dune fields are listed alphabetically. The sites are listed alphabetically for each dune field and are located in Figures 2, 5, and 8. AMS—accelerator mass spectrometry.

*Listed only for reliable ages.

[†]Mistakenly reported as 1000 ± 60 (CAMS-16031) by Holliday (1997a, Table 4), but correctly illustrated in Holliday (1997a, Fig. 4).

[§]Sample taken from soil in lunette.

[#]For a discussion of previously published ages see Haynes and Agogino (1966) and Haynes (1975, 1995).

**Y-2490 was never published but was for the same buried soil as Y-2360 (C.V. Haynes, 2000, personal commun.), but apparently was collected stratigraphically below Y-2360. The material dated is unclear, but probably is either residue or bulk organic matter.

TABLE 3. CALIBRATED LATE-HOLOCENE RADIOCARBON AGES

Dune field site	Age (^{14}C yr B.P.)	Sample number	Age	
			Calendar yr B.P.	1σ
Andrews dunes				
Bedford Ranch	2340 ± 40	A-7432.1	2344	(2352–2333)
Lea-Yoakum dunes				
Elida	3215+355/-340	A-7435.1	3448, 3430, 3405	(3839–2957)
Muleshoe dunes				
Clovis	910 ± 100	Y-2490	788	(931–703)
	1480 ± 60	A-7861.1	1345	(1406–1303)
	3800 ± 60	AA-7095	4149	(4267–4087)
	4855 ± 90	SI-4585	5595	(5657–5483)
Plant X	645 +150/–145	A-7450.1	644, 586, 574	(693–518)
	720 +195/–190	A-7445	662	(880–532)
	4120 +210/–205	A-7446	4799, 4774, 4604, 4594, 4571	(4865–4355)
G				
Tobosa Ranch	450 ± 30	A-6913	506	(515–495)
	755 ± 35	A-6912	669	(690–661)
	850 ± 60	CAMS-16006	736	(886–695)
Beminole sand sheet and miscellaneous				
Terry County	355 ± 60	ETH-16538	437, 355, 331	(494–307)
Red Lake*	1680 ± 65	Beta-59873 ETH-10069	1591, 1581, 1566	(1693–1524)
	1810 ± 70	Beta-61789 CAMS-6033	1770, 1756, 1725	(1868–1627)
Lunettes				
Lubbock Lake†	1335 ± 75	SI-4939	1276	(1299–1174)
Peterson†	1000 ± 85	A-6908	928	(969–789)
Shepard†	3110 ± 45	A-6445	3345	(3367–3263)
Sulphur Springs Draw§	3180 ± 90	Beta-55750	3378	(3470–3274)
	970 ± 70	Beta-55749	918	(939–785)

Note: Radiocarbon ages were calibrated using the CALIB program (Stuiver and Reimer, 1993).
*From Frederick (1993) and Quigg and Frederick (1993, Table 8).
†From Holliday (1997a).
§From Frederick (1998).

was buried. Where the soil is buried in dunes (Barnett Sand Pit; the sediments and soils of the Birdwell surface in Gile's study area, Bw in Fig. 3) (Fig. 2) and in sheet sands (b3 at Cage West and Rabbit Road northeast; Figs. 2 and 3) it has a typical Bt horizon with clay bands (~12 bands, 3–8 mm thick at Rabbit Road northeast; 5 bands 5–8 mm thick at Cage West). This sand sheet overlies lake muds deposited ca. 14 300 ^{14}C yr B.P. and subsequently altered by soil formation at the Cage West site (b3 in Fig. 3; Table 2). The layer was altered by some pedogenesis (clay-band formation) then buried below muds dated to ca. 7600 ^{14}C yr B.P. at the Rabbit Road site (b3 in Fig. 3; Table 2). The unburied sheet sand (Mitchell locality of the Clovis site; Fig. 3) is <1 m thick with stronger Bt expression but no clay bands. This deposit yielded an extensive assemblage of Folsom artifacts (11 000–10 000 ^{14}C yr B.P.) at the Mitchell locality (Boldurian, 1990; Holliday, 1997a). The sand sheet, therefore, probably was in place by 11 000 ^{14}C yr B.P. and stabilized before ca. 7600 ^{14}C yr B.P.

Early to middle Holocene eolian deposits are scarce in the Muleshoe dunes. Gile (1979, 1981, 1985) estimated soils of the Longview surface, characterized by 6–12 continuous clay bands in the Bt horizon (Lv in Fig. 3), to be of middle Holocene age on the basis of limited archaeological data. At the Rabbit Road southwest site, east of Gile's study area, a sand layer ~1 m thick with 15–20 continuous clay bands (b2 in Fig. 3) overlies lake

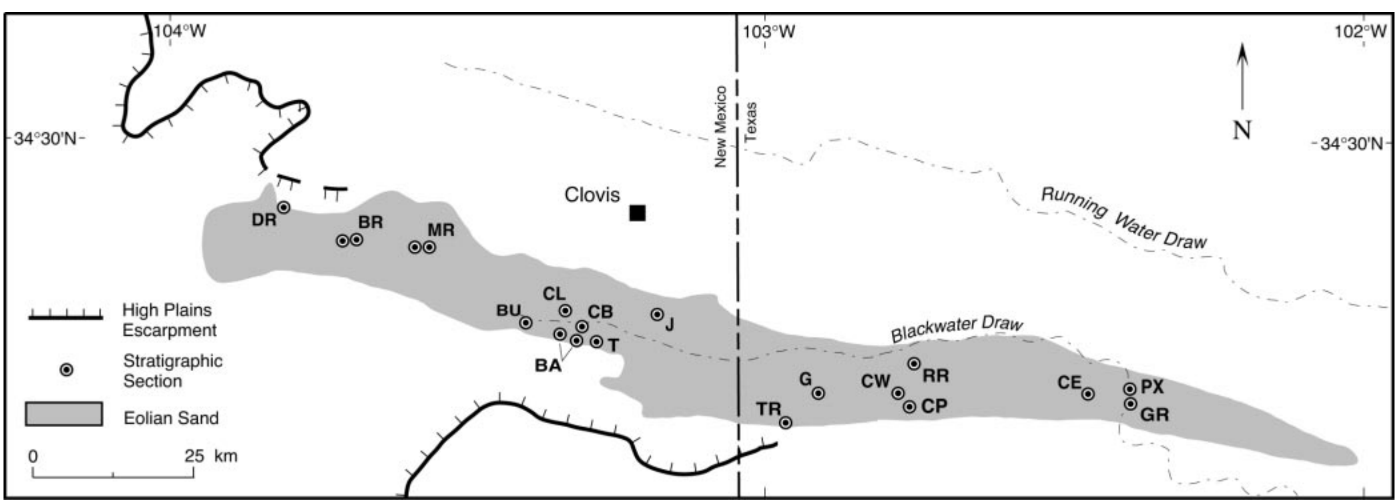

Figure 2. The Muleshoe dunes in northwest Texas and eastern New Mexico with the location of study sites mentioned in this paper (BA—Barnett site, two localities; BR—Boys Ranch, two localities; BU—Burns Ranch; CB—Car Body site: CL—Clovis site; CE—Cage East site; CP—Cage Pit; CW—Cage West site; DR—Dickenson Ranch; G—Gile's study area; GR—Gibson Ranch; J—Jorde site; MR—McFarland Ranch, two localities; PX—Plant X site; RR—Rabbit Road site; T—Keith Terry site; TR—Tobosa Ranch) along with selected cities and physiographic features. Gile's study area refers to the Bailey County field studies reported by Gile (1979, 1981, 1985).

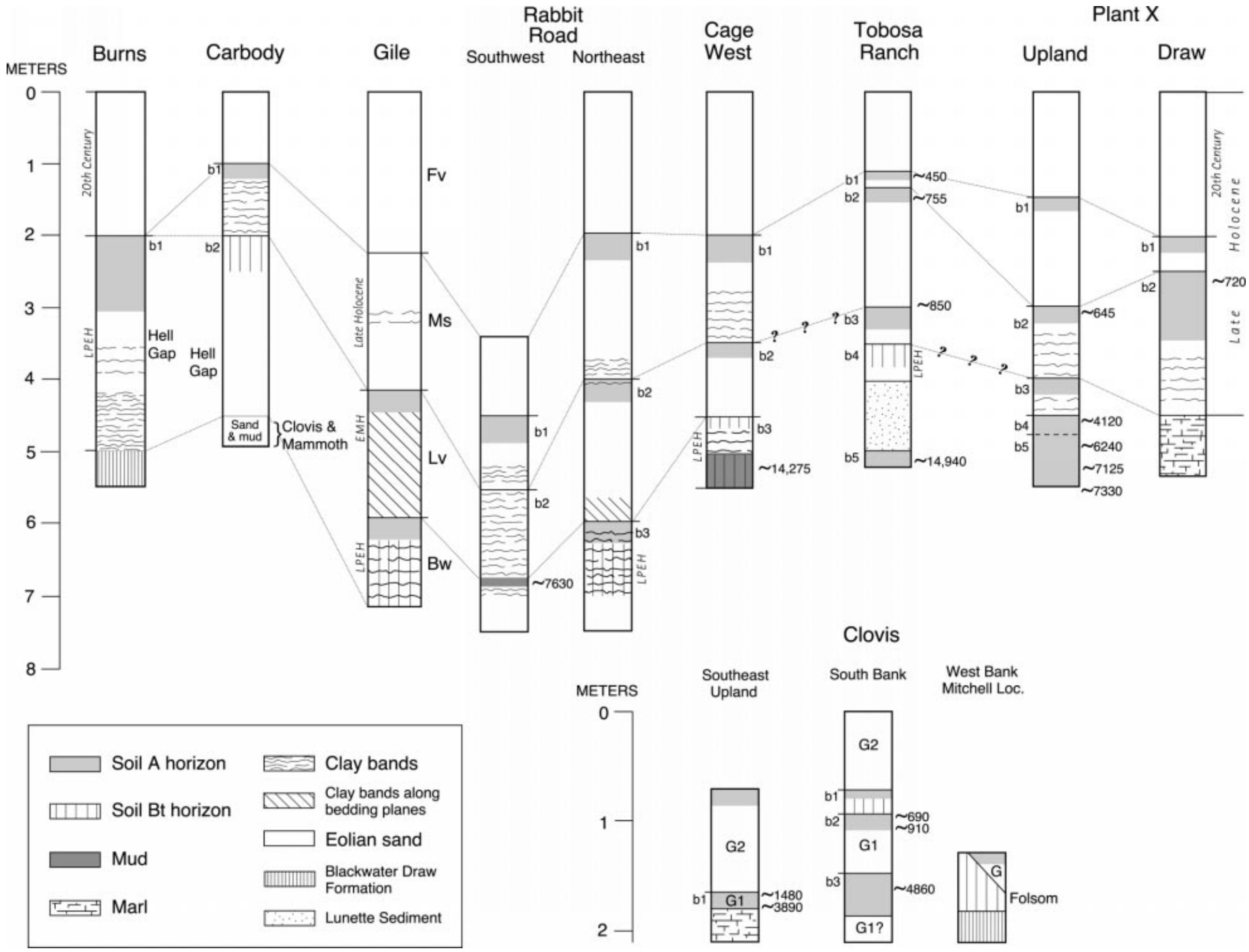

Figure 3. Stratigraphic sections of study sites in the Muleshoe dunes (LPEH—late Pleistocene–early Holocene sand; EMH—middle-Holocene sand). The numbers to the right of some sections refer to rounded means of radiocarbon ages in uncalibrated radiocarbon years (from Table 2). See Table 3 and Figure 5 for calibrations. Other terms refer to artifact associations. Dating of artifact types (in radiocarbon years) follows Holliday (1997b, 2000b): Clovis = 11 500–10 900 ^{14}C yr B.P.; Folsom and Midland = 10 900–10 000 ^{14}C yr B.P.; Plainview, Milnesand, and Agate basin = 10 500–9500 ^{14}C yr B.P.; Hell Gap = 10 000–9000 ^{14}C yr B.P.; Firstview = 9400–8300 ^{14}C yr B.P. For Bt horizons, number and thickness of vertical lines indicate relative degree of development; for clay bands the number represents field observations; the line thickness indicates relative degree of band thickness. For Gile's locality the stratigraphic terminology follows Gile (1979, 1985) (Fv—sediments and soils of the Fairview surface; Ms—sediments and soils of the Muleshoe surface; Lv—sediments and soils of the Longview surface; Bw—sediments and soils of the Birdwell surface). For all sections the nomenclature (e.g., b1, b2) refers to the buried soils numbered from the top down in each section.

muds dated to ca. 7600 ^{14}C yr B.P. (Table 2; Figs. 2, 3, and 4A), confirming Gile's initial age assessment. A sheet sand with a morphologically similar, moderately developed soil is exposed at the Jorde road cut (resting on the late Pleistocene sheet sand), McFarland Ranch #3, and Boys Ranch sites (Fig. 2). Eolian sand comprising a cumulic soil on the South Bank of the Clovis site (unit G1 of Haynes, 1995) was dated to ca. 4860 ^{14}C yr B.P. (Holliday, 1985e; Table 2; Figs. 2 and 3). This limited information suggests, therefore, that there may be a discontinuous early to middle Holocene sheet sand in the western Muleshoe dunes. In contrast to uplands of the Muleshoe dunes, early to middle Holocene eolian deposits with strongly to moderately developed A-Bt soil profiles are ubiquitous in the draws of the region (Haynes, 1975, 1995; Holliday, 1985b, 1985c, 1988, 1995a).

Late Holocene deposits are extensive throughout the Muleshoe dunes. These units are exposed at all localities, usually as at least two and locally as many as four layers (Figs. 3 and 4A). Thicknesses of individual layers vary, but the aggregate thickness of the late Holocene sands typically is 2–5 m. Late Holocene sands were recognized by Gile (1979, 1981, 1985) as sediments and soils of his Muleshoe and Fairview geomorphic surfaces (Ms and Fv in Fig. 3). As with the older sands, these young deposits are most easily differentiated on the basis of soil morphology (Table 1; Fig. 3). The buried soils exhibit simple A–C profiles or minimally expressed clay bands. The surface layer of sand in all exposures is 1–3 m thick and exhibits little to no evidence of pedogenesis or weathering. Three sites yielded reliable radiocarbon ages (Table

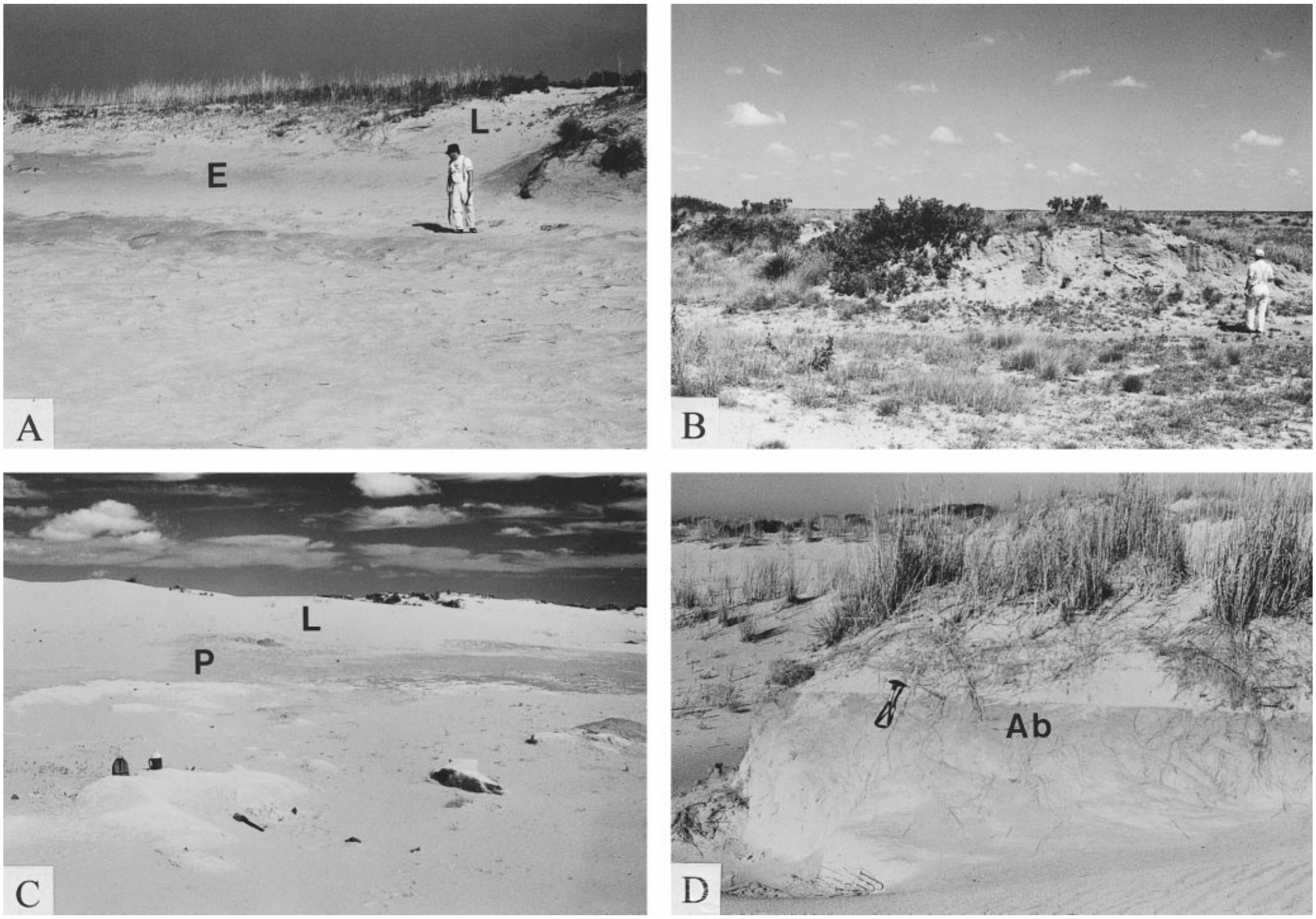

Figure 4. Sections exposed in the dune fields of the Southern High Plains. (A) One of the blowouts at the Rabbit Road site in the Muleshoe dunes (Fig. 2). Immediately in front of the figure is a low bench of palustrine mud (dated to ca. 7600 ^{14}C yr B.P.). Above the mud is early to middle Holocene eolian sand (E), ~70 cm thick, with a well-expressed soil (Ab-Btb-Cgb profile; no clay bands); it is overlain by unweathered, late Holocene (L) (probably historic) eolian sand. (B) A large fence-row dune with a road cut through it in the Lea-Yoakum dunes near the Billbrey site (Fig. 6). Shinnery oak (*Quercus harvardii*) covers much of the dune. (C) One of the blowouts at the Shifting Sands site in the Andrews dunes (Fig. 9) showing lacustrine carbonate (unit V of Green, 1961) exposed on the floor. The carbonate is overlain by late Pleistocene eolian sand (P) ~1 m thick and containing Folsom artifacts (ca. 11 000–10 000 ^{14}C yr B.P.) and a well-expressed soil (Btb profile with 15–20 clay bands). Burying the soil is unweathered, late Holocene (L) (probably historic) eolian sand ~3–5 m thick. (D) An exposure at the Bedford Ranch site in the Andrews dunes showing a typical stratigraphic sequence of late Holocene eolian sand (before ca. 2300 ^{14}C yr B.P.) with a buried soil (Ab-ACb-Cb horizonation), covered by unweathered, probably historic sand.

2). Radiocarbon ages also are available from the Clovis site (Table 2), but the stratigraphic relationships are not always clear (see footnote 1). Radiocarbon ages and soil morphology demonstrate three phases of eolian sedimentation since ca. 1000 ^{14}C yr B.P. (900 yr ago), and at least three between 5000 and 1000 ^{14}C yr B.P. (5.5 ka and 900 yr ago) (Fig. 5). Throughout the Muleshoe dunes the surface sand layer, although stabilized, is considered essentially modern (twentieth century) because of the absence of weathering and because locally it buries modern artifacts and structures. Some of the sands with A–C soils buried by the twentieth century deposits (Fig. 3) probably represent the active dunes reported in the nineteenth century (Muhs and Holliday, 1995).

Lea-Yoakum Dunes

The Lea-Yoakum dunes differ from the other major dune fields of the region in several significant characteristics. This dune belt is a group of individual west-east–trending dune fields extending east from the northern Mescalero dunes (Table 4; Figs. 1 and 6). The individual dune fields form a somewhat anastomosing pattern downwind of the Simanola Valley, a reentrant in the western High Plains escarpment (Figs. 1 and 6).The Lea-Yoakum dunes are moderately well vegetated, more so than the Monahans-Andrews system (see following), but less so than the Muleshoe dunes. A notable characteristic of this dune system is the common occurrence of fence-row dunes (historic dunes formed along field boundaries) (Figs. 4B and 7), more than in any other part of the Southern High Plains. The Lea-Yoakum dunes overlie several substrates (Table 5), but the Blackwater Draw Formation is the most common. In the southwestern part of these

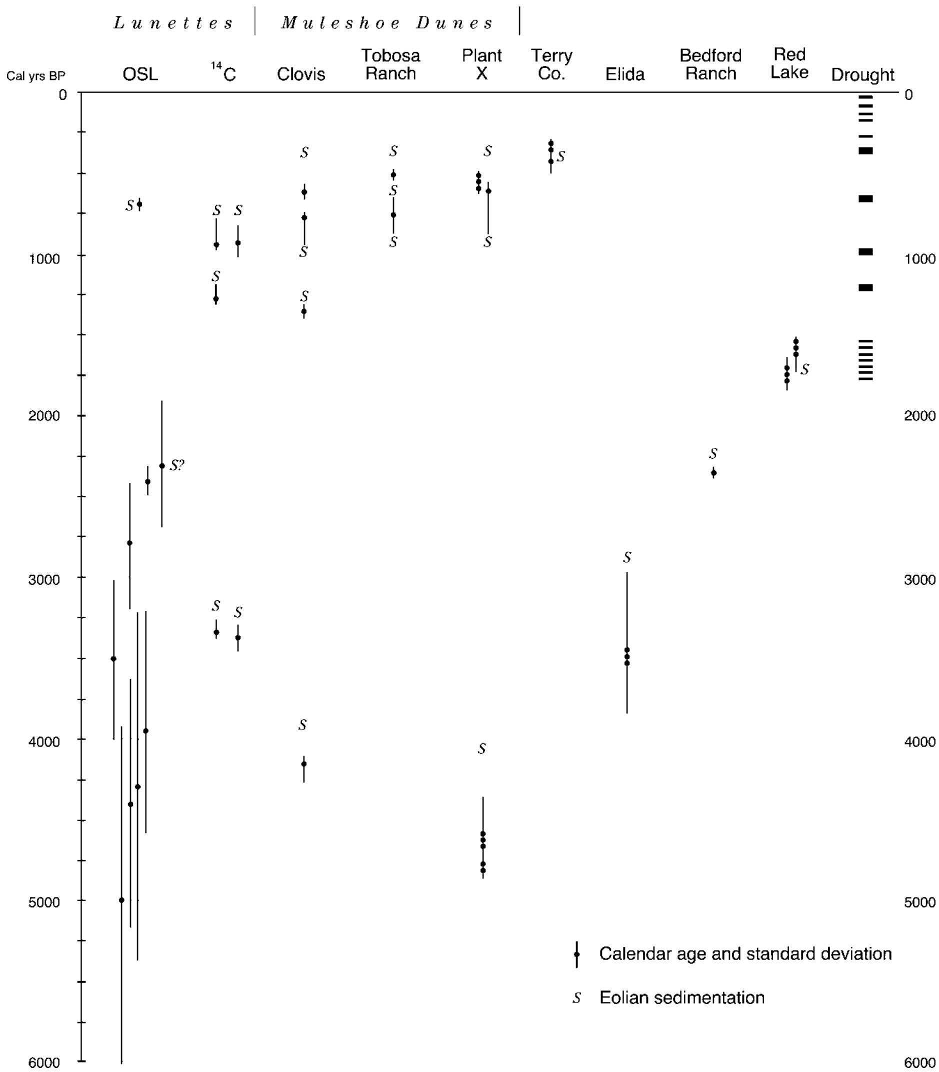

Figure 5. Plots of calibrated radiocarbon ages for late Holocene eolian sand (from Table 3) compared to the geochronology of lunettes (OSL [Optically stimulated luminescence] ages from Rich et al., 1999; radiocarbon ages from Holliday, 1997a; Frederick, 1998) and to the drought chronology of the past 2 k.y. for the central Great Plains (Woodhouse and Overpeck, 1998). The periods of eolian sedimentation are the most minimal interpretations, i.e., most were probably of longer duration, and there were probably other episodes.

dunes the formation is missing and dunes directly overlie the caprock caliche K horizon (petrocalcic horizon) of the Ogallala Formation.

The oldest component of the Lea-Yoakum dunes is a late Pleistocene-early Holocene sheet sand commonly <1 m thick. This deposit seems to be more common in the western part of the dune field (i.e., in New Mexico), but this may be an artifact of a greater number of exposures investigated in that area. The late Pleistocene deposits are strongly modified by pedogenesis. Most exposures exhibit a buried A-Bt or A-Bt-C profile with either typical argillic-horizon morphology (Ro–16 site, b1 at Elida and Tatum sites, b2 at the Lewis site; Table 1; Figs. 6 and 8) or clay bands (Milnesand and Williamson sites; Table 1; Figs. 6 and 8). Five of these sites produced artifacts that date the sands to between 11 000 and 9500 ^{14}C yr B.P. (Holliday, 1997b) (Fig. 8).

Several layers of eolian sand overlie the late Pleistocene–earliest Holocene sheet sand, but age control on these deposits is very poor. There is little or no clear evidence for a younger (post-9500 ^{14}C yr B.P.) early to middle Holocene eolian layer, although probable middle Holocene eolian sediments are reported from the draws in the area (Holliday, 1995a) and on the margins of a playa basin at the Terry County site in the Seminole sand sheet (see following), downwind of the Lea-Yoakum dunes (Figs. 6 and 8). At the Lewis site (Fig. 6), a Bt horizon (b1 in Fig. 8) formed in a sheet sand that overlies a buried A-Bt soil (b2 in Fig. 8) dated to ca. 6100 ^{14}C yr B.P. (Table 2). The dated horizon (lower b2 soil), however, is morphologically identical to the older buried soil, which contains Paleoindian artifacts. The younger sand with the Bt horizon may therefore be a younger early or middle Holocene layer. The Stuck Truck locality (Fig. 6) contains a buried soil with a well-expressed Bt horizon (~10 clay bands in sand overlying an argillic horizon) indicative of eolian sand in place since the middle Holocene.

Above the late Pleistocene–early Holocene layer there is commonly at least one layer of sand in a discontinuous sheet (0.5–2 m thick) or in dunes (3–5 m thick) exhibiting a weakly to moderately expressed soil (Table 1; Fig. 8). At the Elida site playa, this sand is dated to before 3200 ^{14}C yr B.P. (Table 2; Fig. 8). The limited numerical age control and soil morphology suggest that at least one layer of sand was deposited in the late Holocene, but prior to the twentieth century. Unweathered sands 1–3 m thick are ubiquitous throughout the Lea-Yoakum dunes and probably are twentieth century deposits, on the basis of the nearly complete absence of postdepositional alterations.

Monahans-Andrews Dunes

The Monahans dunes follow the east side of the Pecos River valley in Texas (Table 4; Figs. 1 and 9). The Andrews dunes are a small extension trending northeast from the larger Monahans system. The Andrews dunes extend up the informally named Winkler Valley, a reentrant in the western High Plains escarpment (Table 4; Figs. 1 and 9). The Andrews dunes are here identified separately from the Monahans dunes to differentiate their physiographic settings (Winkler Valley versus Pecos Valley), although Green (1961) referred to the entire set of dunes as the Monahans. Most study sections are in or near the Andrews dunes. The Monahans-Andrews dunes are the most active of the dune fields (see Fig. 7 of Muhs and Holliday, 2001) on or adjacent to the Llano Estacado, and also are the most active dune fields on the Great Plains. In 1984, ~300 km^2 of the dunes were active (Muhs and Holliday, 1995).

The field work in the Monahans-Andrews dunes largely confirmed the stratigraphic sequence reported by Green (1961), which in-

TABLE 4. DESCRIPTIVE DATA FOR DUNE FIELDS OF THE SOUTHERN HIGH PLAINS

Dune field	Length (km)	Width (km)	Area (km²)	Dune height		Dune types*	Sand sheet?	Thickness (m)	Mean grain size M_z† Φ (mm)	Sorting†
				Typical (m)	Upper limit (m)					
Andrews	50	6–10	370	2–5		Active barchanoid ridges and parabolic with blowouts Stabilized barchan Coppice			1.14 (0.45)–1.53 (0.35)	ms-mws
Crosby	13	1–5	40	2		Parabolic with blowouts Coppice Some barchan and barchanoid ridges	Yes	1–2	N.D.	N.D.
Lea-Yoakum§	12	2	25	<3		Parabolic with blowouts	Yes	<1	1.34 (0.40)–>2.18 (0.22)	mws-ws
	60	10	620 1330#	<3		Fence-row				
Mescalero	200	10–20		1–3		Barchan and barchanoid ridges Coppice Parabolic with blowouts Aklé**			N.D.	N.D.
Monahans††	100	25	2200††	2–5		Barchan§§ and barchanoid ridges Aklé Parabolic with blowouts Coppice			N.D.	N.D.
Muleshoe	160	8–12##	1850	<5	8	Parabolic*** with blowouts Barchanoid ridges††† Coppice	Yes	<1	1.02 (0.49)–>2.03 (0.24)	ms-mws
Scharbauer	1.7	0.2–0.7	<5	2–4	6	Active blowouts Coppice			1.25 (0.42)	ms

Note: N.D.—not determined.
*Barchanoid ridges are the ‘‘transverse ridges’’ of Melton (1940). Coppice dunes are also referred to ‘‘nabkhas.’’ Aklé dunes are also referred to as ‘‘complex’’ dunes.
†Mean grain size and sorting is the range in means calculated for each site (see GSA Data Repository item 2000xx); ms—moderately sorted, mws—moderately well sorted, ws—well sorted.
§First and second rows for length, width, area, and height provide minimum and maximum ranges for the group of dunes.
#Total area covered by the Lea-Yoakum dunes.
**Found in the southern Mescalero dunes.
††Between the main belt of dunes and the Pecos River (20–70 km west of the dunes) is an area >2500 km² with scattered dunes and sand sheets.
§§Some data from Melton (1940, Fig. 25) and Machenberg (1984). For an air photo, see Muhs and Holliday (2000, Fig. 7).
##Locally up to 18 km wide.
***For an air photo, see Muhs and Holliday (2000, Fig. 6).
†††These are the ‘‘transverse ridges’’ of Melton (1940, p. 139, Fig. 29) in the Portales Valley, near and west of Portales, New Mexico (Fig. 2).

cluded lacustrine and palustrine as well as eolian deposits. The dunes overlie three substrata (including units I and III–V of Green, 1961; Table 5), most commonly the Blackwater Draw Formation.

There are at least two late Pleistocene–early Holocene eolian deposits in the Monahans-Andrews system. Winkler–1, Shifting Sands, Bedford Ranch, and Wyche Ranch (Figs. 1 and 9) contain a sheet sand <1 m thick with an A-Bw or weak A-Bt soil (units VI and VIIb of Green, 1961; Holliday, 1997b) (Table 1; Fig. 10). Above this deposit at the Shifting Sands and Bedford Ranch sites is a layer of eolian sand 1–2 m thick with dozens of clay bands (Fig. 3.55B of Holliday, 1997b; unit VIII of Green, 1961) (Table 1; Fig. 10). The two eolian layers span the time from 11 000 to ca. 9000 ^{14}C yr B.P., based on archaeological information from the four localities (Figs. 4C and 10) (Holliday, 1997b). Green (1961, p. 30–31) identified unit VIIa, a ‘‘light gray loess-like sandy silt,’’ as a stratigraphic equivalent to VIIb. In the recent field studies it was seen in only one exposure and represented sediment deflated from older carbonate, forming a lunette.

At least one sand layer was observed above the late Pleistocene–early Holocene units at all localities in the Monahans-Andrews dunes. At Bedford Ranch and Wyche Ranch in the Andrews dunes there is a sand layer 1–2 m thick with an A-C or A-Bw soil (Table 1; Figs. 4D and 10). This layer is considered to be late Holocene based on: (1) its stratigraphic position below twentieth century deposits; (2) recovery of late Prehistoric (older than 1000 ^{14}C yr B.P.) artifacts from the A horizon; (3) weak soil development; and (4) a radiocarbon age of ca. 2300 ^{14}C yr B.P. on charcoal and ash from the base of the sand at Bedford Ranch (Table 2; Fig. 10). In the Monahans dunes (Winkler County Park and Vest-Wheeler localities G and H; Fig. 9), below the active sands, is a buried eolian sand layer with weakly expressed clay bands (Table 1). It is probably an equivalent late Holocene deposit based on its stratigraphic position and soil development. Unweathered, generally active sands 1–3 m thick are ubiquitous throughout the region (Fig. 4, C and D), and are probably twentieth century deposits. The active sands are unit IX of Green (1961). The sands with the weak soil may also be a component of unit IX.

Other Dune Systems and Sand Sheets

Several other dune systems provided chronologic or stratigraphic data important to this study: the Mescalero dunes, the Scharbauer dunes, the Red Lake sand sheet, the Seminole sand sheet, and the Crosby dunes (Fig. 1). The Mescalero dunes are a belt of eolian sand in the Pecos River valley of New Mexico immediately below and west of the High Plains escarpment (Tables 4 and 5; Figs. 1, 6, and 9). The dunes are essentially a northward extension of the Monahans dunes in New Mexico (Fig. 9). They are by far the most extensive dune system of those investigated, but they provided little information because they are largely inaccessible. Unweathered active or sparsely vegetated, probably twentieth century dunes are ubiquitous in the Mescalero dunes. Somewhat older late Holocene sands are at least locally common. Below the modern sands, a layer 1–3 m thick with an A-Bw-C or A-C soil (Dune Buggy and Center Dune sites, respectively; Fig. 6) was observed. Be-

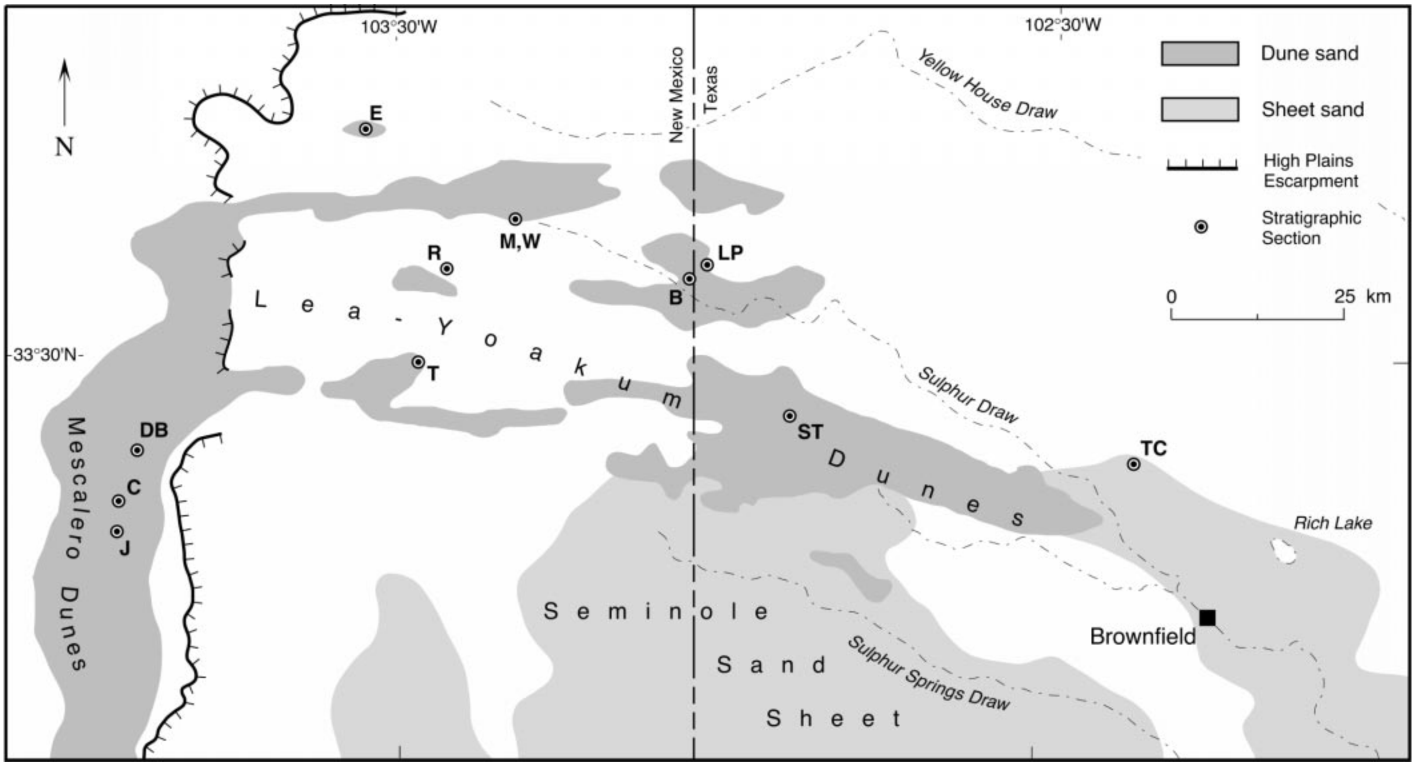

Figure 6. The Lea-Yoakum dunes in northwest Texas and eastern New Mexico, the northern Mescalero dunes in New Mexico, and the northern Seminole sand sheet in Texas and New Mexico and the location of study sites mentioned in this paper. Mescalero dunes: C—Center dune; DB—Dune buggy; J—Judkins dune. Lea-Yoakum dunes: B—Bilbrey site; E—Elida site; LP—Lewis Pit; M,W—Milnesand and Ted Williamson sites; R—Ro–16 site; ST—Stuck Truck site; T—Tatum site. Seminole sand sheet: TC—Terry County Auxiliary Airport. Also shown are selected physiographic features and cities.

low these late Holocene sediments are a variety of deposits that are undated and uncorrelated, including interbedded sands and marls, and sands with well-expressed clay bands along bedding planes.

The Scharbauer dunes form a small, isolated dune field that overlies the Blackwater Draw Formation and overlaps Monahans Draw (Fig. 1). About half of the dune field is active (Table 4). The eolian chronology is based on data from the Midland archaeological site (Wendorf et al., 1955; Wendorf and Krieger, 1959; Holliday, 1995a, 1997b; Holliday and Meltzer, 1996). Four eolian sand layers were identified. The oldest deposit is a fine to very fine sand <1 m thick. All other layers are medium to fine sands. The oldest of these overlies the finer sand, and is 1–2 m thick with an A-Bt-Bw-C soil profile in the upper meter. Folsom and Midland artifacts (11 000–10 000 ^{14}C yr B.P.) were found in the buried A horizon at the top of this sand layer (Holliday, 1997b; Holliday and Meltzer, 1996) (Fig. 10). Above that unit is another sand layer that is also 1–2 m thick. This deposit exhibits an A-Bw-C soil profile, although a few thin clay bands are apparent in some sections. The buried A horizon is a prominent stratigraphic marker. This deposit also is found in the draw where it is dated by stratigraphic correlation to between 10 000 and 5 000 ^{14}C yr B.P. (Holliday, 1995a, 1997b; Holliday and Meltzer, 1996). The uppermost sand layer is draped across the entire dune field. It is <50 cm thick and probably a twentieth century deposit based on the lack of postdepositional alteration.

Red Lake is a small saline playa adjacent to lower Sulphur Springs Draw (Fig. 1). Frederick (1993, 1998) documented the presence of a thin (<1 m thick) sheet sand draped across most of the landscape in the area around the lake. Frederick (1993, p. 38) described the layer as sandy to loamy and modified by pedogenesis with both calcic (Bk) and, less commonly, argillic (Bt) horizons. Deposition of this layer began after ca. 10 000 ^{14}C yr B.P., based on a radiocarbon sample taken from the top of an underlying lunette (Table 2). As part of this study, the sheet sand was investigated along a low wave-cut cliff of Red Lake. At this site there are two sand units (Fig. 10). These layers are not continuous, based on Frederick's (1993) descriptions; they are found in stratigraphic juxtaposition in some areas but not in others. The lower layer is a sandy clay loam, ~55 cm thick, strongly modified by soil formation, exhibiting an A-Bt (argillic) soil profile (b1 soil in Fig. 10). The soil in the lower sheet sand is welded by pedogenesis to a buried A horizon (b2 soil in Fig. 10) formed in underlying lake deposits. This deepest buried A horizon is dated to ca. 8500 ^{14}C yr B.P. (Table 2; Fig. 10). The upper surface unit is also a sandy clay loam ~80 cm thick, but weakly modified by pedogenesis (A-Bw soil). Frederick (1993, p. 38) reported radiocarbon ages on charcoal of ca. 1800 and 1700 ^{14}C yr B.P. (Table 2) from the upper sheet sand. The radiocarbon ages, combined with soil-stratigraphic comparisons to similar kinds of deposits in lowland settings (Holliday, 1988, 1995a), indicate that the lower sheet sand was deposited in the early or middle Holocene, before 8500 ^{14}C yr B.P., and that the upper sheet sand was deposited in the late Holocene, ca. 1800–1700 ^{14}C yr B.P. (1.75–1.55 ka).

The Seminole sand sheet is a large upland area of discontinuous eolian sediment on the southern and southwestern Southern High

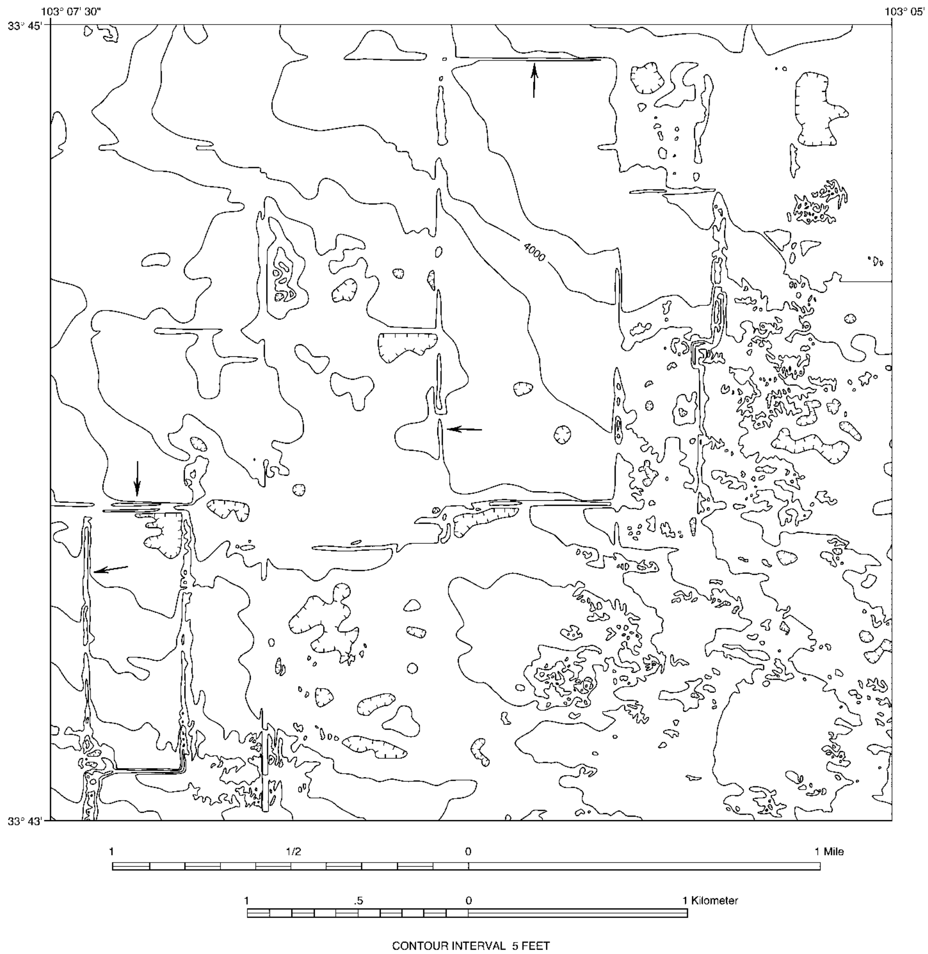

Figure 7. Topographic map showing fence-row dunes (examples indicated by arrows) in the Lea-Yoakum dunes (from U.S. Geological Survey 7.5' quadrangle, Bledsoe northeast, New Mexico), ~15 km north-northwest of the fence-row dune shown in Figure 4B.

Plains, between the Lea-Yoakum and Andrews dunes (Tables 4 and 5; Figs. 1, 6, and 9). Previous mapping of the area (Eifler and Reeves, 1974, 1976) implies that eolian deposits are extensive. However, field checks of this area revealed that: (1) the wind-derived sediments above the Blackwater Draw Formation in this area are thin (typically <1 m) and very localized, covering much less than 50% of the area; (2) the deposits are most common or are at least more commonly exposed along the margins of lowlands such as draws or playas; and (3) the rolling upland topography, interpreted as dunes, represents undulations on the surface of the Blackwater Draw Formation. Further field studies also show that dunes are locally common in the western (New Mexico) portion of the sand sheet and discontinuous eolian deposits are common east of the area originally mapped.

Scattered exposures of the Seminole sand sheet indicate that three phases of eolian sedimentation are represented in addition to twentieth century sand reactivation. An isolated sand dune 3 m high exposed along Monument Draw (Fig. 9) contains a very well developed soil (A-Bt profile 170 cm thick). The degree of pedogenesis is stronger than any other soil formed in the sands of the region and is comparable only to the soils of the late Pleistocene sheet sand in the western Muleshoe dunes. This dune may have been in place throughout Holocene time. A layer of sandy loam 0.5–1.0 m thick with a moderately well expressed Bt horizon was exposed along the margins of a playa basin at the Terry County Auxiliary Airfield (Fig. 6), at the Seminole Draw and E&M sites (Figs. 1 and 9), and at Rich Lake (unit F of Haynes, 1975, p. 77–81; Fig. 6). It represents at least one and possibly two middle Holocene eolian deposits based on (1) a date of ca. 7720 ^{14}C yr B.P. from below the layer at the Terry County site (Table 2; Fig. 8); (2) the presence of Archaic artifacts (ca. 8000–4000 ^{14}C yr B.P.) (M.B. Collins, 1983, personal commun.; Haynes, 1975); and (3) soil-stratigraphic correlation with the lower sheet sand above the date of ca. 8500 ^{14}C yr B.P. at Red Lake. A sheet sand <1 m thick with an A-Bw soil (e.g., Flower Grove and b1 at Terry County Auxiliary Airfield sites, Figs. 1, 6, and 8) is late Holocene based on the degree of soil development, the recovery of artifacts dating to 500–100 ^{14}C yr B.P., and a radiocarbon assay of ca. 360 ^{14}C yr B.P. on charcoal at the Terry County site (Table 2; Fig. 8). Late Holocene and twentieth century dunes (units G and H, respectively, of Haynes, 1975, p. 79–81) also were identified at Rich Lake (Fig. 6).

The Crosby dunes are on the eastern edge of the Llano Estacado (Tables 4 and 5; Fig. 1). These dunes are unusual because they are the only dune field in the eastern half of the Llano Estacado. The only clue to their origin is that they overlie a local sandy facies of the Blackwater Draw Formation, and the sand in the dunes very likely was deflated from this source. Mapping of the Crosby dunes at a scale of 1:250 000 (Eifler et al., 1993) suggests a continuous cover of sand on top of the Blackwater Draw Formation, but field checking shows that some of these areas are simply an undulating topography at the top of the Blackwater Draw Formation.

Three discontinuous layers of eolian sand were recognized in the Crosby dunes. The lower layer, containing Paleoindian artifacts, is as thick as 1 m and has a well-expressed Bt soil horizon. At the Big Sandy site the Bt horizon is ~50 cm thick with 4–5 clay bands 1–2 cm thick (Fig. 10). The zones between the clay bands also are areas of clay illuviation, but are not as clayey as the clay bands. The deposit probably is early Holocene, based on recovery of late Paleoindian artifacts (10 000–8000 ^{14}C yr B.P.) (Fig. 10) from the upper half of this sand layer. At the Robertson site this zone is thinner, but the Bt is expressed as a typical argillic horizon, and artifact styles (Fig. 10) date it to latest Pleistocene–early Holocene time (11 000–8500 ^{14}C yr B.P.). Above the Paleoindian level at the Robertson site is another eolian layer, ~1 m thick, with a moderately expressed Bt horizon (Fig. 10). The degree of soil development suggests that the sediment is of middle Holocene age. The upper layer at Big Sandy also is ~1 m thick and overlies the lower sand layer in some areas or directly on the Blackwater Draw Formation in other areas. The upper sand exhibits an A-Bw-C or A-C soil profile, indicative of minimal weathering and a late Holocene age.

TABLE 5. GEOLOGIC SUBSTRATE OF DUNE SAND AND SHEET SAND

Dune field or sand sheet	Description
Andrews	Petrocalcic (K) horizon (Ogallala Formation ''caprock caliche''?) Pleistocene eolian sand and sandy loam (Blackwater Draw Formation)* Late Pleistocene valley fill (sandy marl)†,§
Crosby	Pleistocene eolian sand and sandy loam (Blackwater Draw Formation)
Lea-Yoakum	Petrocalcic (K) horizon (Ogallala Formation ''caprock caliche'') Pleistocene eolian sand and sandy loam (Blackwater Draw Formation) Late Pleistocene valley fill (marl) in upper Sulphur Draw§
Mescalero	Petrocalcic (K) horizon (Ogallala Formation ''caprock caliche'') Pleistocene eolian sand and sandy loam (Blackwater Draw Formation)
Monahans	Petrocalcic (K) horizon (Ogallala Formation ''caprock caliche''?) Pleistocene eolian sand and sandy loam (Blackwater Draw Formation)* Late Pleistocene marl#
Muleshoe	Pleistocene eolian sand and sandy loam (Blackwater Draw Formation) Late Quaternary fill in playa basins (palustrine mud)** Late Pleistocene valley fill (marl) in upper and middle Blackwater Draw§ Holocene valley fill (marl and mud)§
Scharbauer	Pleistocene eolian sand and sandy loam (Blackwater Draw Formation) Late Pleistocene valley fill (marl)§,††
Seminole sand sheet	Pleistocene eolian sand and sandy loam (Blackwater Draw Formation) Late Quaternary fill in playa basins (palustrine mud)**

*Equivalent to the ''Judkins Formation'' or Unit 1 of Green (1961).
†Equivalent to Unit III or V of Green (1961). Locally contains an interbed of cleaner, less calcareous sand (Unit IV of Green, 1961). Remains of late Pleistocene megafauna (e.g., *Bison antiquus, Mammuthus columbi, Equus* sp.) common in the lower sandy marl (Unit III; Green, 1961). Mastodont was found in the sand interbed (Unit IV; J. Blaine and E. Johnson, 1994, personal commun.), which is the only find of this species reported for the Llano Estacado.
§Late Pleistocene and Holocene valley fill is described and discussed by Holliday (1995a).
#Equivalent to Unit III or V of Green (1961).
**Playa fill described and discussed by Holliday et al (1996).
††''White sand'' or Unit 1 of Wendorf et al. (1955).

DISCUSSION AND CONCLUSIONS

The dunes fields of the Southern High Plains, in particular the three belts of dunes extending across the western part of the region, differ somewhat in their overall morphology, physical appearance, and to some degree stratigraphic records. The issue of the source area for the sand has long been controversial (e.g., Hefley and Sidwell, 1945; Green, 1951; Jones, 1959). Muhs and Holliday (2001) presented mineralogical and geochemical data to show that the dunes are most likely derived from the Blackwater Draw Formation; i.e., they were probably derived locally.

Dune forms are similar among the three west-east dune belts, but there are more varieties in the Mescalero and Monahans dunes. Typical dune forms throughout the region include blowouts, parabolic dunes, and coppice dunes, which are typical of sandy, vegetated, semiarid landscapes (Melton, 1940; Hack, 1941; McKee, 1979; Gile, 1966, 1985, p. 33–39; Pye and Tsoar, 1990, p. 195–196, 219–220; Lancaster, 1995, p. 76–77). Fence-row dunes, locally common in many areas, are historic landforms found around farm fields on sandy soils of the region, and result from poor soil conservation practices. Barchan dunes and barchanoid ridges are also common, particularly in the Mescalero and Monahans dunes, and are in keeping with a region of relatively limited sand supply and an underlying surface that is relatively hard (i.e., the Blackwater Draw Formation) (Fryberger, 1979; Pye and Tsoar, 1990, p. 175; Lancaster, 1995, p. 52). Sand sheets are the single most widespread eolian landform, indicative, in this situation, of eolian sedimentation on a vegetated surface (Kocurek and Nielson, 1986). The presence of the Seminole sand sheet between the Lea-Yoakum and Monahans-Andrews dune systems and their associated reentrant valleys further suggests that sheets may form where sand supply is more limited, i.e., where vegetation is not overwhelmed by sand.

Barchan, barchanoid ridges, and parabolic dunes contrast strongly with aklé (or complex) dunes, which are also common in the Mescalero and Monahans dunes. The complex aklé dunes form in response to more than one seasonal wind regime, but the barchan and barchanoid ridges are indicative of a single prevailing wind direction during dune construction (McKee, 1979; Pye and Tsoar, 1990, p. 219; Lancaster, 1995, p. 52). This seeming contradiction is explained by the topographic settings of the various dune fields. The aklé dunes are in the Monahans and southern Mescalero dunes of the Pecos Valley and are subjected to seasonal winds from three directions during the year (southeast, southwest, and west-northwest) (Carlisle and Marrs, 1982; Machenberg, 1984). The barchans and barchanoid ridges dominate the linear Andrews belt of dunes in or downwind of the reentrant Winkler Valley, which is roughly aligned with westerly winds. Apparently, the valley funnels the westerly winds and produces a dominant orientation in the dunes. Carlisle and Marrs (1982, p. 94–96) noted a shift in dune orientation as the dunes follow the southwestern Caprock escarpment from the Pecos Valley into the Winkler Valley, but did not recognize the Winkler Valley.

Dune activity varies latitudinally; the Muleshoe dunes are the least active (most stabilized with the heaviest vegetation cover) and the Monahans-Andrews dunes are the most active (least vegetation cover). The geographic variability in dune activity appears to be a function of the ratio of precipitation to potential evapotranspiration, which decreases (i.e., conditions become warmer and drier) from north to south (Muhs and Holliday, 1995, p. 203).

In overall plan or patterning the Muleshoe and Andrews dunes are essentially single, linear belts of sand, although each contains a series of individual sand fields; however, the Lea-Yoakum dunes are a group of small dune fields scattered across the High Plains surface (Fig. 6). The Muleshoe and Andrews dunes also are typically higher than the Lea-Yoakum dunes (Table 4). These variations may be a function of either supply-limited or transport-limited conditions. The Muleshoe and Andrews dunes, as described herein, are downwind of wide, deep reentrant valleys that connect the Pecos Valley to the High Plains (the Portales and Winkler Valleys, respectively). The reentrant upwind of the Lea-Yoakum dunes (the Simanola Valley) is a set of relatively narrow valleys, significantly shallower than the other two valleys. These smaller funnels would minimize wind energy available for sand entrainment.

The eolian geomorphic processes that characterized much of the latest Pleistocene and Holocene on the Southern High Plains were likely related to climate, either directly or indirectly. Dune systems are good indicators of

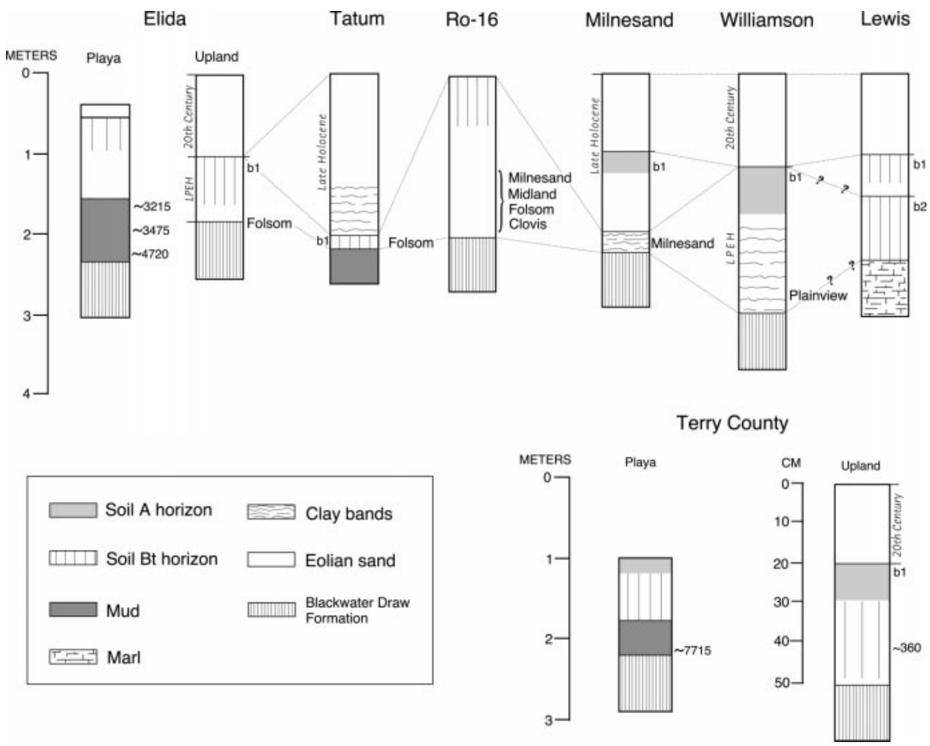

Figure 8. Stratigraphic sections of study sites in the Lea-Yoakum dunes and the Terry County site in the Seminole sand sheet (LPEH—late Pleistocene–early Holocene sand). The numbers to the right of some sections refer to rounded means of radiocarbon ages in uncalibrated radiocarbon years (from Table 2). See Table 3 and Figure 5 for calibrations. Other terms refer to artifact associations. See caption to Figure 3 for additional keys to soil illustrations, soil horizon nomenclature, and dating of artifact types.

climate changes, especially departures toward aridity (Cooke et al., 1993, p. 412–413; Tchakerian, 1994; Lancaster, 1995, p. 228–243). On the Great Plains eolian sediments are important indicators of devegetation and wind erosion resulting from aridity (Muhs, 1985; Forman et al., 1992, 1995; Muhs and Maat, 1993; Madole, 1995; Arbogast, 1996; Muhs et al., 1996, 1997a,b, 2000; Arbogast and Johnson, 1998); these are complemented by other proxy clues to climate. The link between drought, devegetation, and wind erosion also is well established historically (e.g., Weaver and Albertson, 1943; Tomanek and Hulett, 1970).

The dune fields of the Southern High Plains undergo deflation and movement when vegetation is reduced and winds are strong and persistent, i.e., during prolonged drought. No other mechanism of natural, regional vegetation removal is known on the Great Plains. Fires in perennial grasslands burn the canopy but do not destroy the root mats, which hold the soil in place. Fire is instrumental in maintaining grasslands (Axelrod, 1985; Anderson, 1990). Large herds of grazing animals such as bison may locally destroy the grass canopy, but, like fire, grazers are significant players in the evolution and maintenance of grasslands (Collins and Glenn, 1995). In any case, but there are no historic or other accounts of large herds causing dune reactivation. The only known widespread human disturbance to grass cover is from farming, which began on the Great Plains in the second half of the nineteenth century. However, even after the introduction of agriculture, the most significant wind erosion, dune reactivation, and dust production has been during drought years (Kimberlin et al., 1977; Wigner and Peterson, 1987).

The chronologies of sand movement and dune construction combined with the paleoenvironmental data and interpretations from other sites of late Quaternary deposition (Haynes, 1975, 1995; Holliday, 1995a, 1997a, 1997b, 2000a; Johnson, 1986, 1987a, 1987b, 1991) allow for a reasonably complete reconstruction of cycles of drought and aridity on the Southern High Plains.

The oldest layers of late Quaternary eolian sand in or near the dune fields are sheet sands heavily modified by pedogenesis (A-Bt and/or clay-band soil profile) and containing Paleoindian archaeological material, common in the western and middle Muleshoe dunes, the western Lea-Yoakum dunes, and throughout the Andrews dunes. A correlative unit also was identified in the Monahans dunes, Crosby dunes, and very locally in the Seminole sand sheet. The distribution of sites with these oldest layers of sand indicates that roughly half of the area covered by the three west-east dune belts and some component of the Seminole sand sheet, Scharbauer dunes, and Crosby dunes were active dune fields or sand sheets by the early Holocene.

Other stratigraphic and isotopic data and paleontological information show that the Southern High Plains was relatively cool and moist in the late Pleistocene compared to today, but was undergoing warming and drying (Lundelius et al., 1983; Johnson, 1986, 1987b, 1991; Graham, 1987; Holliday, 1995a, 1997a, 1997b, 2000a). Eolian sedimentation began ca. 11 000 ^{14}C yr B.P. and continued into the early Holocene. This process probably resulted from episodic drought that reduced vegetation cover and soil moisture, thereby destablizing the surface of the Blackwater Draw Formation, particularly the sandy facies in the western and southwestern Llano Estacado, leaving it prone to wind erosion (Holliday, 2000a). In the draws, evidence of declining discharge and the interfingering of eolian sediment with marsh or pond deposits is well documented for this period (Haynes, 1975, 1995; Holliday, 1995a). The upland sheet sands dating to ca. 11 000–10 000 ^{14}C yr B.P. are the earliest stratigraphic evidence for regional aridity and the trend toward drier conditions and widespread eolian sedimentation that characterized the early to middle Holocene. The sand sheets also represent the first phase in the construction of the dune fields.

As discussed elsewhere (Holliday, 2000a), a broadly similar stratigraphic and paleoenvironmental record for the period 12 000–8000 ^{14}C yr B.P. is apparent in the central and northern Great Plains. In the eastern Great Plains, however, some evidence suggests that during the last millennia of the Pleistocene and the early millennia of the Holocene the landscape was stable and undergoing pedogenesis. Environmental conditions were generally cooler and more moist than today, but like on the Southern High Plains, were gradually warming and drying (Martin, 1993; Humphrey and Ferring, 1994; Nordt et al., 1994; Valero-Garcés et al., 1997). Isotope data from the Big Eddy site in Missouri show a pronounced warming trend between ca. 11 000 and 10 000 ^{14}C yr B.P. (Hajic et al., 1998, p. 101–106), as

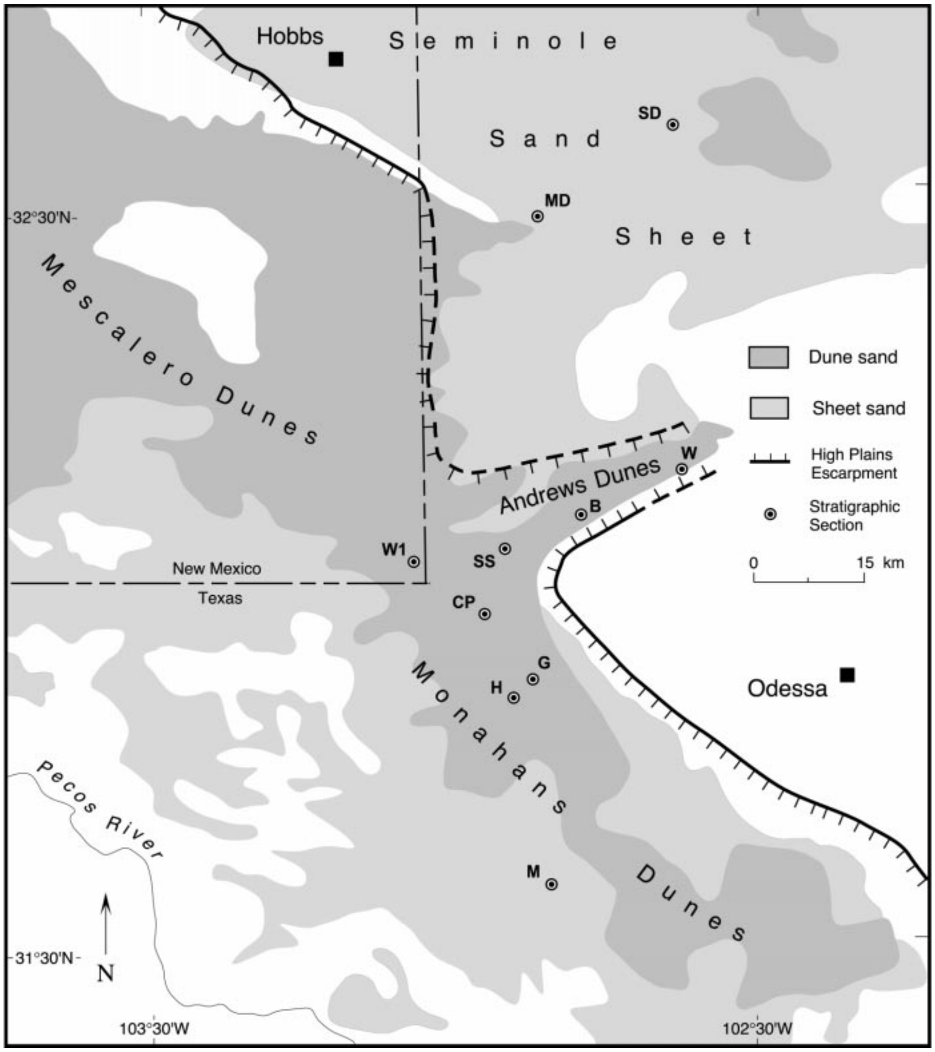

Figure 9. The Monahans and Andrews dunes in western Texas, the southern Mescalero dunes in southeastern New Mexico, and the southern Seminole sand sheet in both Texas and New Mexico with the location of study sites mentioned in this paper. Andrews dunes: B—Bedford Ranch; SS—Shifting Sands site; W—Wyche Ranch; W1—Winkler–1 site; CP—Winkler County Park site. Monahans dunes: G—Vest-Wheeler Ranch locality G; H—Vest-Wheeler Ranch locality H; M—Monahans Dunes State Park. Seminole sand sheet: MD—Monument Draw site; SD—Seminole Draw site. Also shown are selected physiographic features and cities.

do isotopes from the southeastern Great Plains of central Texas (Boutton et al., 1998). Forman et al. (1995, p. 46), drawing on their own and other lines of evidence, emphatically stated ''eolian activity ceased in the midcontinental U.S. between ca. 12 000 and 9000 yr BP.'' This may be true for parts of the eastern Great Plains, but clearly this was not the case for the High Plains. Likewise, there is no stratigraphic or isotopic evidence for a drought during the Clovis archaeological period (11 500–10 900 ^{14}C yr B.P.), proposed by Haynes (1991, 1993). On the contrary, data from the Southern High Plains and elsewhere on the Great Plains suggest that drought affected the region episodically in Folsom and later Paleoindian time (i.e., ca. 11 000–8000 ^{14}C yr B.P.) (Holliday, 2000a).

The eolian activity documented for 11 000–10 000 ^{14}C yr B.P. coincided with the Younger Dryas climate episode. The Younger Dryas in other areas of North America is manifested as a cooler and wetter climate. How the Younger Dryas affected the Great Plains, if at all, is far from clear, however (see discussion in Holliday, 2000a). The Southern High Plains, at the southwestern edge of the Great Plains, is the warmest and driest portion of the region, and likely was throughout Quaternary time. As indicated here and as discussed in Holliday (2000a), the period 11 000–10 000 ^{14}C yr B.P. on the Southern High Plains was characterized by abrupt, brief intervals of significantly drier and probably warmer conditions (the Folsom drought of Holliday, 2000a) relative to immediately preceding and succeeding conditions. The climate changes during the period 11 000–10 000 ^{14}C yr B.P. clearly correlate in time with the Younger Dryas, but whether they are linked is unknown. There is no evidence for cooling 11 000–10 000 ^{14}C yr B.P.

Eolian deposits dating to the middle Holocene are very rare in the dune fields of the Southern High Plains. The only firmly dated deposits of this age are at three localities in the western and central Muleshoe dunes (Clovis, Rabbit Road southwest, and Gile's sections), at the Terry County site in the Seminole sand sheet, and at Red Lake. A component of the sediments in the Scharbauer and Crosby dunes, at the Lewis Pit in the Lea-Yoakum dunes, and at Cage West in the Muleshoe dunes also may be middle Holocene, based on soil morphology or stratigraphic position. Otherwise, the middle Holocene is denoted by erosion or local stability. Formation of the well-developed soils in the latest Pleistocene–earliest Holocene deposits in the Muleshoe, Lea-Yoakum, and Andrews dunes must have spanned some if not all of the early and middle Holocene. In other settings, however, such as the lunettes, playa basins, and draws, middle Holocene eolian sediments strongly modified by pedogenesis are common (Haynes, 1975, 1995; Holliday, 1985b, 1985c, 1988, 1997a, 1997b; Holliday et al., 1996). Early to middle Holocene eolian sediments are the most extensive and thickest deposits in the draws, and become an increasingly common component of the valley fill from the early to the middle Holocene. Their relatively fine texture (sandy loam and sandy clay loam) also is indicative of widespread erosion of the Blackwater Draw Formation. It is clear that wind erosion and eolian sedimentation were important processes on the Southern High Plains in the early and middle Holocene, so the absence of eolian sands of this age is puzzling. The most likely explanation is that the middle Holocene deposits were remobilized in the late Holocene, because late Holocene sediments are common throughout the region.

Elsewhere on the Great Plains, eolian sediments of middle Holocene age are reported, but in general, as on the Southern High Plains, they are neither thick nor extensive. There is limited evidence for eolian remobilization of the Nebraska Sand Hills between 6000 and

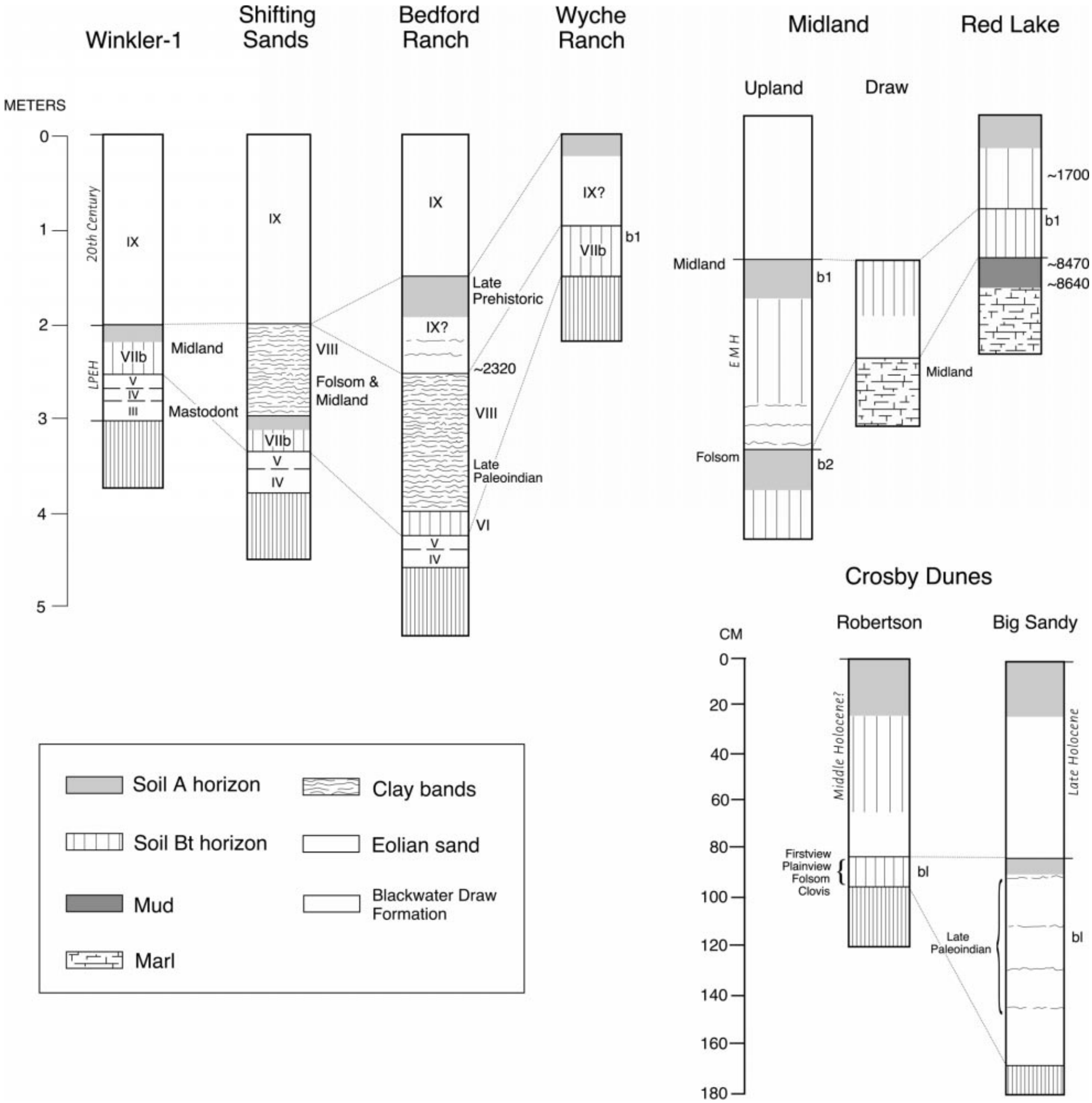

Figure 10. Stratigraphic sections of study sites in the Monahans dunes, Midland dunes, Red Lake, and the Crosby dunes (LPEH—late Pleistocene–early Holocene sand; EMH—early to middle Holocene sand). The numbers to the right of some sections refer to rounded means of radiocarbon ages in uncalibrated radiocarbon years (from Table 2). See Table 3 and Figure 5 for calibrations. Other terms refer to artifact associations. See caption for Figure 3 for additional keys to soil illustrations, soil horizon nomenclature, and dating of artifact types.

5000 ^{14}C yr B.P. (Loope et al., 1995; Stokes and Swinehart, 1997). In northeastern Colorado, Forman et al. (1995) identified middle Holocene sediments, but they appear to be rare in the region (Muhs et al., 1996). Scattered middle Holocene eolian deposits also are reported from the Great Bend sand prairie of Kansas (Arbogast and Johnson, 1998), and on the divide between the Washita River and North Fork of the Red River in western Oklahoma (Thurmond and Wyckoff, 1998).

The widespread wind erosion and eolian deposition documented for the period 7500–4500 ^{14}C yr B.P. on the Southern High Plains coincides with and certainly is a result of aridity, the so-called Altithermal of Antevs (1948, 1955). Multiple lines of evidence from proxy environmental indicators clearly show that in the middle Holocene the region was subjected to conditions warmer and drier than present (e.g., Johnson and Holliday, 1986; Johnson, 1987b; Holliday, 1995a, 2000a; Meltzer, 1991, 1999), evolving from conditions that characterized the early Holocene, although temperatures at 10 000–9000 ^{14}C yr B.P. may have been cooler (Holliday, 2000a). General circulation models of climatic conditions for 9000 and 6000 ^{14}C yr B.P. suggest that the aridity was due largely to warmer than present summer temperatures due to higher insolation (Thompson et al., 1993), which lead to higher evaporation. Environmental conditions undoubtedly fluctuated during the middle Holocene, based on several lines of evidence such as buried soils and stable C isotopes (e.g., Holliday, 1995a, 1997b, 2000a), but the chronology of such fluctuations is poorly dated.

The largest component by far of eolian landscapes and eolian sediments in the dunes and sand sheets of the Southern High Plains dates to the late Holocene. This eolian sedimentation began after 4000 ^{14}C yr B.P. (4500 cal yr B.P.), but most eolian deposits <1500 cal yr B.P. (Fig. 5), including a substantial component of historic sediment. Some dune fields and sand sheets enlarged significantly to the east in the late Holocene, including the eastern Muleshoe and Lea-Yoakum dunes, and a significant portion of the Seminole sand sheet (Fig. 1). In terms of both area (Fig. 1) and volume (Figs. 3, 8, and 10), more than half of the eolian sand composing the dune fields and sand sheets of the Southern High Plains was deposited in the late Holocene.

There were several episodes of eolian sedimentation in the late Holocene, as indicated by multiple buried soils. The radiocarbon chronology is not easy to interpret, however, because some radiocarbon ages have multiple possible calibrations spanning hundreds of years (Table 3; Fig. 5). Nevertheless, some trends are apparent. In the Muleshoe dunes, with the best age control, dating of buried A horizons indicates that the sands were stable ca. 1300, 750–670, and 500 cal yr B.P. (Fig. 5). The minimal degree of development exhibited by the buried soils further suggests that the sand was mobilized not long before or after those dates. Radiocarbon and luminescence ages from nearby lunettes, and the charcoal date from the surficial sheet sand at the Terry County site further support the interpretation of eolian sedimentation between ca. 750 and 500 cal yr B.P. and between 500 and 300 cal yr B.P. (Fig. 5). Additional soils and radiocarbon data are indicative of eolian sedimentation <4500 cal yr B.P. at Plant X and <4100 cal yr B.P. at Clovis, in the Muleshoe dunes; <3500 cal yr B.P. at Elida in the Lea-Yoakum dunes; <2300 cal yr B.P. at Bedford Ranch in the Andrews dunes; and at 1750–1550 cal yr B.P. at Red Lake (Fig. 5). Soils and radiocarbon ages from valley fill in the draws of the region also provide evidence of eolian sedimentation sometime between 1000 and 500 cal yr B.P., stability ca. 500 cal yr B.P., additional eolian sedimentation between ca. 500 and 300 cal yr B.P., and in the past 2 k.y. (Fig. 5) (Holliday, 1995a).

In luminescence dating of lunettes, Rich et al. (1999) reported continuous dune sedimentation from ca. 5000–2300 cal yr B.P. (equivalent to calibrated radiocarbon years), but in part this is due to large, overlapping standard deviations. No stratigraphic data are presented or discussed that allow independent evaluation of presence or absence of buried soils or other unconformities.

The absence of substantial amounts of dune sand or sheet sand dating to the period 5000–1500 cal yr B.P. and abundant evidence for multiple periods of eolian sedimentation after 1500 cal yr B.P. suggest that the landscape of the Southern High Plains was largely stable from the end of the middle Holocene until <2 k.y. ago. Although there were episodes of eolian sedimentation 5000–1500 cal yr B.P., and some deposits from this period may have been removed by erosion <1500 cal yr B.P., the data from the draws (Holliday, 1995a) support this interpretation. Most deposition in the draws ended by 5000 cal yr B.P.. Subsequent conditions were moister and probably cooler than the middle Holocene, conditions essentially similar to those of today, with episodic departures toward aridity increasingly common after 3300 cal yr B.P. Proxy indicators of past environments (discussed in Holliday, 1995a, p. 90–91) generally support the interpretations of both dune and draw stratigraphy. The record of such indicators is sparse, however, in part owing to the general lack of sedimentation in most settings outside of dune fields.

Environmental fluctuations on the southern and central Great Plains during the late Holocene, especially departures toward aridity, are now widely recognized and similar to those proposed for the Southern High Plains (e.g., Madole, 1994, 1995; Forman et al., 1995; Loope et al., 1995; Wolfe et al., 1995; Arbogast, 1996; Muhs et al., 1996, 1997a, 1997b; Stokes and Swinehart, 1997; Arbogast and Johnson, 1998; Thurmond and Wyckoff, 1998; Woodhouse and Overpeck 1998; Yu and Ito, 1999). Further dating suggests that at least some episodes of eolian sedimentation, and presumably aridity, in the late Holocene were regionally extensive. Much of the region was stable, with little erosion or deposition 5000–2000 cal yr B.P., likely the result of conditions similar to the cooler and wetter decades of the twentieth century. Eolian sedimentation is recorded: after ~2300 cal yr B.P. on the Southern High Plains, on the Great Bend sand prairie, and probably in the Nebraska Sand Hills; after ~1500–100 cal yr B.P. on the Southern High Plains, on the Great Bend sand prairie, and in northeastern Colorado; after ~7000 cal yr B.P. on the Southern High Plains, and Nebraska Sand Hills; and between 500 and 300 yr ago on the Southern High Plains, Great Bend sand prairie, and Nebraska Sand Hills. Historic dune remobilization (largely in the nineteenth century) also is documented through much of the Great Plains (Muhs and Holliday, 1995).

The eolian sedimentation ca. 1750–1550 cal yr B.P., after ~1500–1300 cal yr B.P., after ~700 cal yr B.P., and after ~500 cal yr B.P. corresponds well with evidence for widespread drought on the Great Plains (Woodhouse and Overpeck, 1998). Other periods of drought in the region are documented (Woodhouse and Overpeck, 1998), but without corresponding field evidence on the Southern High Plains. This probably is due to the incomplete stratigraphic record and spotty age control. The stratigraphic data, and in particular historic and modern observations of dune activity, dust production, and climate (Holliday, 1987; Muhs and Holliday, 1995; Woodhouse and Overpeck 1998), suggest that regardless of the duration or intensity of drought, the impacts on the landscape were substantial, resulting in widespread wind erosion and dune construction.

Dunes on the Southern High Plains as well as elsewhere on the Great Plains underwent repeated cycles of construction and erosion over the past 10 000 to 12 000 years At least several of these cycles resulted from climate changes that affected most of the Great Plains, such as those occurring 11 000–8000 ^{14}C yr B.P. and since 1500 ^{14}C yr B.P. Mobilization of these sand bodies does not require a dramatic climate change, however. More than half of the late Quaternary eolian sand on the Southern High Plains was deposited in response to relatively minor climatic changes of the late Holocene. Future climate changes such as those related to greenhouse warming scenarios could have a significant impact on the landscape.

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