Origin of late Quaternary dune fields on the Southern High Plains of Texas and New Mexico

Daniel R. Muhs*
U.S. Geological Survey, M.S. 980, Box 25046, Federal Center, Denver, Colorado 80225, USA

Vance T. Holliday
Department of Geography, 384 Science Hall, University of Wisconsin, 550 North Park Street, Madison, Wisconsin 53706-1491, USA

ABSTRACT

Mostly stabilized late Holocene eolian sands on the Southern High Plains of the United States were studied to determine their origins and to assess whether present dune stability depends more strongly on sediment supply, sediment availability, or transport limitations. Geomorphic, sedimentological, and geochemical trends indicate that late Holocene dunes formed under westerly paleowinds, broadly similar to those of today. Mineralogical and geochemical data indicate that the most likely source for the sands is not the Pecos River valley, but the Pleistocene Blackwater Draw Formation, an older, extensive eolian deposit in the region. These observations suggest that new sand is supplied whenever vegetation cover is diminished to the extent that the Blackwater Draw Formation can be eroded, in agreement with modern observations of wind erosion in the region. We conclude, therefore, that Southern High Plains dunes are stabilized primarily due to a vegetation cover. The dunes are thus sediment-availability limited. This conclusion is consistent with the observation that, in the warmest, driest part of the region (where vegetation cover is minimal), dunes are currently active over a large area. Geochemical data indicate that Southern High Plains dunes are the most mineralogically mature (quartz rich) sands yet studied in the Great Plains, which suggests a long history of eolian activity, either in the dune fields or during deposition of the Blackwater Draw Formation.

Keywords: Blackwater Draw Formation, dunes, geochemistry, New Mexico, Pecos River, provenance, Texas.

INTRODUCTION

Stabilized eolian sand is extensive on the Great Plains of North America (Fig. 1). Interest in eolian sand in this region has increased in recent years, based upon the recognition of late Holocene and historic activity of these dune fields (Ahlbrandt et al., 1983; Swinehart, 1990; Swinehart and Diffendal, 1990; Forman and Maat, 1990; Forman et al., 1995; Madole, 1994, 1995; Loope et al., 1995; Holliday, 1995a, 1997a, 2000; Wolfe et al., 1995, 2000; Arbogast, 1996; Muhs and Holliday, 1995; Muhs et al., 1996, 1997a, 1997b; Stokes and Swinehart, 1997). This recent activity is significant, because it means that prospects are high for reactivation of many dunes due to future climate or land-use changes (Muhs and Maat, 1993), with possibly severe regional economic impacts. Critical to any forecast of future eolian activity, however, is understanding whether a dune field is stable because it is limited by (1) sediment supply, (2) sediment availability, or (3) transport capacity. Kocurek and Lancaster (1999) defined sediment supply as the sediment of suitable grain size that is the source material for eolian sand. The source material can be external to a dune field, such as sand derived from a coastal or fluvial system, or internal, derived from interdune sediments or cannibalization of previously stabilized dunes. Sediment availability, in contrast, is the susceptibility of surface grains to entrainment by the wind. Kocurek and Lancaster (1999) pointed out that sediment availability can be restricted by raising the threshold value (by addition of moisture, surface binding by clays, or cementation by carbonate or silica), or increasing the surface roughness (by vegetation cover or a cover of coarse clasts). Transport capacity of the wind is defined as its sediment-carrying capacity, which varies as a cubic function of friction velocity (Kocurek and Lancaster, 1999). Given these three possible limitations on eolian activity, assessing the potential for reactivation of a dune field requires identification of source sediments. The diversity of source sediments for Great Plains dunes has only recently emerged, including playa sediments (Holliday, 1997a), fluvial sediments (Muhs et al., 1996), glaciolacustrine and glaciofluvial deposits (Wolfe et al., 1995; Muhs et al., 1997b), and possibly residuum from bedrock (Muhs et al., 1996, 1997a).

The Southern High Plains, or Llano Estacado, has some of the most extensive dune fields in the Great Plains (Figs. 1 and 2). Eolian sand thicker than 2 m in the region may cover more than 10 000 km^2. Both well-formed dunes and low-angle eolian sand sheets (as defined by Fryberger et al., 1979) are present. Three major east-west–trending dune belts (Muleshoe, Lea-Yoakum, and Monahans-Andrews) and one north-south–trending dune belt (Mescalero) cover large areas of the Llano Estacado and parts of the Pecos River valley to the west (Figs. 3, 4, and 5). Muhs and Holliday (1995) pointed out that dunes on the Southern High Plains may be near the critical climatic limits of stability, because the northern dune fields (Muleshoe, Mescalero, and Lea-Yoakum) are largely stable, whereas ~300 km^2 of the southernmost dune field (Monahans) is active. Therefore, if the dunes are transport limited or sediment-availability limited, only a small shift in moisture balance, wind strength, or intensity of land use might be sufficient to activate them. However, if the

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*E-mail: dmuhs@usgs.gov.

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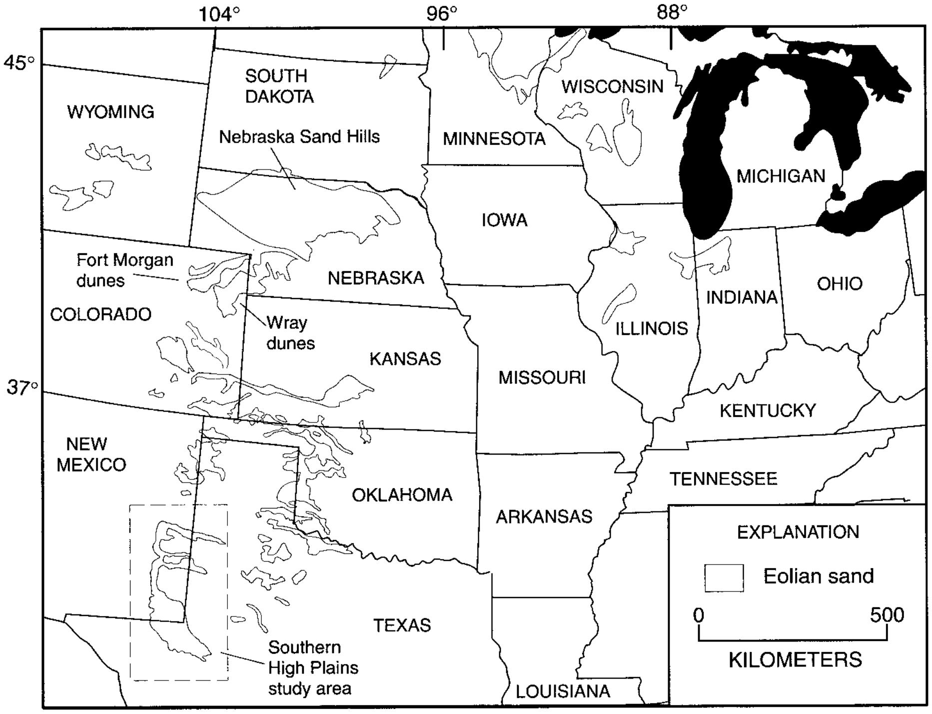

Figure 1. Map showing the location of eolian sand in the central United States, location of the Southern High Plains study area, and other dune fields referred to in the text and figures. Eolian sand distribution is mostly from compilation by Muhs and Holliday (1995), except that shown in eastern states, which is from Thorp and Smith (1952).

dunes are supply limited, then future climate changes may be of lesser consequence to dune activation.

Although several investigators have speculated on the origin of the dunes, there has been no systematic effort to link the composition of Southern High Plains dunes to potential source sediments. In a summary of many years of Great Plains eolian research, Lugn (1968) stated categorically that the Pliocene–Miocene Ogallala Formation was the main source of Pleistocene and Holocene eolian sand for the entire Great Plains region, from Nebraska to Texas. Although the Ogallala Formation is extensive under the southern Great Plains, it has a well-cemented pedogenic calcrete in its upper part and is usually overlain by the Pleistocene Blackwater Draw Formation (Holliday, 1990; Gustavson and Holliday, 1999). Thus, we do not consider the Ogallala Formation to be a very likely source for Southern High Plains dune sands. Green (1961), Hawley et al. (1976), and Carlisle and Marrs (1982) suggested that the dune fields of the Southern High Plains owed their origins to funneling of winds through reentrants in the High Plains escarpment. Although these workers did not explicitly state it, this model implies that sediments of the Pecos River valley were the sources of eolian sand. Conversely, Hefley and Sidwell (1945) proposed that eolian sands in the Muleshoe dune field were derived from underlying Tertiary sands, which we interpret to mean the Blackwater Draw Formation. The two possible sources have vastly different implications with regard to potential future dune reactivation. If the Pecos River valley is the source of eolian sands, then dune mobility may be linked to changes in the fluvial regime as they apply to sediment supply (e.g., following the model of Muhs and Holliday, 1995). However, if the Blackwater Draw Formation is the source, then climate or land-use effects (see effects of agriculture in Fig. 6) alone, through a decrease in vegetation cover (and therefore increase in sediment availability), could bring about dune mobility. In this paper we present sedimentological, mineralogical, and geochemical data that shed new light on the origin of these dune fields.

METHODS

Samples were collected mostly from sand dunes and sand sheets that are stabilized by vegetation and are estimated to be no older than late Holocene. This age estimate is based on the presence of A-AC-C soil profiles that are characteristic of eolian sand of late Holocene age (see Holliday, 1995a, 2000). The exceptions to this sampling scheme are in the Monahans dune field, where many dunes are active today. Thus, herein, "eolian sand" refers to either stabilized but young eolian sand or active eolian sand. Samples were collected well below the zone of pedogenesis in order to avoid effects of weathering and soil formation at the site of collection. Particle-size distribution of selected eolian sands was determined by sieving (for the sand-sized fractions) at 0.5 phi intervals after destruction of organic matter with H_2O_2 and dispersion with Na-pyrophosphate. Silt and clay contents were determined by the sedimentation and pipette method. Graphic mean and standard deviation (as defined by Folk, 1974) were calculated for all samples. Concentrations of certain major and trace elements were measured in the eolian sands and potential source sediments using energy-dispersive X-ray fluorescence. Semiquantitative mineralogical analyses were made using X-ray diffraction methods. For geochemistry and mineralogy, samples of eolian deposits analyzed included all size fractions. Valid mineralogical and geochemical comparisons to eolian sands can only be made, however, on source sediments that are of the same size as those in eolian sands. For geochemical and mineralogical analyses of potential source sediments (the Pecos River and the Blackwater Draw Formation), only the very fine, fine, and most of the medium sand fractions (53–425 μm) were analyzed. These size fractions cover the bulk of sizes found in eolian sands. Gravels were removed by dry sieving. Carbonates were removed with an Na-acetate buffer (pH = 5), after which the samples were treated with an Na-pyrophosphate dispersant. Sands were separated from silts and clays by wet sieving; sand fractions were then concentrated by dry sieving.

REGIONAL CLIMATIC SETTING

The Southern High Plains region has a continental climate and is semiarid. Mean annual precipitation and mean annual temperatures both show northeast-southwest gradients. The northern part of the region is both cooler and wetter; mean annual precipitation at Amarillo is almost 500 mm and mean July and January (1961–1990) temperatures are 26 °C and 1.7 °C, respectively. In contrast, Pecos receives only ~280 mm of precipitation per year and mean July and January temperatures are 29 °C and 6.4 °C, respectively. As a consequence of these moisture and temperature gradients, ratios of precipitation to potential evaporation

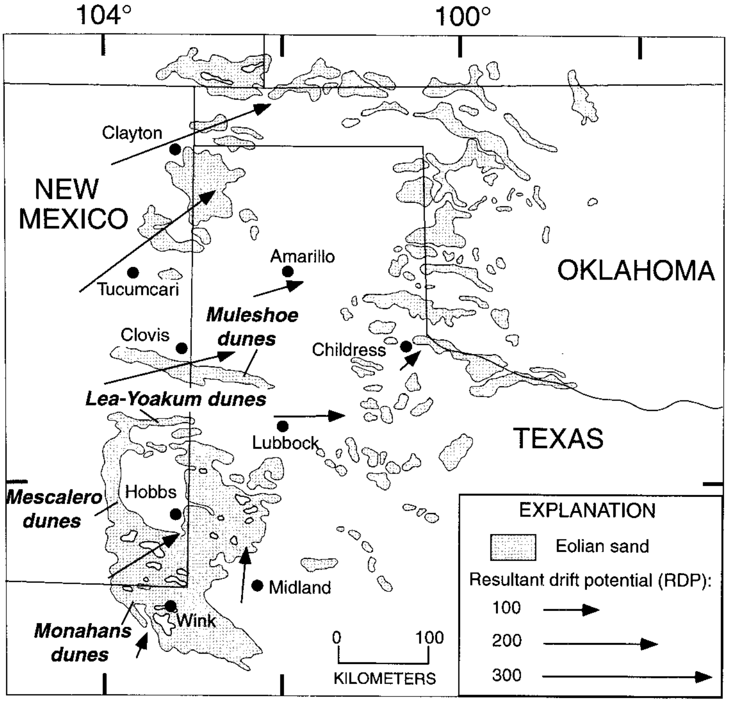

Figure 2. Map showing the location of eolian sand in the Southern High Plains and adjacent areas, redrawn from compilation by Muhs and Holliday (1995). Also shown are annual resultant drift potentials (RDP) and resultant drift directions (RDD) that show potential net sand migration directions. For clarity, we omit the multidirectional arms that are often shown in sand roses and present only RDP (length of the arrow) and RDD (direction of the arrow).

range from ~0.60 in the northern part of the region to ~0.30 in the southern part. Muhs and Holliday (1995) pointed out that climatically, the southernmost part of the Great Plains (including the Monahans dune field) is part of the Chihuahuan Desert. Over the entire region, maximum precipitation occurs between May and September.

Wind regimes, as they apply to the formation of sand dunes and sand sheets, can be characterized in terms of sand-moving potential. Fryberger and Dean (1979) developed a method for graphic representation of sand-moving potential called sand roses, which are circular histograms showing the weighted magnitudes and directional variability of winds for a given station. The arms in a sand rose are weighted sums of the amount of time that the wind is above the threshold velocity for sand from a given direction. Higher velocity winds are weighted higher in the summation because the sand-moving capacity of wind is a function of the cube of wind speed. Fryberger and Dean (1979) defined several parameters from sand rose data: drift potential, which is the scalar sum of all sand-moving winds, regardless of direction; resultant drift potential, which is the vector sum of all sand-moving winds and will always be less than or equal to drift potential; and resultant drift direction, which is the net direction of sand movement. Good agreement between resultant

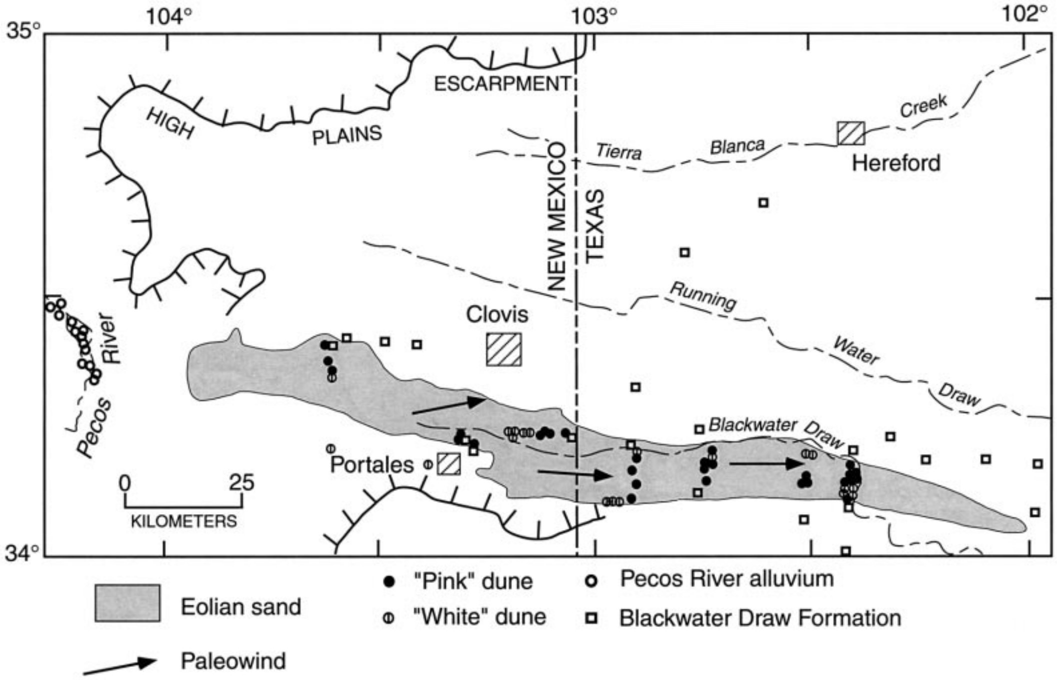

Figure 3. Map of the Clovis 1° × 2° quadrangle and adjacent areas showing the extent of the Muleshoe dune field, sample localities, and late Holocene paleowinds based on parabolic dune orientations.

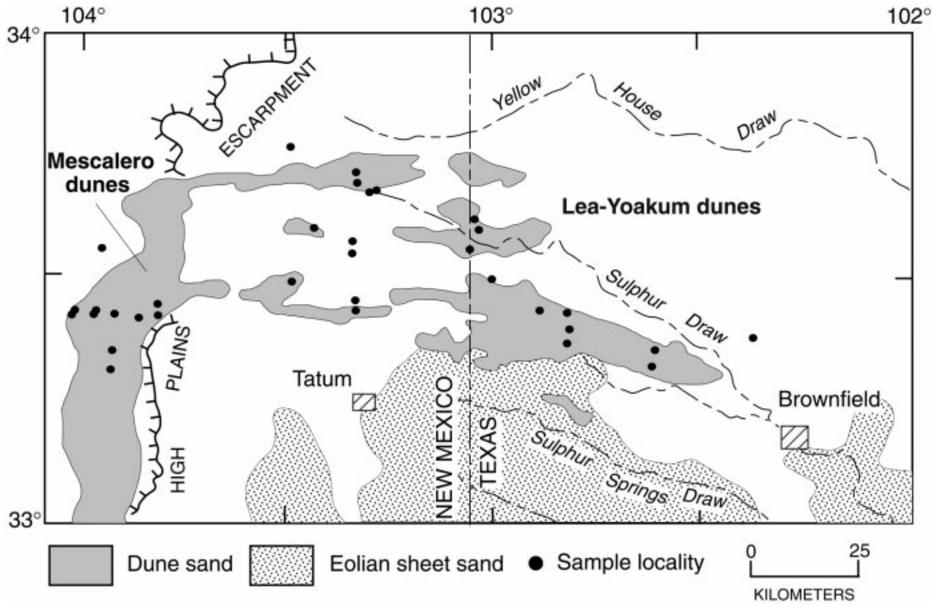

Figure 4. Map of the Brownfield 1° × 2° quadrangle and adjacent areas showing the extent of the Lea-Yoakum dune field, part of the Mescalero dune field, adjacent sheet sands, and sample localities.

drift direction values and dune orientations from many parts of the world suggest that it is a valuable parameter in studying dune forms and their relations to winds (Fryberger and Dean, 1979; Breed et al., 1979; Ahlbrandt and Fryberger, 1980; Muhs, 1985; Lancaster, 1989; Wells et al., 1990; Muhs et al., 1996, 1997a, 1997b, 2000).

We were able to obtain climate records of sufficient detail to construct sand roses for nine localities in the Southern High Plains (Fig. 2). Although Lubbock shows a resultant drift direction from west to east and Midland shows a resultant drift direction from south to north, the annual resultant drift direction for the region is dominantly from southwest to northeast. The Southern High Plains have resultant drift potential values that range from 47 to 318, with a mean value of about 155 ($n = 9$). Resultant drift potential values are generally higher (155–318) in the New Mexico portion of the region. Elsewhere in the Great Plains, resultant drift potential values are somewhat higher, such as in southeastern Colorado and southwestern Kansas (range of 39–762, with a mean of 241) and Nebraska (range of 97–284, with a mean of 211) (Muhs et al., 2000, and unpublished data; Arbogast and Muhs, 2000). However, Southern High Plains resultant drift potential values are as high as those found in many of the world's desert regions where there are large sand seas (cf. Fryberger and Dean, 1979; Breed et al., 1979). Relatively high resultant drift potential values for the Southern High Plains are significant in assessing possible dune reactivation because it means that wind is not a limiting factor. Reactivation of dunes is likely to be more sensitive to changes in sediment supply, sediment availability, degree of vegetation cover, and land use.

GEOMORPHOLOGY AND SEDIMENTOLOGY

Geomorphology

As discussed in Holliday (2000), latest Pleistocene sheet sands and late Holocene dune sands (which overlie the older sheet sands) are the most extensive deposits in Southern High Plains dune fields. Similar to the central Great Plains of Colorado and Nebraska (Swinehart and Diffendal, 1990; Madole, 1994, 1995; Muhs et al., 1996, 1997a), there are very few mid-Holocene eolian sands preserved in the Southern High Plains other than those deposited in draws and lunettes (Holliday, 1995b, 1997a, 1997b). Most of the following discussion regarding the geomorphology of the dune fields refers to late Holocene dunes, as described by Holliday (2000).

A wide variety of eolian landforms exists on the Southern High Plains (see Holliday, 2000, for detailed descriptions). In the Muleshoe dune field (Fig. 3), low-relief eolian sand sheets and both simple and compound parabolic dunes occur (Fig. 6). The simple parabolic dunes are commonly 200–400 m long, similar to parabolic dunes found in the central Great Plains region of Colorado (Muhs, 1985; Madole, 1994, 1995; Muhs et al., 1996). Dune morphology is less well expressed in the Lea-Yoakum dunes (Fig. 4), but highly degraded compound parabolic dunes to ~2–3 km long can be found in places, adjacent to very low relief sand sheets and abundant shinnery oak–(*Quercus harvardii*)–covered coppice dunes. The Lea-Yoakum dune field also has abundant fence-line dunes, some to 3–4 m high, that developed in historic time. In the Mescalero dune field (Figs. 4 and 5), there are small fields of stabilized parabolic dunes, ~400–800 m long, as well as one small area of partially active northwest-trending barchanoid ridges ~200–800 m long. In other areas of the Mescalero dune field, we observed mostly sand sheets and low (1–3 m high) coppice dunes. The Monahans dune field, and a northeast-trending extension of it called the Andrews dune field (Fig. 5), have the greatest variety of eolian bedforms on the Southern High Plains, and also show the greatest degree of activity. Fully active dunes are found in many parts of the Monahans dune field, and include both barchanoid ridges as long as 1000 m and parabolic dunes (Fig. 7). The western portion of the Monahans dune field has stable or partially active parabolic dunes and sand sheets.

In the areas surrounding the Monahans dune field, and to the south of the Lea-Yoakum dune field, there are extensive areas that were mapped previously as eolian sand (Eifler, 1976; Eifler and Reeves, 1974, 1976), but that do not show distinctive dune morphology on aerial photographs. We examined these deposits and found that they include small coppice dunes, thin continuous sand sheets, and thin discontinuous sand sheets, almost all of which are underlain by calcrete of the Ogallala Formation. We map these deposits as eolian sheet sand in Figures 4 and 5.

Dune orientations were measured in detail in the Muleshoe dune field and on a reconnaissance basis in the other dune fields. In the Muleshoe dune field, measurement of the long axes (based on dune arms) and nose orientations of ~180 stabilized parabolic dunes shows a relatively narrow range, with noses pointing from N79°E to E4°S and an average of almost due east, indicating paleowinds dominantly from the west (Fig. 3). At Clovis, the nearest locality for which we have wind data, annual resultant drift direction is from the southwest, but winter resultant drift directions are from the northwest and summer resultant drift directions are from the southeast. The parabolic dune orientations in the Muleshoe field show the best agreement with the winter and spring resultant drift directions, which is also the time when vegetation cover may be at a minimum. It is possible, however, that the dunes may have been modified slightly by summer winds when the dunes were active. Alternatively, late Holocene paleowind annual resultant drift directions may have been more consistently from the west at the times of dune formation. In the Lea-Yoakum and Mescalero fields, there are fewer parabolic dunes and many dunes are not well expressed geomorphically. Interpretation of aerial photographs shows, however, that most stabilized dunes are oriented similarly to those in the Muleshoe field, with arms pointing to the west and noses pointing to the east, indicating dominantly westerly winds.

The active dunes of the Monahans field show the most complex orientations of the region. The geomorphology of the dunes in this region reflects seasonally variable wind directions. On the basis of climate data for Midland, Wink, and Hobbs, winds are from the southwest, west, or northwest from November through April, and from the south or southeast from May through October. On the basis of examination of aerial photographs taken in November 1984 (Fig. 7), active barchanoid ridges have slip faces that dip to the northwest, which reflect the summer wind pattern. In contrast, active and stabilized parabolic dunes have arms that point to the northwest, indicating formation under predominantly northwesterly, winter winds. Machenberg (1984) pointed out that the bimodal wind directions in the Monahans dune field result in little annual net migration in the active portion of the dunes.

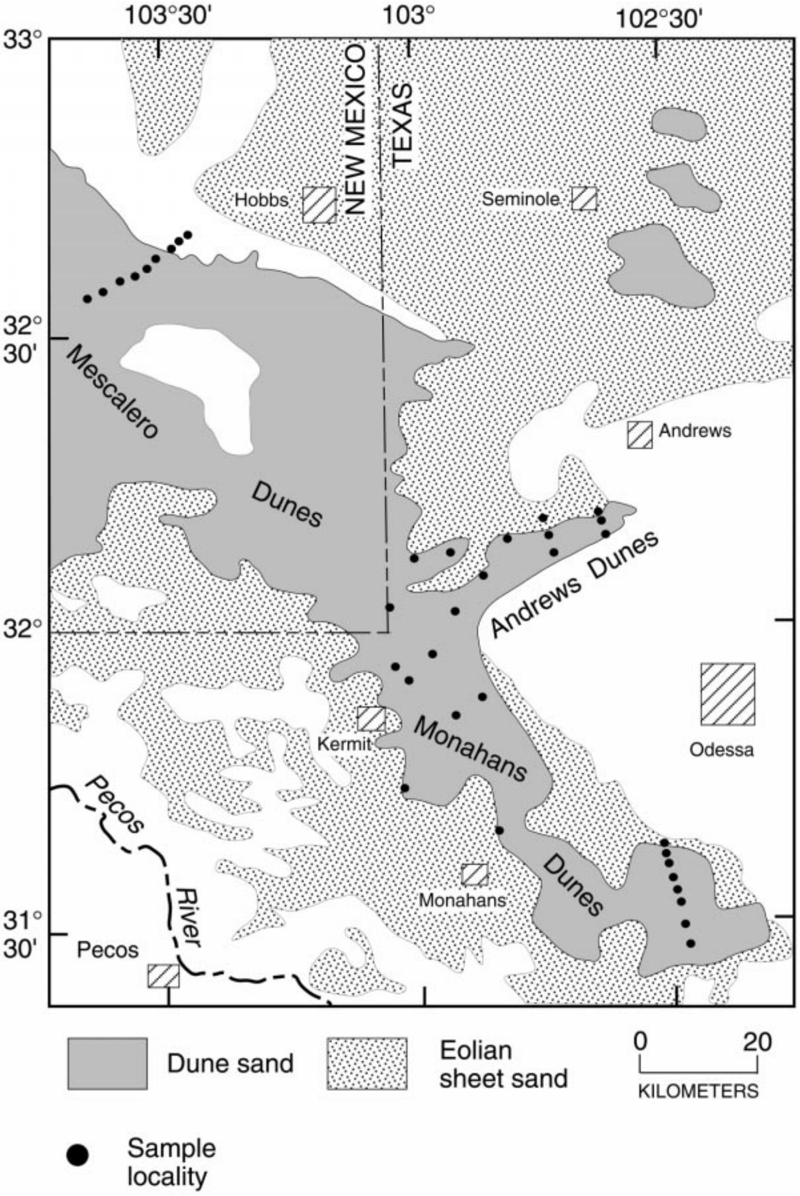

Figure 5. Map of parts of the Hobbs and Pecos 1° × 2° sheets showing the Monahans-Andrews dune fields, part of the Mescalero dune field, adjacent sheet sands, and sample localities.

Sedimentology

Sediments of the Muleshoe dune field have considerable spatial variability of color, carbonate content, mean particle size (in the sand fraction), and clay content. Dune color varies within the Muleshoe field in two ways. Some dunes have predominantly reddish (5YR and 7.5YR) hues and others have mostly light gray or light brown colors (e.g., 10YR 6/2, 10YR 6/3, 10YR 6/4, and 10YR 7/2, all dry colors). For convenience, we refer to these as pink and white dunes, respectively. Mineralogical and chemical data (discussed in the following sections) indicate that the white dunes contain varying amounts of carbonates, whereas the pink dunes are largely carbonate free. A more systematic spatial variation in dune color, seen within the pink dunes, is decreased redness in a downwind direction (Fig. 8). In the western part of the field, dunes have mostly 5YR hues, whereas dunes farther downwind have 7.5YR hues and those on the periphery of the eastern half of the dune field have 10YR hues. This trend is contrary to observations made in other regions that dunes become redder in a downwind direction (Walker, 1979; Gardner and Pye, 1981; Lancaster, 1989; Pye and Tsoar, 1990). However, particle size data shed light on this apparent contradiction, which we discuss later.

Late Holocene sands in the Muleshoe dune field are mostly fine sands and are generally moderately well sorted (Fig. 9). In this regard, Muleshoe sands are close to average values for eolian sands for many of the world's dune fields (Ahlbrandt, 1979). Compared to dune fields elsewhere in the Great Plains, the Muleshoe sands are similar to those in the Nebraska Sand Hills, but finer and better sorted than sands in northeastern Colorado (Fig. 9). Mean particle size decreases with distance east of the Pecos River, which, based on modern winds and dune orientations, is the downwind direction. The eastward decrease in mean particle size is a function of expected winnowing of coarse particles downwind, although this explains only about half of the variation (Fig. 10). Downwind distance, however, explains 66% of the variation in clay content, which also decreases in an eastward direction (Fig. 10). Both a downwind decrease in mean particle size of sand and clay content would seem initially to be contradictory trends. However, Gillette and Walker (1977) showed that eolian sands in the Southern High Plains have abundant clay mineral coatings. These coatings are very fragile and are easily abraded away during eolian transport. Therefore, a greater distance of travel would result in more abrasion of the sand-sized particles as well as a loss in clay. This trend may also explain the eastward decrease in sediment reddening in the Muleshoe dune field, in a process described by Gillette and Walker (1977) and Walker (1979). The 5YR hues in sands in the western part of the dune field may be due to a greater amount of iron oxides and clay coatings, and the downwind decreased in redness reflects the abrasion of this pigment. These observations suggest that the source for the Muleshoe dunes is a sediment that is high in sand but contains at least some clay.

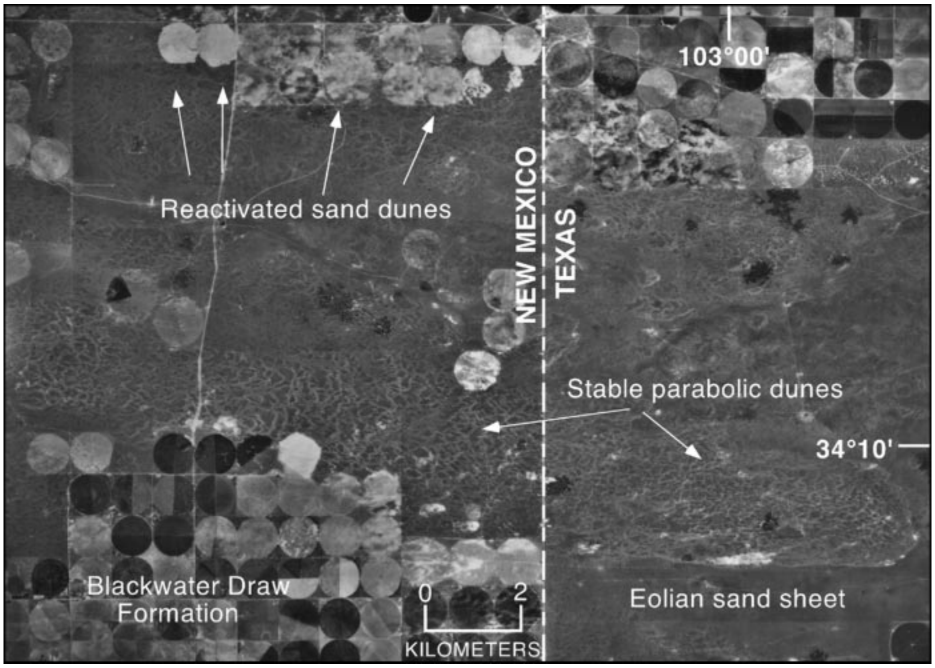

Figure 6. Aerial photograph of a portion of the Muleshoe dune field, showing morphology of parabolic dunes and sand sheets.

MINERALOGY

Bulk mineralogical analyses indicate that eolian sands in the Muleshoe dune field are dominated by quartz (Fig. 11). Both K-feldspar and plagioclase were detected in some samples, but the quantities of these minerals are extremely low. These observations agree with those of Gile (1985), who reported that soils developed in eolian sands in the Muleshoe dune field are dominated by quartz in their sand fractions. The Muleshoe dunes may have some of the highest quartz contents (relative to feldspars) of any Great Plains dune fields. Quartz contents are much higher in the Muleshoe dunes than in dunes of northeastern Colorado and even those of the Nebraska Sand Hills region, which has been regarded as a mineralogically mature dune field (Muhs et al., 1997a).

The relative amount of quartz vs. feldspar in the Muleshoe dunes is similar to the two most likely source sediments (Fig. 11). Pecos River sediments are relatively high in quartz, but have slightly more plagioclase and K-feldspar than the Muleshoe dunes. However, there is virtually no difference in the relative abundances of quartz, K-feldspar, and plagioclase in Muleshoe sands and sands derived from the Blackwater Draw Formation.

GEOCHEMISTRY

Bulk geochemical analyses[1] reflect the mineralogical differences of the pink and white sands in the Muleshoe dune field. The main difference between these two eolian sands is the slightly higher amount of carbonate in the white dunes, and this difference is reflected in variable, but generally higher, Ca and Sr contents (Fig. 12). The relative amounts of quartz, K-feldspar, and plagioclase in the two dune types are similar, and this is reflected in the similar abundances of K and Rb (found in K-feldspar). The K/Rb values in the two dune types do not show a significant difference, which suggests that the noncarbonate minerals in the two dune types have a common origin. This interpretation is supported by the similar concentrations of Ti and Zr in both dune types, which reflect the abundances of heavy minerals such as ilmenite, anatase, rutile, titanomagnetite, and sphene (Ti) and zircon (Zr). The Ti/Zr value for both groups is similar, suggesting a common source for the heavy mineral fraction.

Heavy mineral fractionation during eolian transport is reflected in the declining downwind concentrations of Fe, Ti, and Zr (Fig. 13). Plots shown are for pink dunes only and probably reflect winnowing of heavy minerals in the same way that coarse particles are winnowed with distance from a source. These observations reinforce the interpretation that the dominant dune-forming winds have been from the west, at least during the late Holocene.

In evaluating potential source sediments for eolian sands, it is important, when using bivariate element plots, to use elements that not only have different concentrations in the competing sources, but also have different elemental ratios. This approach helps avoid an interpretation of apparently different sources that are due simply to dilution by quartz. We evaluated four complementary element pairs in this manner for Pecos River sediments and the Blackwater Draw Formation (Figs. 14–17). Much of the difference in element concentrations in the two sediment groups is a function of the amount of quartz, which has high concentrations in the Blackwater Draw Formation (Holliday, 1989). Both Ca and Sr, found in Ca-bearing minerals, have much higher concentrations and different Ca/Sr values in Pecos River sediments than in the Blackwater Draw Formation. Therefore, these two elements can be considered to be good discriminators for the two source sediments. Note that because the sample processing required removal of carbonates, the Ca and Sr shown in Figures 14–17 are found in Ca-bear-

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[1] GSA Data Repository item 2001013, geochemical data for eolian sands and source sediments, 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: editing@geosociety.org.

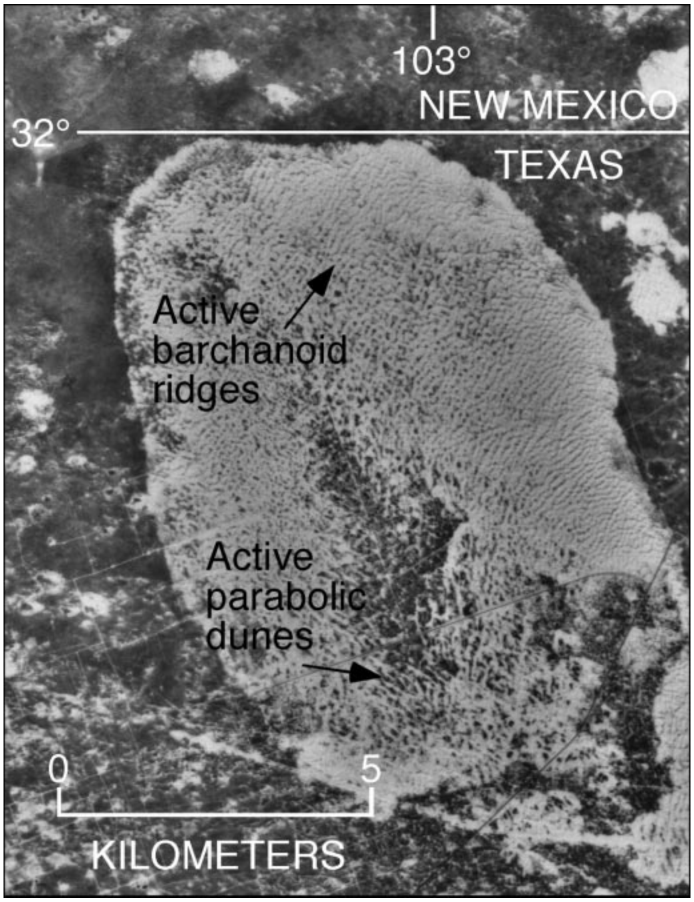

Figure 7. Aerial photograph of a portion of the Monahans dune field. Arrows point to representative active barchanoid ridges and parabolic dunes. Note that dune orientations reflect seasonally variable winds, which come from the west in winter and from the south or southeast in summer (see discussion in text).

ing noncarbonate minerals such as calcic plagioclase. Although Zr shows some overlap between the two sources, Ti/Zr values are quite different, and therefore Ti/Zr can be considered to be a reasonable discriminator. Fe and Mn have greater abundances in Pecos River sediments, but the two sediment groups have very similar Fe/Mn values. K-feldspar abundances are represented by Ba and Rb, which substitute for K. Compared with the Blackwater Draw Formation, Pecos River sediments are high in Ba and have high Ba/Rb values. Overall, therefore, we consider Ca, Sr, Ti, Ba, and Rb concentrations and Ca/Sr, Ti/Zr, and Ba/Rb values to be the best sand source discriminators.

Eolian sands in the Muleshoe dune field have compositions that most closely resemble sediments of the Blackwater Draw Formation (Fig. 14). Because many eolian sands in the Muleshoe dune field are calcareous, we analyzed only sediments from the pink dunes, and took the added precaution of pretreating these samples with Na-acetate in order to remove any trace amounts of carbonates that might be present. Ca and Sr concentrations (in noncarbonate minerals) in Muleshoe sediments overlap those of the Blackwater Draw Formation and are significantly lower than in Pecos River sediments. Moreover, Ca/Sr values in most Muleshoe dunes are closest to those in the Blackwater Draw Formation. Concentrations of Ti and Zr are lower in the Muleshoe dunes than in either potential source sediment, but Ti/Zr values are very close to those in the Blackwater Draw Formation and are much lower than in Pecos River sediments. The same is true for Ba and Rb concentrations and Ba/Rb values; all are lower in Muleshoe dunes and Blackwater Draw Formation sediments compared to Pecos River sediments. Thus, elements that represent low-density (light) minerals, such as feldspars (Ca, Sr, Ba, Rb) and those that represent high-density (heavy) minerals (Ti and Zr) have values in Muleshoe dunes that are closest to sediments of the Blackwater Draw Formation.

Eolian sands from the other dune fields were not pretreated for carbonate removal prior to analysis because field examination of these sands suggested that little or no carbonate was present. This assumption proved to be mostly, but not completely, correct based on geochemical results. In sediments of the Lea-Yoakum dune field, all samples have Sr con-

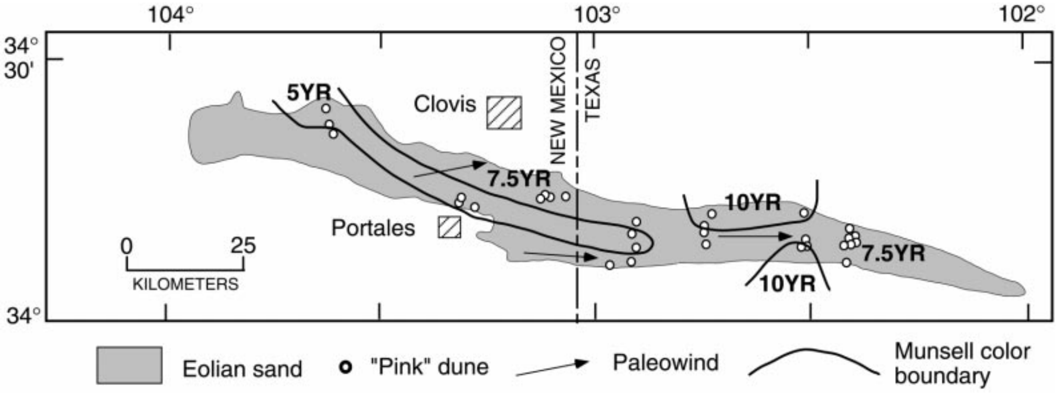

Figure 8. Map of the Muleshoe dune field, showing dominant Munsell hues in late Holocene eolian sands.

centrations that overlap with the Blackwater Draw Formation, but some samples have slightly higher Ca concentrations, probably due to trace amounts of carbonate minerals (Fig. 15). Most samples of the Lea-Yoakum dunes have Ca/Sr values that overlap with the Blackwater Draw Formation and are lower than Pecos River sediments. Concentrations of Ti and Zr and Ti/Zr values in Lea-Yoakum dunes overlap both sediment groups. However, concentrations of Ba and Rb, as well as Ba/Rb values, are much closer to the Blackwater Draw Formation than Pecos River sediments. The same interpretations can be made for sands from the Mescalero and Monahans dune fields for most element pairs, with two exceptions. A few samples have very high Ca and Sr abundances, probably due to the presence of carbonate minerals (Figs. 16 and 17). In addition, the Ti and Zr data for the Mescalero dunes suggest the possibility of a mixture of Pecos River and Blackwater Draw Formation sediments as a source.

Mineralogical maturity in sandstones or sandy sediments derived from crystalline rocks is characterized by an abundance of quartz and depletion of feldspars (Blatt et al., 1972). Because of their dominance by quartz, many of the world's largest dune fields are therefore mineralogically mature (Cooke et al., 1993; McKee, 1983; Pye and Tsoar, 1990). In some cases, mineralogical maturity can simply be inherited from a quartz-rich parent material, as is the case with the Algodones dunes in California (Muhs et al., 1995). Muhs et al. (1997a) showed, however, that different Great Plains dune fields show different degrees of mineralogical maturity, even though all have relatively high-feldspar source sediments. The Nebraska Sand Hills region has much higher quartz contents than dunes of northeastern Colorado. Muhs et al. (1997a) interpreted this difference to reflect K-feldspar depletion over long periods of activity due to ballistic (presumably grain to grain or grain to surface) impacts (Dutta et al., 1993). The degree of mineralogical maturity in the Southern High Plains dune fields is important because potentially it has significance for the long-term evolution of the dune fields.

On the basis of abundances of K, Rb, and Ba as proxies for K-feldspar contents, dune fields of the Southern High Plains are the most mineralogically mature dune fields in the Great Plains (Fig. 18). Concentrations of all three elements (done on untreated samples of pink dunes for this purpose) are even significantly lower than in the Nebraska Sand Hills. The geochemical data are supported by the mineralogical analyses, which show high

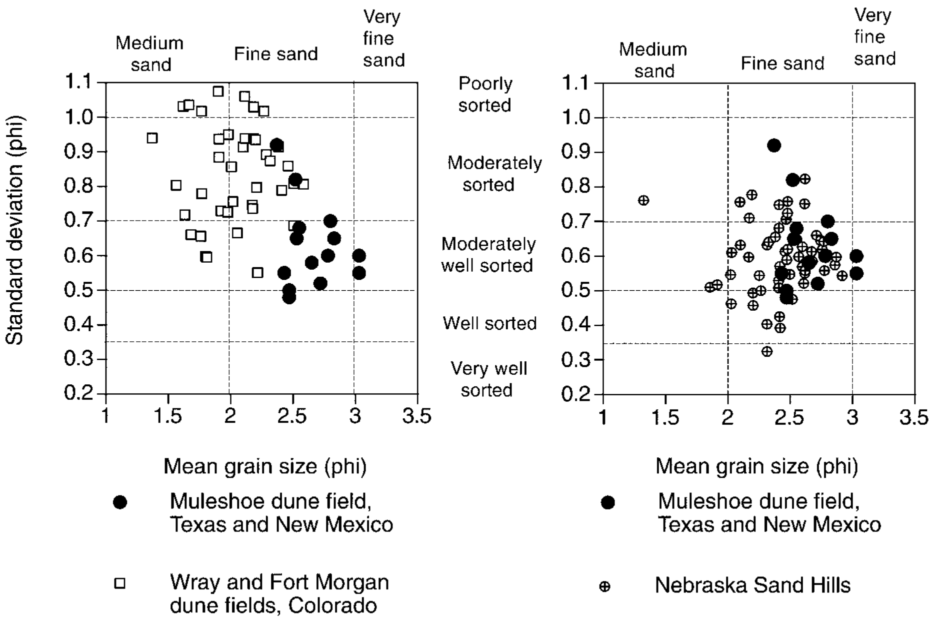

Figure 9. Textural parameters of eolian sands in the Muleshoe dune field compared to dunes in Nebraska and Colorado. Nebraska data are from Ahlbrandt and Fryberger (1980); Colorado data are from Muhs et al. (1996).

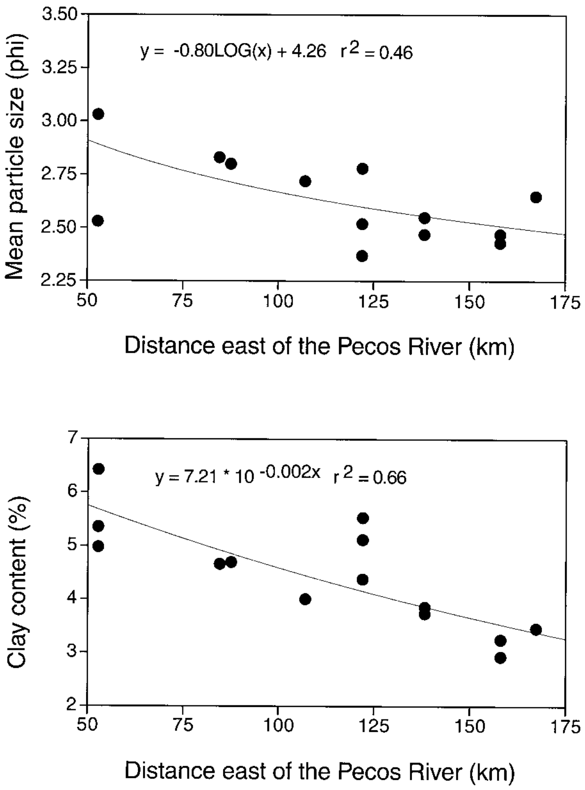

Figure 10. Variation of mean particle size and clay content in the Muleshoe dune field as a function of distance from the Pecos River.

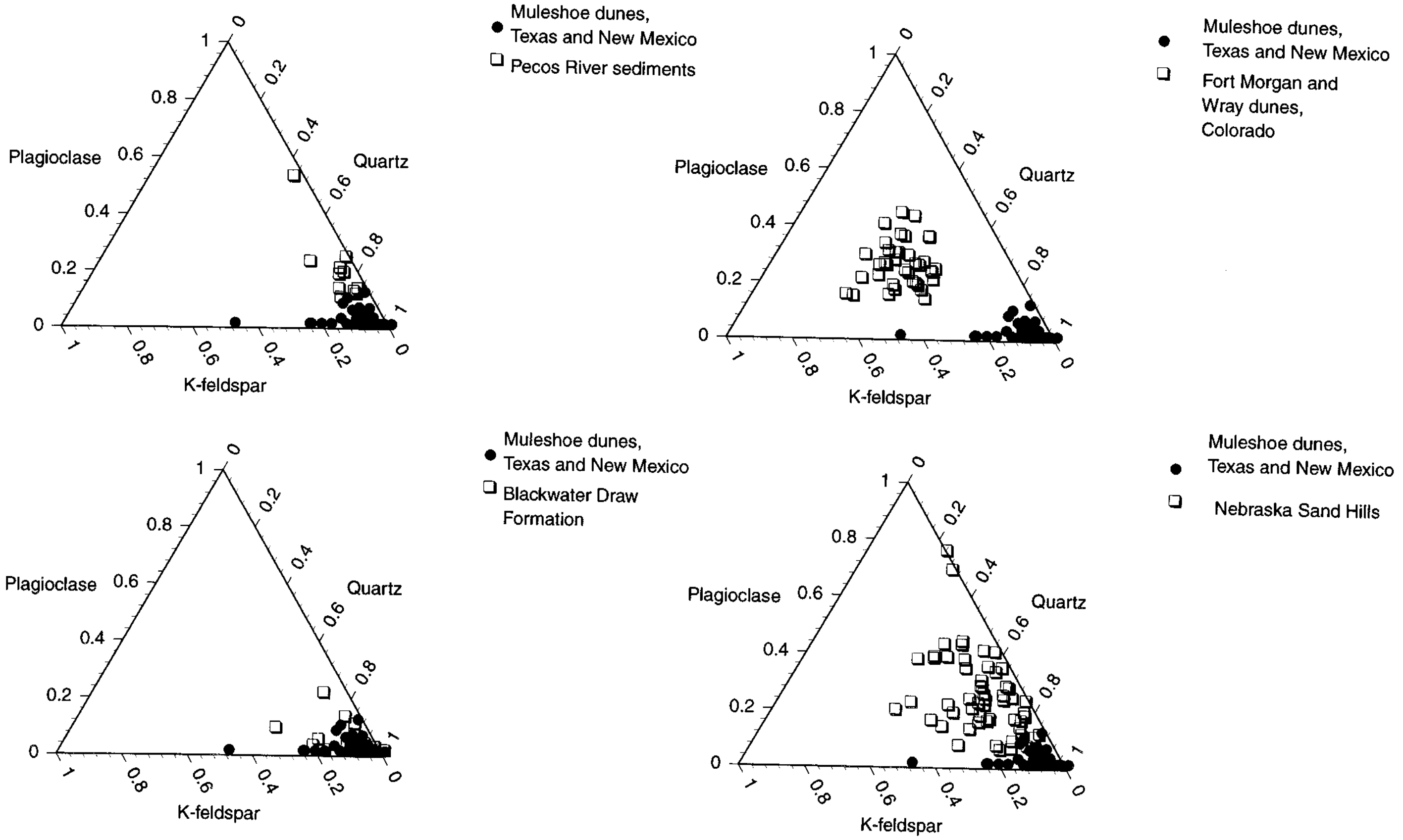

Figure 11. Ternary diagrams showing relative proportions (from X-ray peak heights) of quartz, plagioclase, and K-feldspar in Muleshoe dune sands compared to Pecos River sediments, the Blackwater Draw Formation, and Nebraska and Colorado dune sands (locations shown in Fig. 1). Relative proportions of minerals are based on the 20.8° (quartz), 27.4° (K-feldspar), and 27.8° (plagioclase) peaks. Nebraska and Colorado data are from Muhs et al. (1996, 1997a).

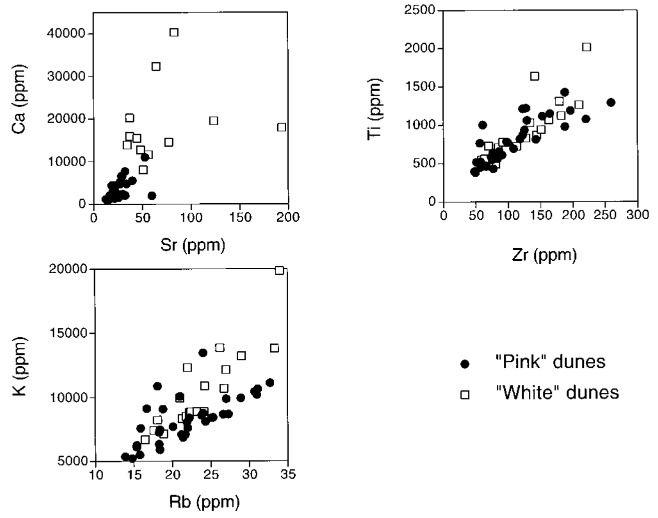

Figure 12. Comparison of concentrations of Ca, Sr, K, Rb, Ti, and Zr in pink (carbonate-free) and white (calcareous) dunes in the Muleshoe dune field.

quartz and low K-feldspar in Southern High Plains dunes compared to both Nebraska and Colorado (Fig. 11). In addition, Southern High Plains dune fields show differences: the Monahans dunes are much more K-feldspar depleted than the Muleshoe dunes.

DISCUSSION

Dune geomorphology, sedimentology, mineralogy, and geochemistry allow reconstruction of late Holocene eolian sand movement and the source of sand in the Southern High Plains. Annual resultant drift potentials suggest that there should be a generally southwest to northeast movement of eolian sands over much of the region. The resultant drift potentials are in partial agreement with dune orientations, particle size, and geochemical trends, which suggest a more west to east movement of sand. Three possibilities may explain the differences: (1) much of the sand movement may take place seasonally, in the winter and early spring, when resultant drift

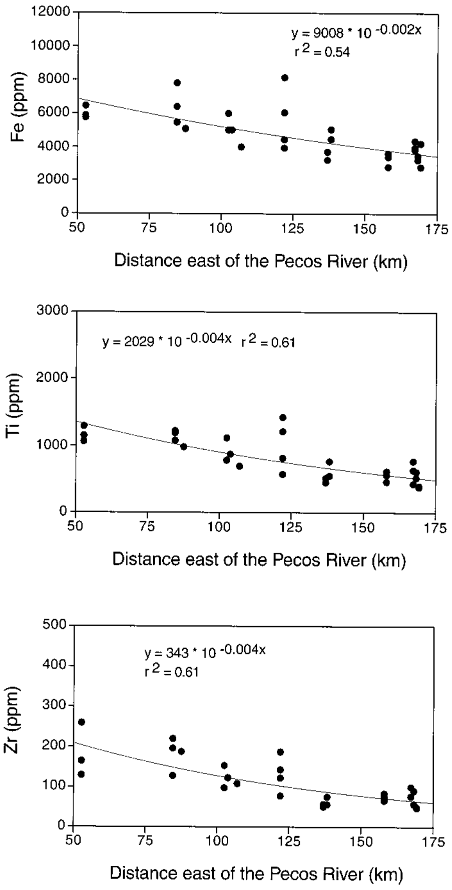

Figure 13. Variation in concentrations of Fe, Ti, and Zr as a function of distance from the Pecos River in the Muleshoe dune field.

directions are more west to east; (2) paleowinds may have been more westerly during the late Holocene times of dune formation; or (3) as suggested by Green (1961), Hawley et al. (1976), and Carlisle and Marrs (1982), funneling of winds through reentrants in the High Plains escarpment may modify regional southwesterly winds into local westerly winds. None of these explanations are mutually exclusive, and based on data in this study, we cannot favor one over the other.

Mineralogical and geochemical analyses indicate that two types of dunes in the Muleshoe field—those dominated by pink colors and those dominated by white-gray colors—are distinguished on the basis of carbonate contents. Abundances of elements that represent noncarbonate minerals in the two dune types are similar, indicating that the noncarbonate fractions of both dune types have a common source. The carbonate fraction may be derived from late Pleistocene lacustrine carbonates that are found in middle and upper Blackwater Draw Formation deposits that underlie significant areas of the Muleshoe dune field (Holliday, 1995b). Sediment in the Muleshoe dune field also changes in degree of redness and in clay content, both diminishing in a downwind direction. We interpret the decreasing redness to be caused by increasing downwind abrasion of red-pigmenting clay coatings.

On the basis of both mineralogical and geochemical analyses, dunes of the Southern High Plains have compositions that are closer to the Blackwater Draw Formation than to Pecos River sediments. Ca/Sr and Ba/Rb (and to a lesser extent, Ti/Zr) values in dunes and Blackwater Draw sediments are similar and all are lower than Pecos River sediments. The red (5YR and 7.5YR) clay coatings on Muleshoe dune sands support this interpretation as well: modern surface soils developed in the Blackwater Draw Formation commonly have 5YR or 7.5YR hues, and have both high sand and clay contents (Holliday, 1989). Erosion of soils of the Blackwater Draw Formation during historic time has resulted in the formation of low sand dunes or sheets that closely resemble those of the Muleshoe and other dune fields (see Holliday, 1987; his Fig. 31; reproduced here as Fig. 19). Furthermore, deposits of the Blackwater Draw Formation are extensive over the Southern High Plains and occur upwind of, or underlie, many of the dune fields, particularly the Muleshoe dune field and parts of the Lea-Yoakum and Monahans-Andrews dunes.

A Blackwater Draw Formation source for the dunes would also partially explain the mineralogical maturity of Southern High Plains dune fields, because that formation is also of eolian origin (Holliday, 1989) and much K-feldspar depletion apparently took place during its long history. Some of the K-feldspar depletion in dune sand of the Southern High Plains could have taken place during extensive mid-Holocene periods of activity, for which there is little stratigraphic record (Holliday, 2000). A Blackwater Draw Formation source for sand is favored because most reaches of the Pecos River are entrenched and little sediment is at present available for transport to the Llano Estacado.

Parts of some of these dune fields (particularly the Mescalero and Monahans dunes) are upwind of the Southern High Plains, and west of known extents of the Blackwater Draw Formation, which raises new questions about their origins. Recent field work in these areas (described by Holliday, 2000) shows that a Blackwater Draw Formation equivalent (a sandy loam to sandy clay loam with a well-expressed Bt-Bk soil profile called the Judkins Formation by Huffington and Albritton, 1941) is below the dunes in at least some areas. This unit is discontinuous beneath the western parts of the Monahans dunes. Its extent beneath the Mescalero dunes could not be determined owing to few exposures, and the overall discontinuous nature of the unit may be due to wind erosion. As shown by the Ti and Zr data, however, these dunes may contain sediments derived from the Pecos River (Fig. 16).

CONCLUSIONS

We conclude from geomorphic, sedimentological, mineralogical, and geochemical data that most late Holocene dunes in the Southern High Plains were formed by dominantly westerly winds, which may be the result of funneling of winds through gaps in the High Plains escarpment, as suggested by several previous workers and Holliday (2001, which is a companion paper in this issue of the *Bulletin*). Mineralogical and geochemical data suggest that most Southern High Plains dunes probably have, as their immediate sources, the Blackwater Draw Formation rather than sediments derived from the Pecos River valley. If this is true, it indicates that climate, through its effects on sediment availability, is the major control on mobility of dunes in the Southern High Plains. The Blackwater Draw Formation is extensive over the region, and historic droughts indicate that it can generate eolian sand sheets and dunes that resemble, on a smaller scale, the dune fields of the Southern High Plains. Dune fields in the region (as well as sand in the Blackwater Draw Formation) therefore appear to be sediment-availability–limited systems, as that term was defined by Kocurek and Lancaster (1999). On the basis of geochemical data, dune fields of the Southern High Plains are the most mineralogically mature eolian sands yet studied in the Great Plains, which suggests either inheritance from a quartz-rich source sediment and/or a long history of reworking.

The conclusion that Southern High Plains dunes are sediment-availability–limited systems is consistent with the observation that in the warmest, driest part of the region (the Monahans dune field) dunes are mostly active today. It also leads to implications regarding possible future dune mobility. Using the Lancaster (1988) dune mobility index, and 1961–1990 climate data, the area of Midland, Texas (near the Monahans dune field), has a dune mobility index value of 101, which places it in an activity field of fully mobile dunes, except for interdune areas. In contrast, Clovis (near the Muleshoe dune field) and Hobbs,

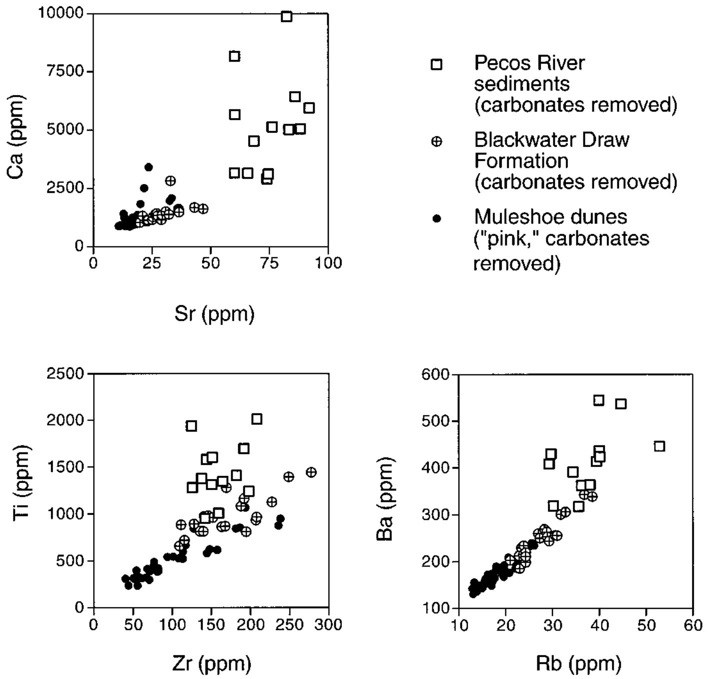

Figure 14. Comparison of concentrations of Ca, Sr, Ti, Zr, Ba, and Rb in Muleshoe dune sands, Pecos River sediments, and Blackwater Draw Formation sediments. Carbonates removed prior to analysis in all samples.

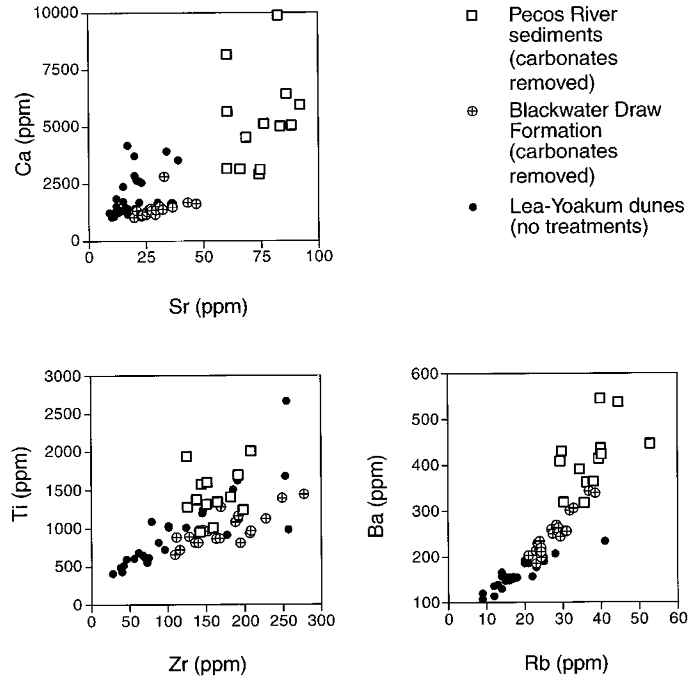

Figure 15. Comparison of concentrations of Ca, Sr, Ti, Zr, Ba, and Rb in Lea-Yoakum dune sands, Pecos River sediments, and Blackwater Draw Formation sediments.

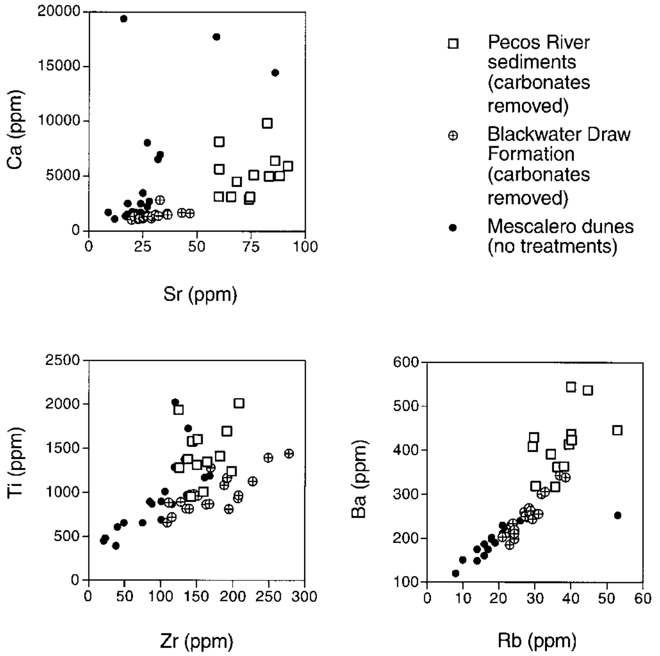

Figure 16. Comparison of concentrations of Ca, Sr, Ti, Zr, Ba, and Rb in Mescalero dune sands, Pecos River sediments, and Blackwater Draw Formation sediments.

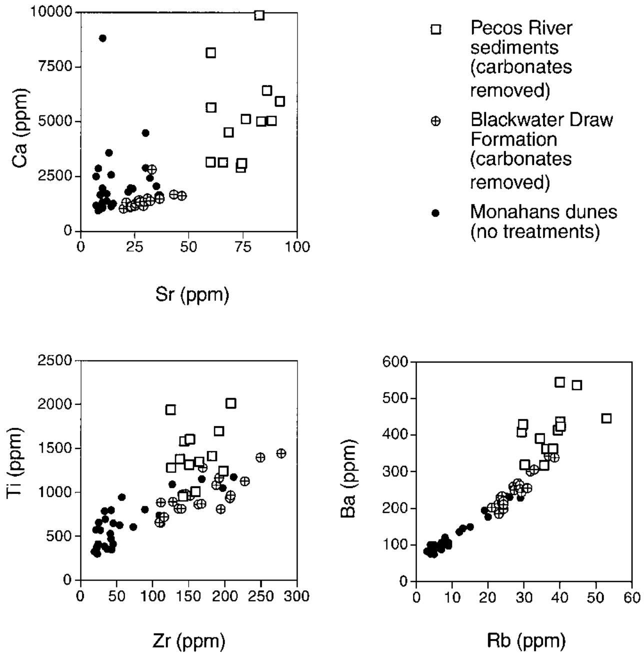

Figure 17. Comparison of concentrations of Ca, Sr, Ti, Zr, Ba, and Rb in Monahans-Andrews dune sands, Pecos River sediments, and Blackwater Draw Formation sediments.

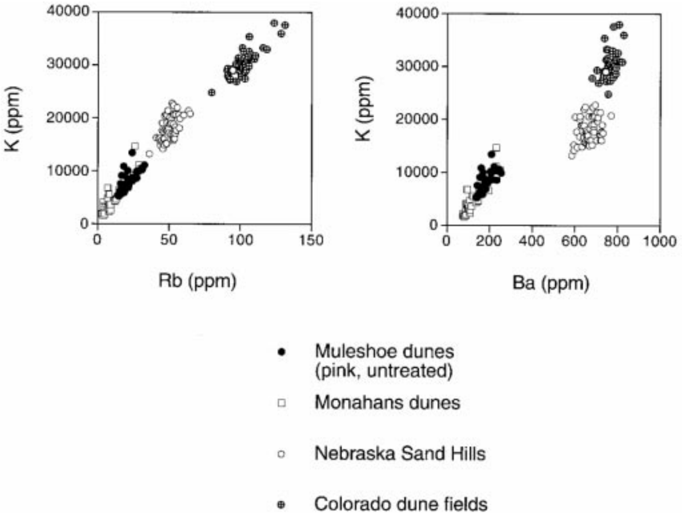

Figure 18. Comparison of concentrations of K, Rb, and Ba in Muleshoe and Monahans dune sands and sands from northeastern Colorado and Nebraska. Colorado and Nebraska data are from Muhs et al. (1996, 1997a).

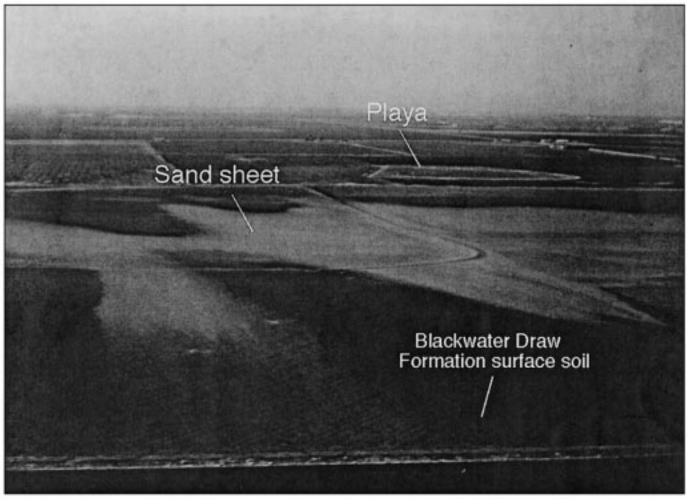

Figure 19. Modern erosion of soils in the Blackwater Draw Formation near Lubbock, Texas, to form quartz-rich sheet sands downwind. Photograph by V.T. Holliday (see Holliday, 1987).

New Mexico (near the Lea-Yoakum dune field), have dune mobility index values of ~80, placing them in an activity field of only mobile dune crests. Thus, only modest (10%–15%) decreases in precipitation accompanied by similar increases in evapotranspiration (due to higher temperatures) might be necessary to mobilize currently stable dunes.

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