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A B S T R A C T

The Nebraska Sand Hills region is the largest dune field in North America and has diverse aeolian landforms. It has been active during both the late Pleistocene and late Holocene. Despite decades of study, the source of sediment for this large sand sea is still controversial. Here we report new trace element compositions of aeolian sand that are compared to four hypothesized sediment sources, Tertiary rocks of the Arikaree Group and Ogallala Group, unconsolidated sands of Pliocene age, and Platte River system sands. All four potential sources have a mineralogy that is similar to the Nebraska Sand Hills. K/Rb, K/Ba, Sc-Th-La, Eu/Eu*, La_N/Yb_N, As/Sb, and Fe/Sc values show, however, that Pliocene sediments and sands from the Platte River system are not likely sources. The Arikaree Group could be a minor contributor, but sands from the Ogallala Group appear to have the best compositional fit to the Nebraska Sand Hills. Although past studies have proposed the Ogallala Group as an important sand source, the hypothesis has been questioned, because the unit is well cemented by calcrete in its upper part. However, examination of the landscape upwind of the Nebraska Sand Hills shows that the Ogallala Group, where it occurs at the land surface, is highly dissected in much of this region, which makes sand-sized particles available for aeolian entrainment whenever drought conditions diminish a protective vegetation cover.

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1. Introduction

Dune fields of Quaternary age occupy large areas of the world's arid and semiarid regions, many of them in subtropical deserts and in rain-shadowed zones of the mid-latitudes (Wilson, 1973; Lancaster, 1989, 1995; Pye and Tsoar, 1990; Cooke et al., 1993; Lancaster, 1989, 1995; Livingstone and Warren, 1996; Goudie, 2002; Muhs et al., 2013; Warren, 2013; Lorenz and Zimbelman, 2014). Some of the largest dune fields, in the deserts of Asia and Africa, are unvegetated and fully active (Yang et al., 2004; Lancaster, 2007; Sun and Muhs, 2007). In contrast, dune fields of South America and North America are mostly vegetated and inactive (Zárate and Tripaldi, 2012; Muhs, 2017). In Australia, dune fields are also largely inactive, but dune field stabilization is due not only to vegetation cover, but also cementation and pedogenesis (Hesse, 2011).

Whether a dune field is active or stable, as well as what sort of dune forms evolve, requires an understanding of the controls on sand entrainment, transport, and deposition. More than seven decades ago, Hack (1941) articulated what are now considered to be the main variables in dune field activity and evolution, namely sand supply, wind strength, and degree of vegetation cover. Later studies have emphasized the importance of climatic factors, primarily moisture balance (precipitation vs. evapotranspiration) as controls on the degree of vegetation cover on sand dunes (Lancaster, 1988; Muhs and Maat, 1993; Muhs and Holliday, 1995; Wolfe, 1997; Lancaster and Helm, 2000). Still other studies have proposed wind strength as the dominant climate factor in explaining degree of dune activity (Tsoar, 2005; Tsoar et al., 2009; Yizhaq et al., 2009). All of these studies assume, however, that sand supply is adequate to form a dune field in the first place. Thus, understanding the source or sources of sand is key to understanding the origin and subsequent evolution of a dune field. In support of this concept, Kocurek and Lancaster (1999) proposed the idea of an "aeolian system sediment state," which includes, within a dune field, the degree of aeolian activity vs. stability. These investigators emphasized the components of sediment supply and sediment availability, in addition to transport capacity of the wind. Halfen et al. (2016), in a recent review of North American dune fields of late Quaternary age, also emphasized the importance of sediment supply and sediment availability (as a result of drought episodes) as controls on dune field activity. Thus, provenance of sand is fundamental to understanding the genesis of a dune field and its potential for future activity.

Inland dune fields of Quaternary age, most of them stabilized by vegetation, are common across much of North America (see reviews in Wolfe, 2007 and Muhs, 2017). Within the USA, areas of aeolian sand are concentrated in three physiographic regions, the Basin and Range, the Colorado Plateau, and the Great Plains (Fig. 1). The largest areas of aeolian sand are those within the Great Plains province (Fig. 2). The Great Plains region is semiarid because it lies within the rain shadow

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Fig. 1. Map of North America showing physiographic provinces. Dashed box outlines the Great Plains physiographic province within the USA (Fig. 2).

of the north-south-trending ranges of the Rocky Mountains, which shield the region to the east from westerly storm tracks. Active aeolian sand in the Great Plains region is limited to the southernmost dunes in Texas and New Mexico and a few other areas where human activities, such as grazing, cultivation, or development of infrastructure have reactivated previously stabilized sand.

The Nebraska Sand Hills dune field, in the central part of the Great Plains, covers an area of ~57,000 km^2 (Fig. 2). Much of the dune field was active during the last glacial period, based on extensive drilling and optically stimulated luminescence (OSL) dating reported in a landmark study by Mason et al. (2011). Although most dunes in the Nebraska Sand Hills are presently stabilized by vegetation, there is ample evidence that sand also has been active within the late Holocene, based on radiocarbon and OSL dating (Ahlbrandt et al., 1983; Swinehart, 1990; Loope et al., 1995; Muhs et al., 1997; Stokes and Swinehart, 1997; Goble et al., 2004; Mason et al., 2004; Forman et al., 2005; Miao et al., 2007; Schmeisser et al., 2010; Schmeisser McKean et al., 2015) and even historical accounts (Muhs and Holliday, 1995). These studies have shown that this large dune field is highly sensitive to changes in moisture regime that control the degree of stabilizing vegetation.

Although there has been a significant effort to understand the timing of dune activity in the Nebraska Sand Hills, there have been few studies of the actual sources of the sand. Recently, Muhs (2017) re-examined the origin of many of the dune fields of the Great Plains and Basin and Range provinces. This investigation utilized K/Rb and K/Ba values as proxies for the compositions of K-feldspars from different source sediments. Results show that some previous concepts of dune field origins are supported by the new data, some dune sand sources not previously considered to be important are actually significant contributors, and the origin of some dune fields still remains elusive. One of the dune fields whose source sediments are still uncertain is the Nebraska Sand Hills.

In the Nebraska Sand Hills region, modern observations show that on an annual basis, the dominant sand-moving winds (computed as resultant drift directions, or RDD, using methods of Fryberger and Dean, 1979) come from the northwest (Fig. 3). Late Holocene paleowinds, based on the orientations of parabolic dunes examined on aerial photographs, indicate that the dominant sand-moving winds were also from the northwest (Fig. 3). Thus, a simple interpretation might be that past wind directions were similar to those of the present and sources of the Nebraska Sand Hills must lie to the northwest of the dune field. However, in a continental-interior, mid-latitude region such as Nebraska, there are

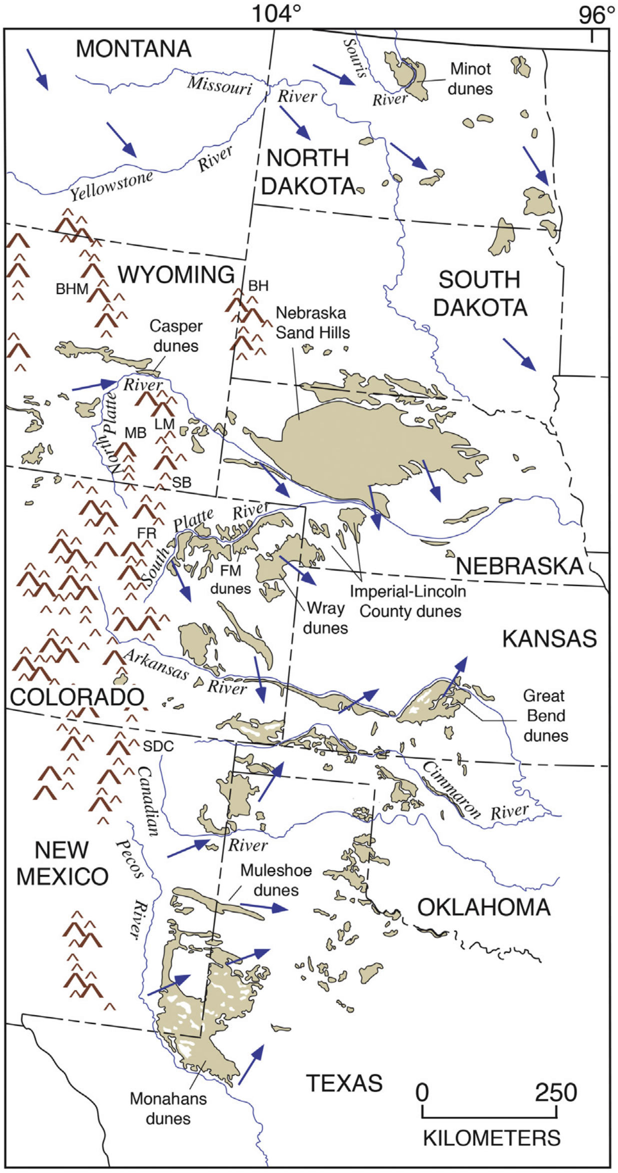

Fig. 2. Map of the Great Plains region in the central USA, showing the distribution of dune fields and annual wind RDD (resultant drift direction; see Fryberger and Dean, 1979). Aeolian sand distribution modified slightly from compilation in Muhs and Holliday (1995), who used the following sources: Dane and Bachman (1965), Morrison (1969), Westin et al. (1971), Scott (1968, 1978), Sharps (1976, 1980), Love and Christiansen (1985), Swinehart (1990), Kuzila et al. (1990), Ross et al. (1991), Hartman and Scranton (1992), Swinehart et al. (1994a), and Muhs et al. (1996). Most areas mapped here were also field-checked by the authors; see also digital form of this distribution in Soller and Reheis (2004). Arrows show RDD values of modern, sand-moving winds calculated by the authors. Abbreviations: BH, Black Hills; BHM, Bighorn Mountains; LM, Laramie Mountains; MB, Medicine Bow Mountains; SB, Sherman batholith; FR, Front Range; FM, Fort Morgan; SDC, Sangre de Cristo Mountains.

strong seasonal contrasts in temperature, precipitation, and wind direction. During October through April, the RDD of sand-moving winds in Nebraska are dominantly from the northwest (represented in Fig. 4a by RDD for April). However, during winter months, soils and sediments of the central Great Plains are frozen and/or snow-covered for extended periods, limiting particle mobility by wind. In contrast, during the warmer months of May through September, although resultant drift potential (RDP) values are lower, meaning weaker winds, many localities in Nebraska show sand-moving winds dominantly from the south, southwest, or southeast (represented in Fig. 4b by RDD for August). Thus, although dune sand sources in areas situated to the northwest of the Nebraska Sand Hills might be important in the cooler months of the year, dune sand sources to the south, southwest, or southeast may be more important during the warmer months.

Trace element geochemistry is a powerful tool for investigating the origin of dune fields, particularly those with high quartz content, where major element geochemistry may provide only limited interpretations. A number of investigators have used trace element compositions, including the rare earth elements (REE) to determine the origin of dune fields in Mexico (Kasper-Zubillaga et al., 2007), China (Yang et al., 2007; Liu and Yang, 2018), and Africa (Garzanti et al., 2012). Here, four potential sources of aeolian sand for the Nebraska Sand Hills, identical to those studied by Muhs (2017) are considered in light of a larger suite of trace elements.

Potential source sediments for the Nebraska Sand Hills span a considerable range of geologic ages. One of these sources is unconsolidated fluvial sediments, sands from the Platte River system (North Platte, South Platte and Platte rivers), situated to the west, southwest, south, and southeast of the dune field (Fig. 5). Other potential source sediments for the Nebraska Sand Hills are of pre-Quaternary age. Pliocene sheet sands, some of which are thought to be of aeolian origin, occur beneath the Nebraska Sand Hills. These sediments, mostly unconsolidated, are as much as 28 m thick. The full geographic extent of these Pliocene sands is unknown, but a minimum distribution has been documented by Myers (1993), Swinehart et al. (1994b), and May et al. (1995), primarily beneath the south-central part of the Nebraska Sand Hills (Fig. 5). In the present study, samples were analyzed from localities where Pliocene sands are exposed either in quarries or along cut banks of streams. Two other potential dune sand sources, exposed to the northwest of the Nebraska Sand Hills, are the Miocene Ogallala Group and the Oligocene-Miocene Arikaree Group. These rocks occur at both the surface and subsurface over much of western Nebraska and adjacent parts of southern South Dakota, eastern Wyoming, and northeastern Colorado (Figs. 3 and 5). Some sediments of the Ogallala Group and Arikaree Group are well cemented due to long-term diagenesis or pedogenesis, but other occurrences of these units are loose, unconsolidated sands. Sediments of the Niobrara River valley, situated to the northwest and north of the Nebraska Sand Hills, are also a potential source, but because this river drains only rocks of the Arikaree and Ogallala Groups (Burchett, 1969; Love and Christiansen, 1985), possible contributions from it can be assessed from those two sources.

2. Methods

Aeolian sands from the Nebraska Sand Hills were sampled from unaltered sediments found below the modern soil. These were analyzed as bulk samples, with no pretreatments other than pulverization. Alluvial and bedrock samples from potential source sediments were sampled from outcrops and road cuts in Nebraska, Wyoming, and South Dakota. All source sediment samples were pretreated to yield a particle-size distribution similar to that of aeolian sand. After disaggregation and removal of coarse gravel, the samples were placed in deionized water, a Na-pyrophosphate dispersant was added, particles in suspension were stirred, and then allowed to sit overnight. After this treatment, the samples were stirred again by ultrasonication and then wet-sieved to remove fine gravel and the coarsest sands using a 500-μm sieve. Silt and clay were removed by wet-sieving with a 53-μm sieve. Thus, the final sediment separates, 500 μm–53 μm, contain grains ranging from medium sand to very fine sand, similar to the size range of aeolian sediments of the Nebraska Sand Hills (Ahlbrandt and Fryberger, 1980). Sample localities are shown in Fig. 5 and specific coordinates and analytical data are given in Supplementary Data Table 1.

Muhs et al. (1997) compared the relative abundances of quartz, K-feldspar, and plagioclase in the Nebraska Sand Hills with those of dune sands in nearby eastern Colorado. Here, we use the same mineralogical data reported in that study for the Nebraska Sand Hills, but we compare these compositions to the mineralogy of the 500-μm to 53-μm separates of candidate source sediments, prepared as described above. We

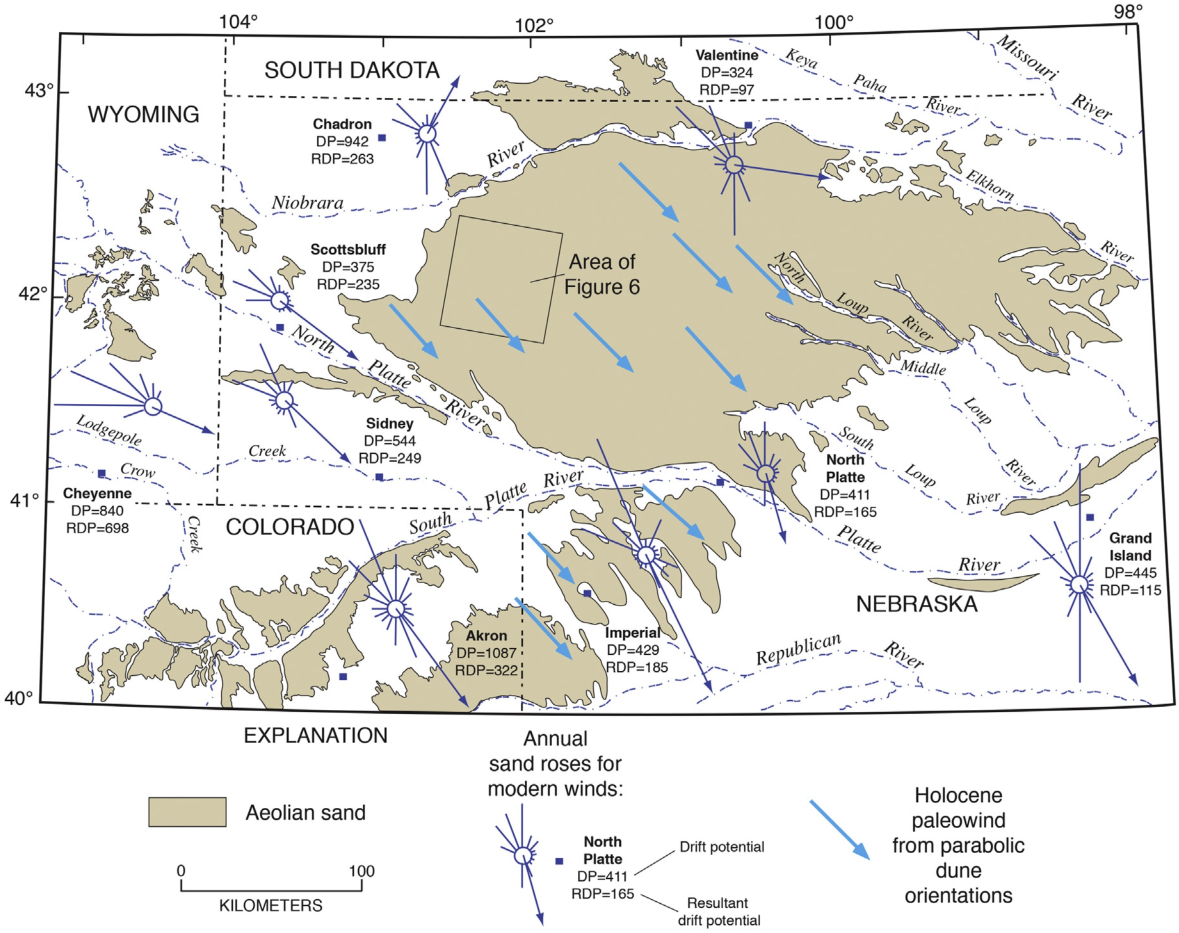

Fig. 3. Map showing Holocene aeolian sand of the Nebraska Sand Hills and adjacent areas and sand roses showing wind data for nearby weather stations (calculated by the authors using methods in Fryberger and Dean, 1979; DP = drift potential; RDP = resultant drift potential). Large arrows of sand roses show resultant annual drift direction (RDD) as a vector summation, using equations in Fryberger and Dean (1979); arrows point downwind. Aeolian sand distribution in the Nebraska Sand Hills based on Swinehart (1990) and Swinehart et al. (1994a); aeolian sand distribution in Wyoming from Love and Christiansen (1985); aeolian sand distribution in South Dakota from Martin et al. (2004); aeolian sand distribution in Colorado from Scott (1978) and Muhs (2017). Holocene paleowinds determined by the authors from interpretation of late Holocene dune orientations on 1:80,000 black and white NHAP (National High Altitude Photography, USGS) aerial photographs. Wind data for some localities are from the Wind Energy Resource Information System (WERIS) archived by the National Climatic Data Center, National Oceanic and Atmospheric Administration (NOAA); other data are from the International Station Meteorological Climate Summary, version 4.0, produced jointly by the U.S. Navy Fleet Numerical Meteorology and Oceanography Detachment, the National Climatic Data Center (NOAA), and U.S. Air Force USAFETAC OL-A.

measured the *relative* amounts of the primary minerals using X-ray diffraction (XRD) peak heights for quartz (20.9° 2-theta), K-feldspar (27.4° 2-theta), and plagioclase (27.8° 2-theta). The data for the Nebraska Sand Hills are identical to those reported by Muhs et al. (1997), but differ slightly from later analyses of the same samples in Muhs (2017). For potential source sediments, the XRD analyses of quartz, K-feldspar, and plagioclase were done using the same methods, XRD instrument, and machine settings as those for the Nebraska Sand Hills samples given in Muhs et al. (1997). Thus, XRD data from both the Nebraska Sand Hills and potential source sediments are all directly comparable.

Concentrations of trace elements, including the REE, were determined by instrumental neutron activation analysis (INAA), following methods in Budahn and Wandless (2002). For assessment of possible aeolian sand sources, we use ratios of trace elements that have been effective in tracing origins of loess (Muhs and Budahn, 2006). These ratios utilize trace elements with a minimum degree of mobility in near-surface environments (Taylor and McLennan, 1985; McLennan, 1989) and include Sc, Th, La, As, and Sb.

The REE are found in a broad range of minerals including pyroxenes, micas, chlorite, clay minerals, amphiboles, zircon, feldspars, and apatite (see summary tables in Taylor and McLennan, 1985). We use two sensitive indicators of REE composition, La_N/Yb_N, and Eu/Eu*, where the "N" subscript indicates the element concentration is normalized, by convention, to chondritic meteorite values. Concentrations of REE in chondritic meteorites are considered to be representative of cosmic abundances. Normalization of REE concentrations in rocks or sediments to chondritic meteorite values effectively evens out what would otherwise be a confusing "zig-zag" pattern of absolute REE abundances. These elements are often divided into light REE (La through Sm) and heavy REE (Gd through Lu) because partial melting of mantle or crustal rocks tends to cause an enrichment of the light REE over the heavy REE (McLennan, 1989). By convention, the degree of light REE enrichment over heavy REE is typically represented by a simple ratio of chondrite-normalized concentrations of La (La_N) to Yb (Yb_N). Mid-ocean ridge basalts have an average La_N/Yb_N value of 0.68, andesites have an average La_N/Yb_N value of 5.8, and upper continental crust has an average La_N/Yb_N value of 9.2 (Taylor and McLennan, 1985). Thus, sediments derived from a suite of rocks with varying compositions along this continuum will have intermediate La_N/Yb_N values.

The REE occur in a trivalent state under most of the pressure and temperature conditions of the Earth, but under reducing conditions (e.g., in the mantle or lower crust), Eu may occur in a divalent state (McLennan, 1989). With this charge and its ionic radius, Eu can easily substitute for Sr, found in Ca-plagioclase, and Eu is also therefore enriched in Ca-plagioclase. Thus, rocks with abundant Ca-plagioclase (anorthosites) will have higher Eu concentrations relative to Sm and Gd on a chondrite-normalized REE plot, a condition referred to as a positive Eu anomaly. Rocks from the lower continental crust also have

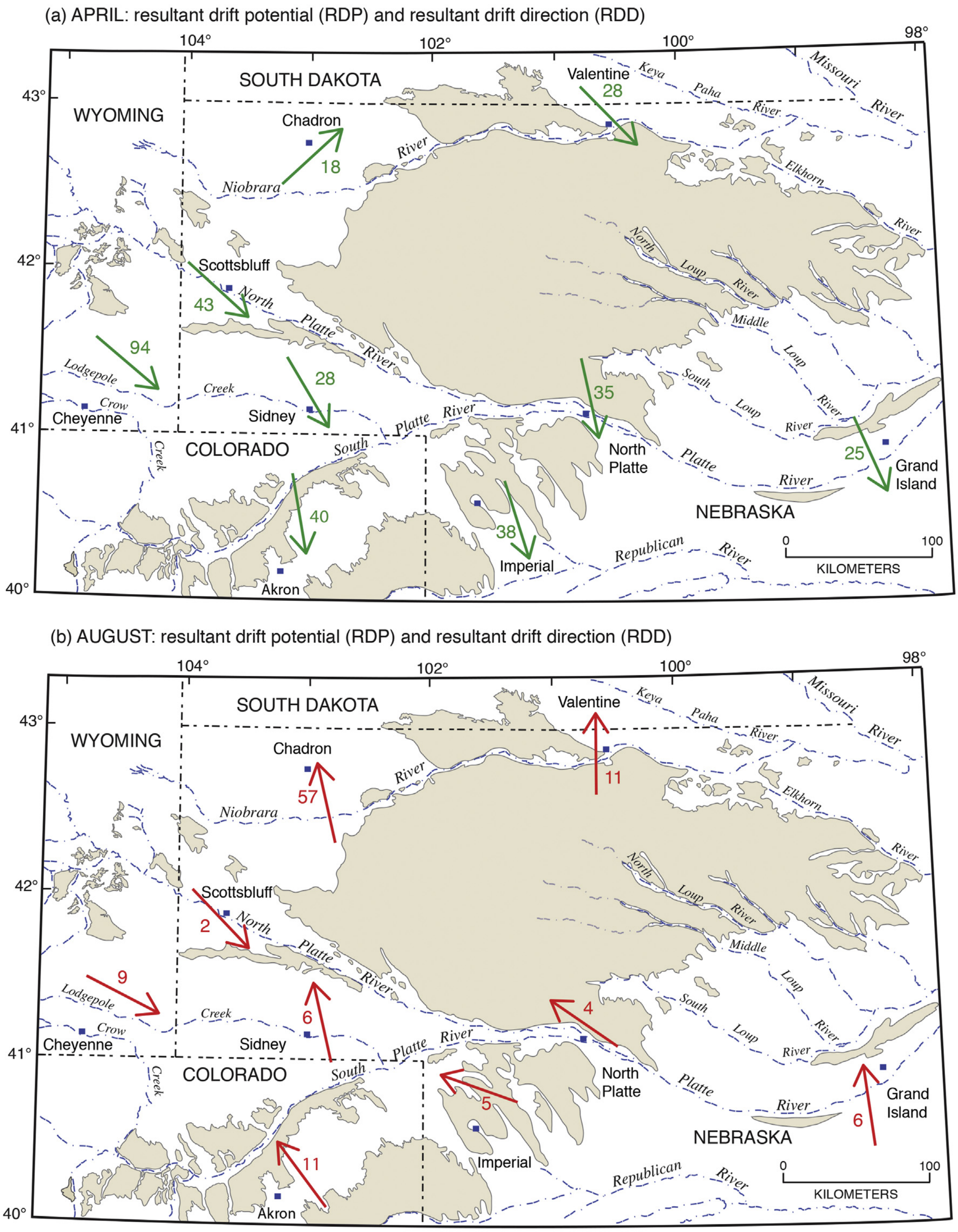

Fig. 4. Maps showing aeolian sand of the Nebraska Sand Hills and adjacent areas (same sources as in Fig. 3) and resultant monthly drift directions (RDD) as arrows pointing downwind; numbers beside each arrow are monthly RDP values. Map in (a) shows monthly RDP and RDD for April, representative of conditions during cold months of the year (October through April) and map in (b) shows monthly RDP and RDD for August, representative of conditions during warm months of the year (May through September). Wind data from same sources as in Fig. 3 and computed by the authors.

positive Eu anomalies (Taylor and McLennan, 1985). In contrast, the upper continental crust (which has an average composition of granodiorite) is depleted in Eu, relative to Sm and Gd on a chondrite-normalized REE plot, a condition referred to as a negative Eu anomaly.

The sign and degree of any Eu anomaly can be quantified by the Eu/Eu* value, where Eu is the chondrite-normalized Eu concentration (Eu_N), and Eu* is $(Sm_N \times Gd_N)^{0.5}$. Basalts that reflect a dominantly mantle origin typically have no Eu anomaly and therefore have Eu/Eu* values of 1.0 (see examples in Budahn and Schmitt, 1985). Values less than 1.0 indicate “negative” Eu anomalies; values greater than 1.0 indicate “positive” Eu anomalies. Because igneous rocks of the upper continental crust typically have negative Eu anomalies, sedimentary rocks derived from them do too, with Eu/Eu* values ranging from 0.5 to 0.6 to just under 1.0 (Taylor and McLennan, 1985; McLennan, 1989). Plots

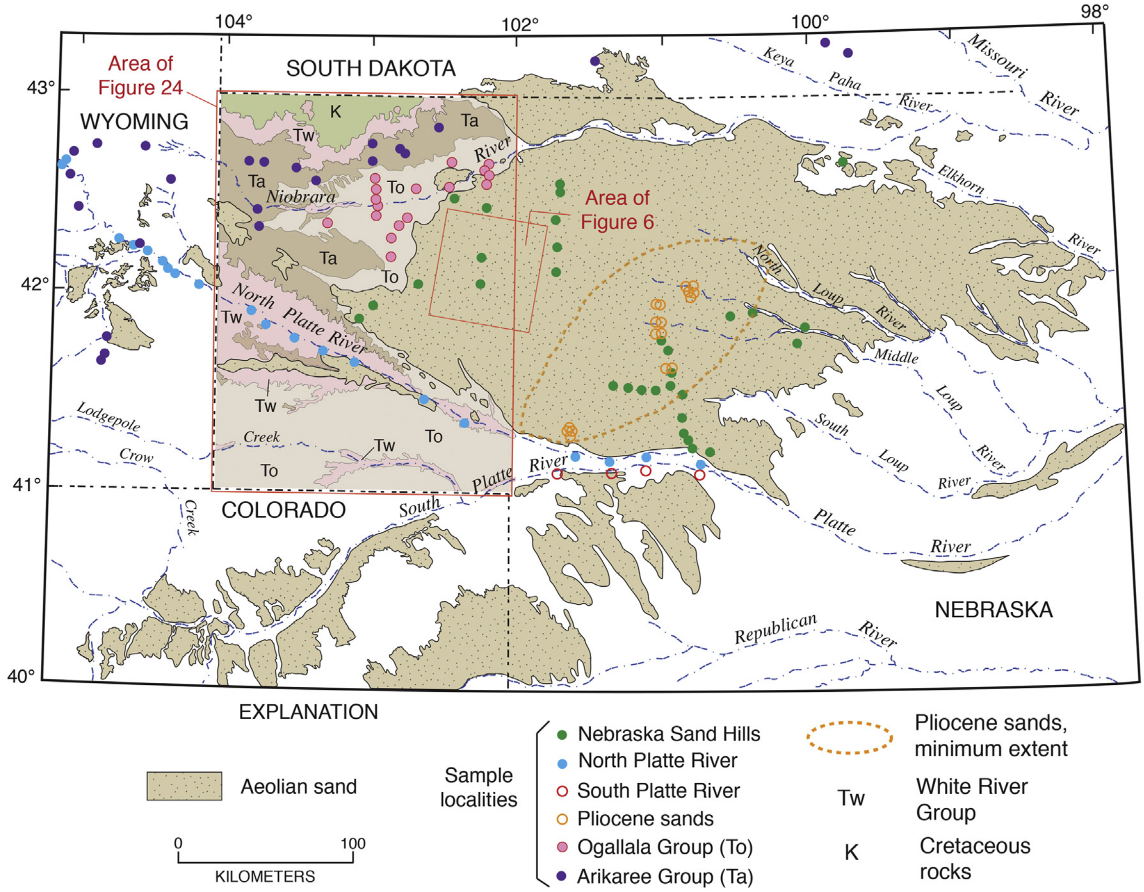

Fig. 5. Map showing Holocene aeolian sand of the Nebraska Sand Hills and adjacent areas; aeolian sand distribution from sources as given in Fig. 3. Bedrock geology for western Nebraska only is simplified from Swinehart et al. (1985). Extent of Pliocene sediments is taken from Myers (1993) and Swinehart et al. (1994b). Also shown are sample localities for geochemical analyses conducted in the present study. Detailed coordinates and all geochemical data for all localities shown are given in Supplementary Data Table 1.

of La_N/Yb_N vs. Eu/Eu* are powerful tools for differentiating candidate sources of aeolian sediments (Muhs and Budahn, 2006; Sun et al., 2007; Yang et al., 2007; Liu and Yang, 2018; Muhs, 2018).

Finally, because Muhs (2017) pointed out the potential slight bias of determining K concentrations determined by energy-dispersive X-ray fluorescence (ED XRF), we re-determined K, Rb, and Ba concentrations in Nebraska Sand Hills samples from that study using INAA. With these new data, we recalculated K/Rb and K/Ba values to evaluate the earlier conclusions of Muhs (2017) based on ED XRF analyses.

3. Results

3.1. Geomorphology and soils of the Nebraska Sand Hills

The Nebraska Sand Hills host one of the richest arrays of aeolian landforms in North America. Swinehart (1990) mapped all the major types of aeolian landforms in this sand sea, including barchanoid ridges, barchans, linear dunes, parabolic dunes, dome-like dunes, and aeolian sand sheets. He further subdivided these landforms on the basis of those having low and moderate relief (sand sheets), spacing (barchans), and simple, compound, and complex forms (dome-like dunes). All these dune forms are easily visible on satellite imagery (Fig. 6) and are highlighted by the presence of interdune lakes or wetlands, which are important wildlife habitats.

Barchanoid ridges are some of the most spatially extensive dunes in the western half of the dune field. Although stabilized by vegetation, these dunes are easily recognized on aerial photographs and many are several kilometers long (Fig. 7a). The old slip faces, although degraded, are still identifiable in the field, with most dips to the southeast, indicating paleowinds from the northwest (Fig. 7b). Based on deep drilling and OSL analyses by Mason et al. (2011), it is likely that many of the barchanoid ridges were built during the last glacial period. Nevertheless, most of these large landforms are actually complex dune forms, with much smaller parabolic dunes superimposed on the barchanoid forms.

Barchan dunes occur primarily in the western part of the Nebraska Sand Hills (Swinehart, 1990). These dunes are often separated from one another by interdune lakes and wetlands, as is the case with the barchanoid ridges (Fig. 8a). Most barchans are smaller landforms, however, with many having arm-to-arm distances of ~2 km. Degraded slip faces of these dunes are also visible on aerial photographs and in the field, and like the barchanoid ridges, dip to the southeast, indicating paleowinds from the northwest (Figs. 8a,b). As with the barchanoid ridges, barchans usually host smaller, younger, parabolic dunes.

Linear dunes are dominant in the southern portion of the eastern half of the Nebraska Sand Hills (Swinehart, 1990). Such dunes are also found north of the Middle Loup River in the east-central part of the dune field, with long axes that trend northwest-southeast (Fig. 9a). Most of these dunes are ~1 km to ~3 km in length, but dunes up to ~5 km long are also found. Cross-beds with dips to the southwest are sometimes exposed in blowouts, such as those in a northwest-southeast-trending linear dune arm northeast of the town of Dunning (Fig. 9b). Sridhar et al. (2006) proposed that these dunes were built during the Medieval Warm Period, ~800 to ~1000 yr ago, when moist air flow from the southeast in spring and summer was replaced by dry air from the southwest, bringing about drought conditions.

Finally, parabolic dunes are found extensively over the Nebraska Sand Hills (Fig. 10). Swinehart (1990) mapped this dune type as the

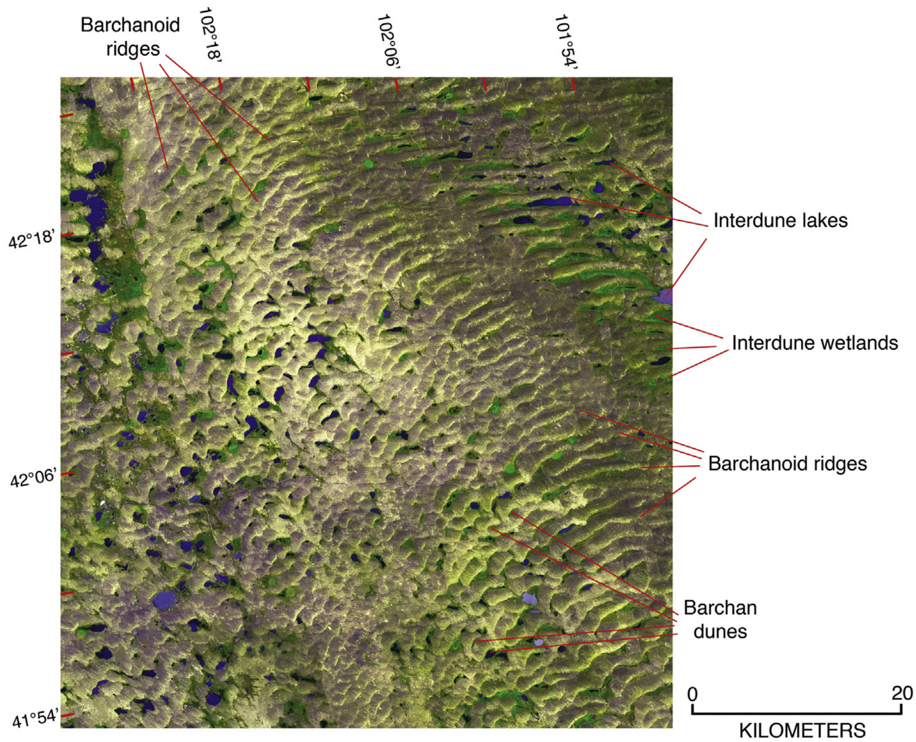

Fig. 6. Simulated natural-color image of inactive (stable) barchan and barchanoid-ridge dunes in the Nebraska Sand Hills, USA, from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on NASA's Terra satellite, acquired 10 September 2001[image courtesy NASA/GSFC/METI/ERSDAC/JAROS and U. S./Japan ASTER Science Team].

dominant landform in the southwestern part of the region. As described above, however, small, younger parabolic dunes are superimposed on the much larger barchans or barchanoid ridges, forming complex dunes. Virtually all of the parabolic dunes that we have observed have noses that point to the southeast and arms that point to the northwest, indicating formation under dominantly northwesterly winds.

Despite their simple morphology and young ages, parabolic dunes of the Nebraska Sand Hills host a diverse suite of primary and secondary structures. Paleosols, typically with A/AC/C profiles, are common, indicating multiple cycles of aeolian sand activity and stability during the late Holocene (Figs. 11a, b). Although cross-bedding is exposed in some parabolic dunes, horizontal or low-angle, pin-stripe ripple strata can also be observed (Figs. 11c, d), indicating the likelihood of some aeolian sediment being deposited as sheet sands (Fryberger and Schenk, 1988). Both cross-bedded sands and horizontal pin-stripe laminations often have been deformed by prehistoric bison, first noted by Loope (1986). Bison hoof prints often show impressive preservation in both cross section and plan view, even though the host sands are young and unconsolidated (Fig. 11e).

In northeastern Colorado, where aeolian sand is also extensive (Figs. 2-5), radiocarbon and luminescence ages indicate that there are both late Pleistocene dunes or sand sheets and late Holocene dunes (Madole, 1995; Muhs et al., 1996; Clarke and Rendell, 2003; Madole et al., 2005; Berry et al., 2015). These studies have shown that aeolian sands dating to the late Pleistocene, specifically the last glacial period, host soils with A/Bt/Bk/C profiles. In contrast, aeolian sands dating to the late Holocene host soils with only simple A/AC/C profiles. In the Nebraska Sand Hills, soils developed in aeolian sand or in alluvium derived from aeolian sand are all minimally developed, with A/AC/C profiles (Fig. 12). The implications of this soil geography are quite profound. Minimally developed soils over the entire Nebraska Sand Hills region implies that there has been aeolian activity of late Holocene age virtually everywhere in this sand sea, though all dunes were not necessarily active at the same time. All Nebraska Sand Hills samples we collected were from localities with A/AC/C profiles, indicating late Holocene ages.

3.2. Geology and geomorphic setting of potential source sediments

To consider sediments to be potential sources for the Nebraska Sand Hills, they must meet several requirements. Because the Nebraska Sand Hills are composed of fairly well sorted sands composed of primary rock-forming minerals (quartz and feldspars), potential source sediments must have a favorable particle-size distribution and mineralogy. This eliminates fine-grained sedimentary rocks in the Great Plains region such as the Cretaceous Pierre Shale (clay-mineral-dominated) and the Oligocene White River Group (silt-dominated), but sand-dominated units such as the Arikaree Group (Oligocene-Miocene) and Ogallala Group (Miocene) are suitable candidates. Younger, sand-rich sediments are also potential sources, including Pliocene sands that underlie the Nebraska Sand Hills and sandy point bars of major rivers. A second requirement is that a potential source must be in a geographically favorable position, either upwind of the Nebraska Sand Hills or at least formerly upwind if it is now buried beneath the dune field. Sediments of the Arikaree Group and Ogallala Group are exposed at the surface to the northwest of the dune field and are therefore candidate source sediments when winds are from the northwest, during the period from October through April (Fig. 4a). The Niobrara River, which drains these two sediment groups, is also situated to the northwest of most of the Nebraska Sand Hills (Figs. 3 and 5). Pliocene sediments are found beneath the Nebraska Sand Hills mostly in the south-central part of the dune field, and the North Platte, South Platte, and Platte Rivers are found to the west, southwest, south, and southeast of the dune field. Thus, these younger sediments are potentially important sources of aeolian sand if transport occurred during the warmer months of the year, May through September (Fig. 4b). Finally, potential source sediments must be unconsolidated and exposed at the surface, or if partially consolidated, a landscape with a potential source rock must be dissected to the extent that loose particles are available for aeolian entrainment. Here we report field observations of the Arikaree Group, Ogallala Group, Pliocene sediments and North Platte River sediments in light of these requirements.

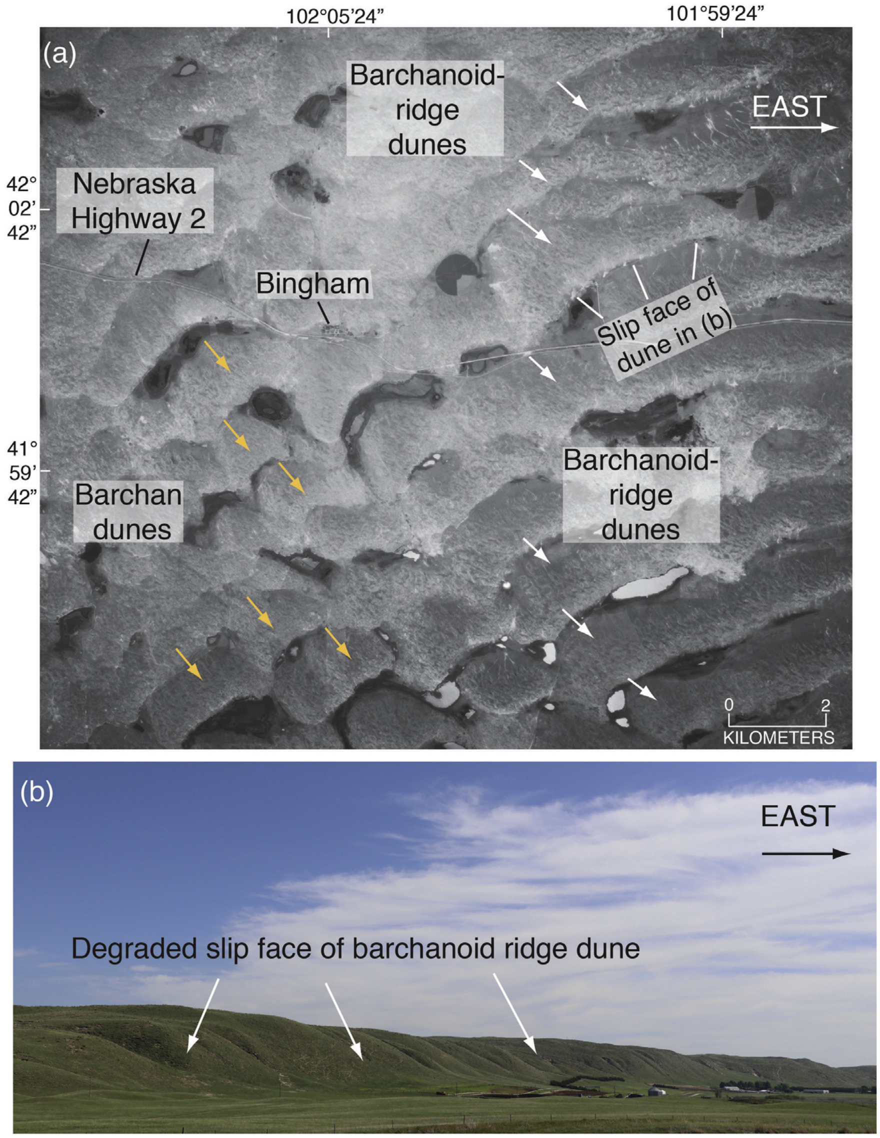

Fig. 7. Barchanoid-ridge dunes in the northwestern Nebraska Sand Hills. (a) U.S. Geological Survey National High Altitude Aerial Photograph (NHAP) Program, black and white, visible band photo number NB1NHAP840092019, acquired 22 June 1984, Grant County, Nebraska, showing barchanoid-ridge and barchan dunes, both thought to be of Pleistocene age (Mason et al., 2011). Arrows indicate inferred paleowinds during times of dune formation (arrows point downwind); gold arrows are for barchan dunes, white arrows are for barchanoid-ridges. (b) Ground photograph of the degraded slip face of one of the barchanoid-ridge dunes in (a); dip of slip face is to the southeast; view is from Nebraska Highway 2 at N42°01.049′, W102°02.130′. Photo in (b) by D.R. Muhs.

The Arikaree Group is exposed at the surface over a large area of eastern Wyoming (Love and Christiansen, 1985), and smaller but still-extensive areas of South Dakota (Martin et al., 2004), and Nebraska (Fig. 13). Most of these surface occurrences are situated to the northwest of the Nebraska Sand Hills. The Arikaree Group is primarily unconsolidated sands and sandstone, but includes some silty beds (Swinehart and Loope, 1987; MacFadden and Hunt Jr., 1998). Where the Arikaree Group crops out in northwestern Nebraska, it forms the substrate for the scenic Pine Ridge area, an unusual and isolated occurrence of *Pinus ponderosa*, more commonly found at higher elevations in the Rocky Mountains. The landscapes dominated by the Arikaree Group are broad, flat tablelands (Fig. 13a). These mesa-like landscapes are, however, dissected by first-order and second-order streams that deliver sediment eroded from the Arikaree Group to major river systems such as the White River, Niobrara River, and North Platte River. Examination of road cuts and stream cuts exposing the Arikaree Group shows that although some units are cemented (hence forming the resistant tableland landscapes), other units are unconsolidated (Fig. 13b). Rhizoliths, faunal burrows, and other secondary structures are also common within sediments of the Arikaree Group (Fig. 13c).

The Ogallala Group is spatially the most extensive pre-Quaternary geologic unit in central and western Nebraska (Burchett, 1969). As with the Arikaree Group, resistant, well-cemented beds within the Ogallala Group form extensive mesas at the surface over large areas of western Nebraska, eastern Wyoming, and eastern Colorado (Fig. 14a). Similar to the Arikaree Group, however, these tableland areas are dissected by first-order and second-order streams that deliver sediment to much larger drainage systems. The Ogallala Group is also found below the Nebraska Sand Hills, based on drill-hole data (Swinehart and Diffendal Jr., 1990). The youngest and most widespread unit within the Ogallala Group is the Ash Hollow Formation. This formation is also one of the thickest units within the Ogallala Group and is ~50 m thick in its type area (Diffendal Jr., 1987). Road cut and stream cut exposures show that the Ash Hollow Formation of the Ogallala Group consists of sediments with highly variable particle sizes (Diffendal Jr., 1987), ranging from silty volcanic ash beds to gravels (Fig. 14b). Paleosols, including

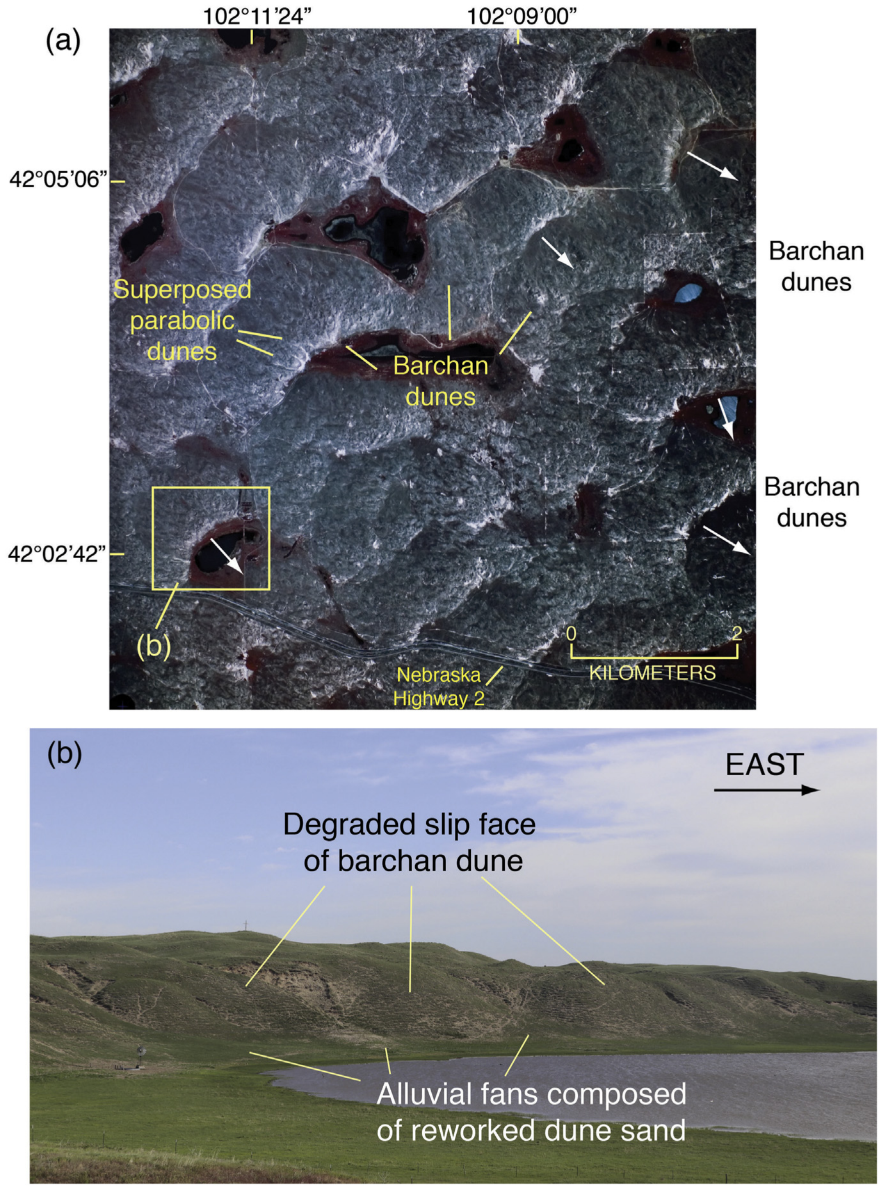

Fig. 8. Examples of barchan dunes between Ellsworth and Bingham, Nebraska, western Nebraska Sand Hills area. (a) False-color infrared aerial photograph (red = healthy vegetation; blue or black = water) showing barchan dunes (Pleistocene?) with high-angle slip faces sloping to the southeast, with superimposed late Holocene parabolic dunes, arms pointing to the northwest. White arrows indicate inferred paleowinds at the time of dune formation (arrows point downwind). (b) Ground photograph of degraded barchan dune slip face, view to north (see (a) for location). Aerial view in (a) is U.S. Geological Survey National Aerial Photography Program (NAPP) photograph 895–167 acquired on 16 May 1988; ground photography in (b) taken by D.R. Muhs.

very resistant calcrete layers (K horizons) are also visible in many outcrops of the Ogallala Group (Fig. 14c). However, much Ogallala Group sediment found between paleosols is unconsolidated sand and provides sediment delivered to first-order and second-order stream valleys west of the Nebraska Sand Hills.

Pliocene sediments, some of which are part of the Broadwater Formation in western Nebraska (Swinehart and Diffendal Jr., 1987), are found below and to the west of the Nebraska Sand Hills. Swinehart and Diffendal Jr. (1990), Myers (1993), and Swinehart et al. (1994b) reported a minimum extent of these deposits found beneath the Nebraska Sand Hills (Fig. 5). Along the Middle Loup River, we measured as much as ~28 m of these sediments exposed in river cuts (Fig. 15), underlying 11–12 m of aeolian sand dated by Muhs et al. (1997) to the late Holocene. The Pliocene sands here are horizontally bedded, very poorly consolidated or entirely loose, silt-rich in the younger parts, and sand-rich in the older parts.

Under favorable circumstances, major river valleys can be sources of aeolian sand and there are numerous examples of these from both the Great Plains and Basin and Range regions of the USA. There are several river systems adjacent to the Nebraska Sands Hills. The most important of these is the Platte River with its two major tributaries, the North Platte River and the South Platte River. Both of these tributaries head in the mountains of Colorado, but while the downstream reaches of the South Platte River are in eastern Colorado and southwestern Nebraska, the North Platte River drains much of eastern Wyoming and western Nebraska. All three rivers (North Platte, South Platte, and Platte) have, at present, fairly narrow channels with perennial flow and floodplains and channel bars that are largely vegetated. Williams (1978) has shown, however, that the perennial conditions of these rivers, along with their channel morphology and vegetated bars and floodplains, are a function of historical river regulation. Prior to regulation, these rivers experienced high-discharge events during the spring

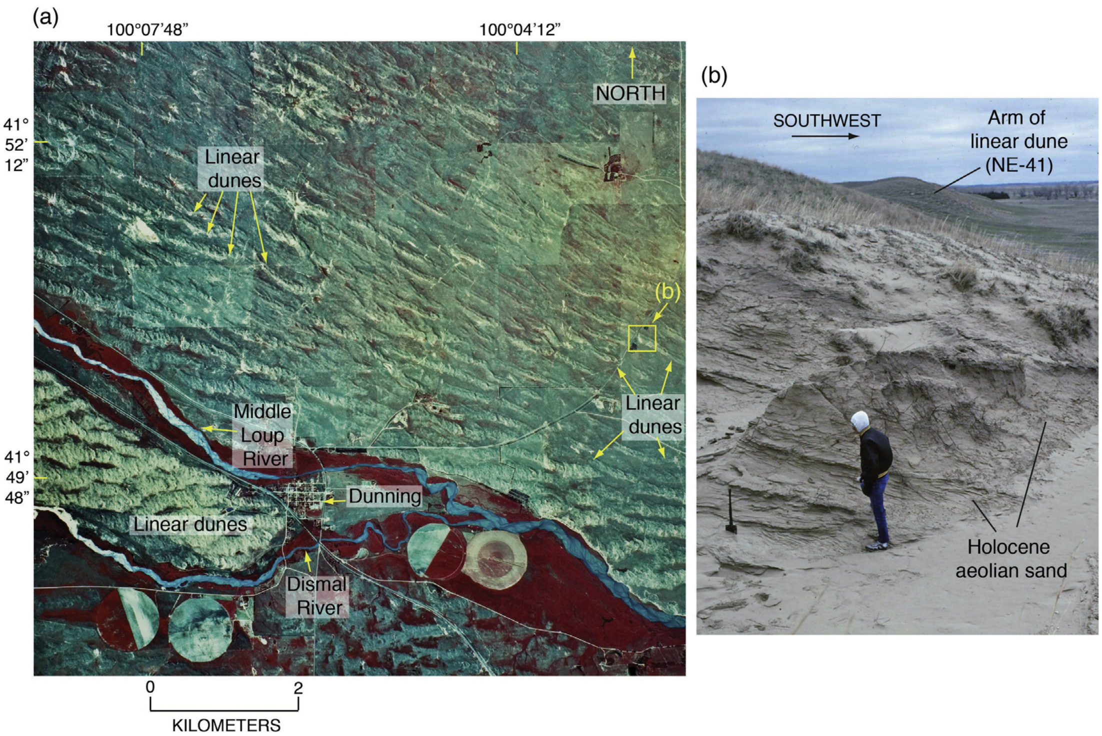

Fig. 9. Examples of longitudinal (linear) dunes near Dunning, Nebraska. (a) False-color infrared aerial photograph (red = healthy vegetation; blue = water) showing northwest-to-southeast-trending longitudinal (linear) dunes of late Holocene age north of the Middle Loup River near Dunning, Nebraska. (b) Blowout exposure showing southwest-dipping cross beds in late Holocene aeolian sand in a linear dune (see location in (a)). Aerial view in (a) is U.S. Geological Survey National Aerial Photography Program (NAPP) photograph 918–96 acquired on 18 June 1989; ground photography in (b) taken by D.R. Muhs.

snowmelt season that removed much of the vegetation that could have potentially stabilized sandy point bars. Furthermore, at the end of summers in the pre-regulation era, discharge in all three rivers was usually diminished substantially; the rivers were intermittent, not perennial. As a consequence, channel morphology was of a braided nature, with abundant sandy, unvegetated point bars. It is likely that many channels

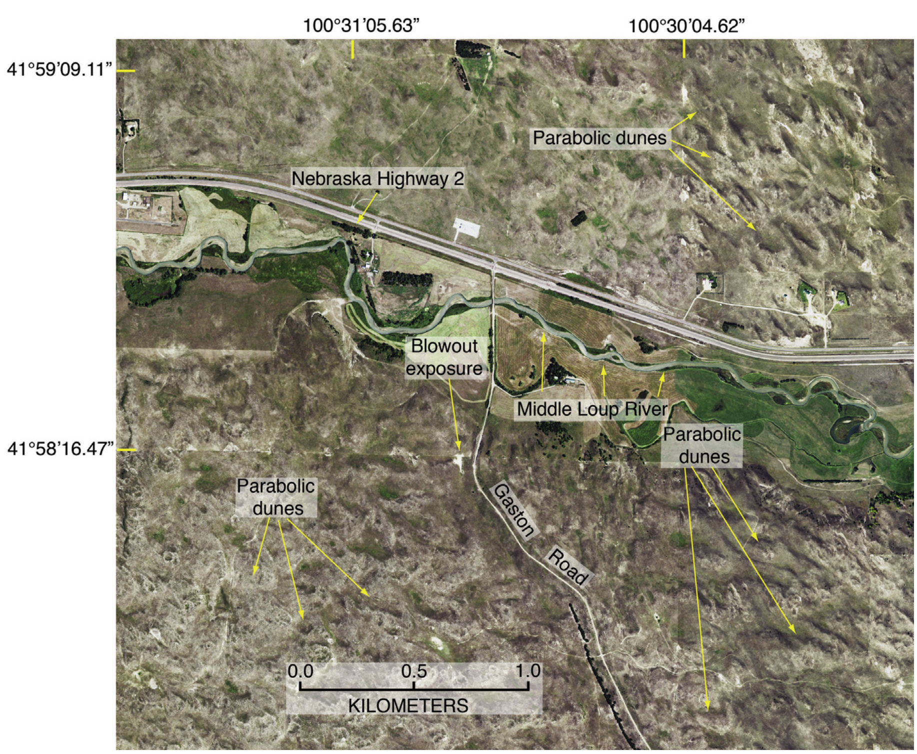

Fig. 10. Natural-color aerial photograph of a portion of the Nebraska Sand Hills east of Thedford, Nebraska, along the Middle Loup River valley, showing Holocene parabolic dunes on both sides of the river and blowout exposure within a parabolic dune along Gaston Road shown in Fig. 11. U.S. Department of Agriculture, National Agriculture Imagery Program (NAIP) aerial photograph.

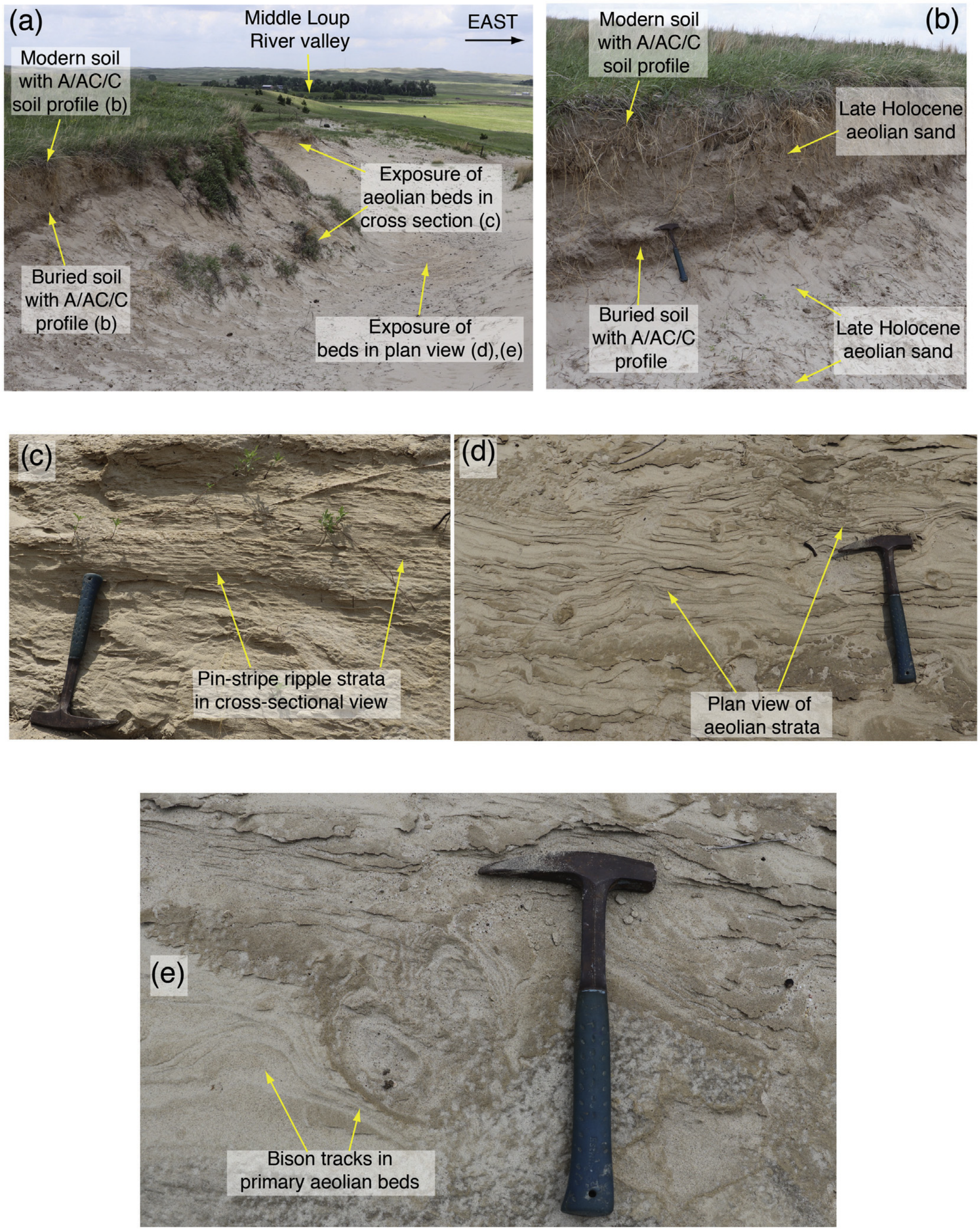

Fig. 11. Blowout exposure (see Fig. 10 for location) of aeolian strata in the Middle Loup River valley, ~5 km southeast of Thedford, Nebraska, along Gaston Road access to Nebraska National Forest (coordinates of exposure: N41°58.246′; W100°30.742′). (a) Overview of exposure looking north; (b) detail of modern soil and shallow paleosol; (c) pin-stripe ripple strata in aeolian sand at depth on east-facing exposure (see (a) for location); (d) plan view of horizontal aeolian strata in floor of blowout (see (a) for location); (e) bison tracks exposed in primary aeolian strata in floor of blowout. Hammer in all photos is ~0.3 m long. Photos by D.R. Muhs.

were even dry during late summer, fall, and early winter of some years. Construction of dams and reservoirs in historical time, as well as return flow from irrigation canals, brought about perennial flow; creation of deeper, narrower channels (without a braided morphology); and a decrease in discharge magnitude during the spring snowmelt season. As a consequence, channel bars and floodplains became more vegetated. Muhs and Holliday (1995) pointed out that contemporary, post-regulation conditions are not particularly favorable to the Platte River system being a significant source of aeolian sand. However, in pre-regulation time, rivers with broad valleys, shallow braided channels, and abundant, unvegetated sandy bars were ideal for providing an abundant source of aeolian sand (Fig. 16). We focused most of our efforts on characterizing fine-grained sands from the North Platte River, with some exploratory characterization of sands from the reaches of the South Platte River within Nebraska.

The Niobrara River valley is situated to the west and north of most of the Nebraska Sand Hills and is a candidate source as well (Fig. 3). In its downstream reaches, to the north of the Nebraska Sand Hills, the Niobrara River occupies a narrow, deep channel cut into bedrock, conditions that are not particularly favorable for providing a source of sand for dunes. In its upstream reaches, west of the Nebraska Sand Hills, the Niobrara River occupies a broader valley, but drains only the Arikaree Group and Ogallala Group, from its headwaters in eastern Wyoming to where it enters the dune field in Nebraska (Burchett, 1969; Love and Christiansen,

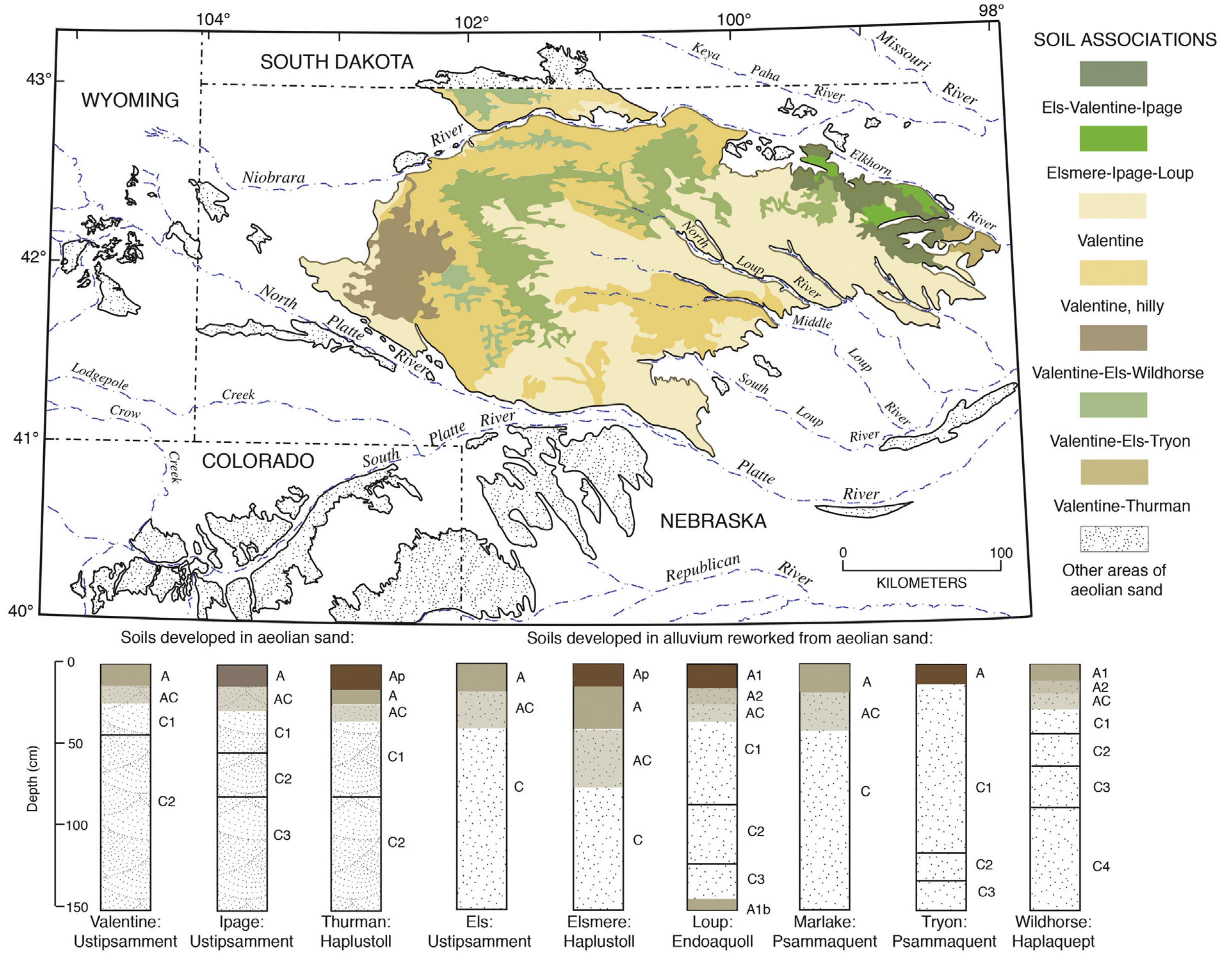

Fig. 12. Map of soil associations in the Nebraska Sand Hills and typical examples of soil profiles in the series that make up those associations. Distribution of aeolian sand is from sources given in Fig. 3; soil association distribution and representative soil profiles are from Kuzila (1990).

1985). Thus, the composition of Niobrara River sediments in its headwaters is likely a mix of Arikaree Group and Ogallala Group sediments.

3.3. Mineralogy of the Nebraska Sand Hills

In order for a sediment group to be considered as a source for the Nebraska Sand Hills, it must have a favorable mineralogy. Ahlbrandt and Fryberger (1980), Winspear and Pye (1996), Muhs et al. (1997), and Muhs (2017) present mineralogical data for the Nebraska Sand Hills. All these studies are in broad agreement with one another and show that the dominant minerals are quartz, K-feldspar, and plagioclase. We have found no substantial amounts of calcite or dolomite in the Nebraska Sand Hills nor have other investigators reported carbonate minerals. Using point counts in thin sections, quartz contents of the Nebraska Sand Hills are estimated to be 50–75% ($n = 7$) by Ahlbrandt and Fryberger (1980) and 75–85% ($n = 6$) by Winspear and Pye (1996). Based on calibrated abundances using mineral XRD peak heights, Muhs (2017) estimated quartz contents to be 45–85% ($n = 55$), with two samples having less than 40% quartz. K-feldspar content is estimated to be 5–29%, with most samples ranging from 5 to 15%, and plagioclase is estimated to be 10–67%, with most samples ranging from 12 to 36% (Muhs, 2017). Heavy minerals are present in small amounts in the Nebraska Sand Hills and include muscovite, amphiboles, and pyroxenes, with smaller amounts of biotite, epidote, zircon, and tourmaline (Lewis, 1976).

To facilitate comparisons of Nebraska Sand Hills dune sands with those of potential source sediments, we present relative abundances of quartz, K-feldspar, and plagioclase of dune sands and source sediments as ternary plots using XRD peak heights. We emphasize that these plots do not represent precise measures of mineral percentages, but merely provide a graphical presentation of relative differences between the sediment groups in an analytically consistent way. Results indicate that with the exception of two low-quartz samples, Nebraska Sand Hills samples define a compositional field similar to that reported by Muhs (2017), with most samples falling close to the quartz pole (Fig. 17). All four source sediments examined also contain quartz, K-feldspar, and plagioclase. Sands from the Arikaree Group show a much wider range in quartz and plagioclase contents and have only partial overlap with Nebraska Sand Hills sands. North Platte River sands also have only a partial overlap with Nebraska Sand Hills sands, as most of the latter are more quartz rich. In contrast, Pliocene sands and sands from the Ogallala Group define mineralogical compositional fields that overlap that of the Nebraska Sand Hills fairly closely.

3.4. Trace element geochemistry of the Nebraska Sand Hills and potential source sediments

In utilizing K/Rb vs. K/Ba values to determine dune sand sources (including the Nebraska Sand Hills) for many parts of North America, Muhs (2017) noted that determinations of K concentrations by energy-dispersive X-ray fluorescence (ED XRF) can be biased high by ~5% of the reported concentration, based on analyses of U.S. Geological Survey rock standards (Govindaraju, 1989) and comparison with K concentrations determined by wavelength-dispersive XRF. Hence, we re-determined K, Rb, and Ba concentrations by INAA for samples from the Nebraska Sand Hills and compared the results to values for the same samples determined by

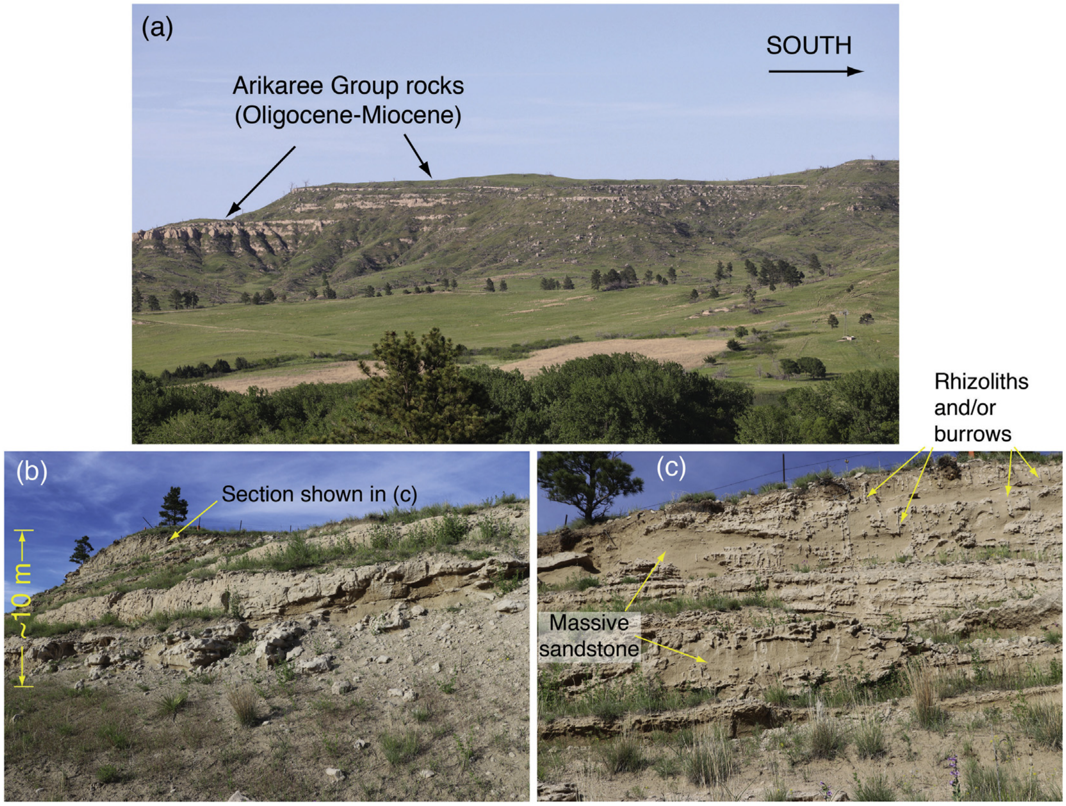

Fig. 13. (a) Mesa composed of Arikaree Group rocks. Photo taken from US Highway 385 a few km south of Chadron, Nebraska (view to northeast from locality at N42°45.797′, W103°00.440′). (b) and (c) Road cut exposure on east side of US Highway 385 at N42°44.484′, W103°00.508′. Photos by D.R. Muhs.

ED XRF reported by Muhs (2017). Results indicate that both Rb and Ba show good agreement between the two methods, but as noted by Muhs (2017), K concentrations determined by ED XRF are higher than those determined by INAA. Thus, we recalculated K/Rb and K/Ba values for Nebraska Sand Hills samples and potential source sediments as a further test of the interpretations made by Muhs (2017).

Results of the new K/Rb and K/Ba analyses show that potential source sediments define geochemical fields similar to those shown in Muhs (2017). With the lower K concentrations determined by INAA, all K/Rb and K/Ba values are of course systematically lower. Nevertheless, the geochemical fields defined by these elements have the same general form as those determined by ED XRF. With the exception of one dune sand sample with anomalously low K concentrations (which we have no explanation for), Nebraska Sand Hills samples have K/Rb and K/Ba values that fall dominantly within the range of values for Arikaree Group sands (Fig. 18a). On the other hand, dune sand samples have compositions that fall mostly outside the ranges of Pliocene sands, North Platte River sands, and South Platte River sands (Figs. 18b,c). Nebraska Sand Hills samples show fairly good compositional agreement with sands from Ogallala Group sediments (Fig. 18d). These results are in broad agreement with those of Muhs (2017), permitting an interpretation of Arikaree Group sands and/or Ogallala Group sands as dune sources.

Among the trace elements we employ here to explore potential sources for the Nebraska Sand Hills, plots of Sc, Th, and La are particularly effective in discriminating sediments of different origins (Taylor and McLennan, 1985; Bhatia and Crook, 1986; Olivarez et al., 1991). Scandium is enriched in pyroxenes from mafic igneous rocks, whereas Th and La have high concentrations in silicic rocks. Thus, on a ternary plot, sediments from mafic sources will plot near the Sc pole, whereas sediments from silicic sources will plot near the Th and La poles. Given that all the possible sources for the Nebraska Sand Hills are themselves derived mostly from rocks that have a dominantly upper continental crustal origin, we expected that samples would fall near the Th and La poles and this is found to be true (Fig. 19a). Nevertheless, within this broad range for average upper continental crustal rocks, there are small but important differences that are apparent. Nebraska Sand Hills samples fall only within the higher-La range of the field defined by Arikaree Group rocks (Fig. 19b). Generally lower relative La abundances for Pliocene sands, North Platte River sands, and South Platte River sands result in geochemical fields for Sc-Th-La that overlap very little with Nebraska Sand Hills sediments (Figs. 19c,d). However, as with the K/Rb and K/Ba fields, the Sc-Th-La data show good agreement between dune sands of the Nebraska Sand Hills and Ogallala Group sands (Fig. 19e).

As discussed in the methods section earlier, the REE are very sensitive indicators of sediments derived from rocks of different compositions. Loess is often considered to be a good example of sediment that is a natural composite of the upper continental crust and its REE composition reflects this (Taylor and McLennan, 1985; McLennan, 1989). Glacial till deposited by large, continental ice sheets, from which much loess is derived, also can be considered to be a natural, upper crust composite. This is particularly true in North America, where the Laurentide Ice Sheet eroded Precambrian igneous and metamorphic rocks, Paleozoic carbonate rocks, and Paleozoic and Mesozoic shales. Both loess and till from the Laurentide Ice Sheet in North America show REE abundance plots that are very similar to average upper continental crust. In Peoria Loess of western Iowa, Des Moines Lobe till of central Iowa, and James Lobe glacial till from southeastern South Dakota, REE plots show the salient features of average upper continental crustal compositions: (1) enrichment of light REE, (2) strongly negative Eu anomalies, and (3) a relatively “flat” curve for heavy REE (Figs. 20a,b). Aeolian sediments from the Nebraska Sand Hills show some similarities to average upper continental crust, with enriched light REE and somewhat depleted heavy REE, but importantly, most show only slightly negative Eu anomalies and two show positive Eu anomalies (Figs. 20c,d).

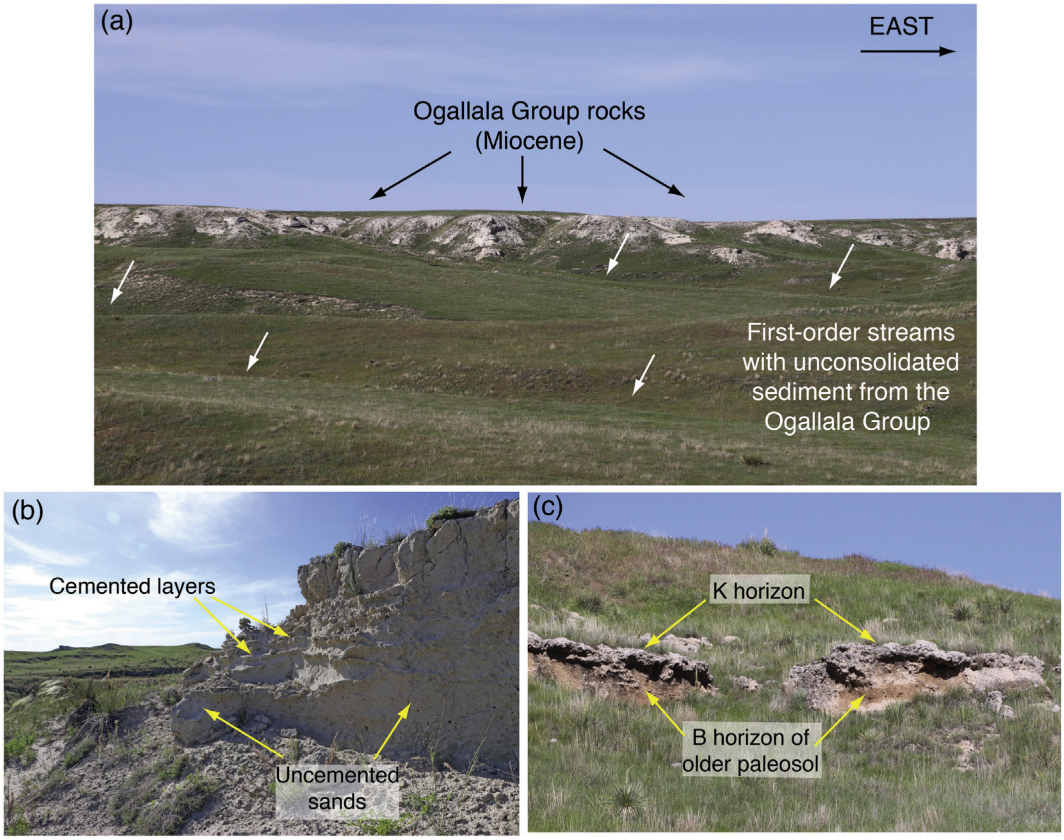

Fig. 14. (a) Mesa composed of Ogallala Group rocks. Photo taken from US Highway 385, Dawes County, Nebraska (view to north from locality at N42°28.025′; W102°57.942′). (b) Detail of Ogallala Group rocks near locality NE-75 of Muhs (2017), showing massive sandstone, cemented layers, and eroded sandstone below outcrop; vertical face is ~1.0 m thick. Locality coordinates for (b): N42°28.027′, W102°58.062′. (c) outcrop of K horizon (calcrete) and older paleosol B horizon (clay-rich) exposed near the southern end of Lake McConaughy; locality coordinates: N41°12.149′, W101°43.362′. Photos by D.R. Muhs.

Plots of La_N/Yb_N vs. Eu/Eu* for potential source sediments of the Nebraska Sand Hills show a surprisingly large range of values (Fig. 21). Samples from the Arikaree Group show a range of La_N/Yb_N values that are typical of upper crustal rocks, but have a broad range of Eu/Eu* values, from ~0.4 to ~1.4 (Fig. 21a). Pliocene sands have a much smaller range of values for both La_N/Yb_N and Eu/Eu* (Fig. 21b). North Platte River sands define a La_N/Yb_N vs. Eu/Eu* field that overlaps the Arikaree Group, but is smaller; South Platte River sands show lower La_N/Yb_N values (Fig. 21c). Sediments of the Ogallala Group define a La_N/Yb_N vs. Eu/Eu* compositional field that has a similar range of Eu/Eu* values as Arikaree Group sediments, but with a much larger range of La_N/Yb_N values (Fig. 21d). Nebraska Sand Hills samples show a narrow range of Eu/Eu* values (though high compared to average upper crustal rocks), but a wide range of La_N/Yb_N values. Only those dune sands with the lowest La_N/Yb_N values overlap the fields for Arikaree Group rocks, Pliocene sands, and North Platte River sands, and there is no overlap of dune sands with South Platte River sands. In contrast, all but one of the dune sand samples overlap the compositional field for La_N/Yb_N vs. Eu/Eu* defined by Ogallala Group sediments.

Although heavy minerals constitute a minority of the sediments of the Nebraska Sand Hills (Lewis, 1976; Winspear and Pye, 1996), such minerals have long been key provenance indicators in sedimentary petrology (Pettijohn et al., 1972). Here, we report two element ratios (Fe/Sc and As/Sb) that are indicative of the composition of particles in the heavy mineral suite. A broad range of minerals host Fe, but one of the most important is pyroxene, which also hosts Sc. Magnetite is a major carrier of As and Sb, and these elements can also be found in ilmenite and olivine (Onishi and Sandell, 1955; Esson et al., 1965). Arikaree Group sediments show a wide range of As/Sb values with a smaller range of Fe/Sc values (Fig. 22a). Pliocene sands show a much smaller range of both As/Sb and Fe/Sc values (Fig. 22b), but North Platte River sands, like Arikaree Group sands, show a broad range of As/Sb values (Fig. 22c). South Platte River sands fall close to, but do not overlap North Platte River sands. Sediments of the Ogallala Group show a narrow range of As/Sb values but a wide range of Fe/Sc values (Fig. 22d). Nebraska Sand Hills sediments do not show the extreme ranges of As/Sb values seen for Arikaree Group and North Platte River sands and overlap the fields of these source sediments only slightly (Arikaree Group) or not at all (North Platte and South Platte River sands). There is some overlap between dune sands and Pliocene sands, but the dune sands show a wider range of values for Fe/Sc. The dune sands show very good agreement with the range of both As/Sb and Fe/Sc seen in Ogallala Group sands.

3.5. Relation of the Nebraska Sand Hills to loess in central and eastern Nebraska

Loess is widespread over central and eastern Nebraska (Swinehart et al., 1994a; Mason, 2001; Muhs et al., 2008). It has long been hypothesized that the Nebraska Sand Hills are linked to the origin of loess in Nebraska and adjacent parts of Kansas (Lugn, 1939, 1962, 1968; Condra et al., 1947; Thornbury, 1965; Reed, 1968; Wright Jr., 1970). These early studies were not specific about the role that the Nebraska Sand Hills might have played in loess genesis, although most investigators seem to have perceived loess to be a downwind, finer-grained facies of the dune sand, with both having a common source or sources. Here we present additional geochemical data to evaluate this hypothesis.

To compare the composition of loess in central and eastern Nebraska with that of dune sand from the Nebraska Sand Hills, we analyzed last-glacial-aged (Peoria) loess from two loess sections (near Elba and

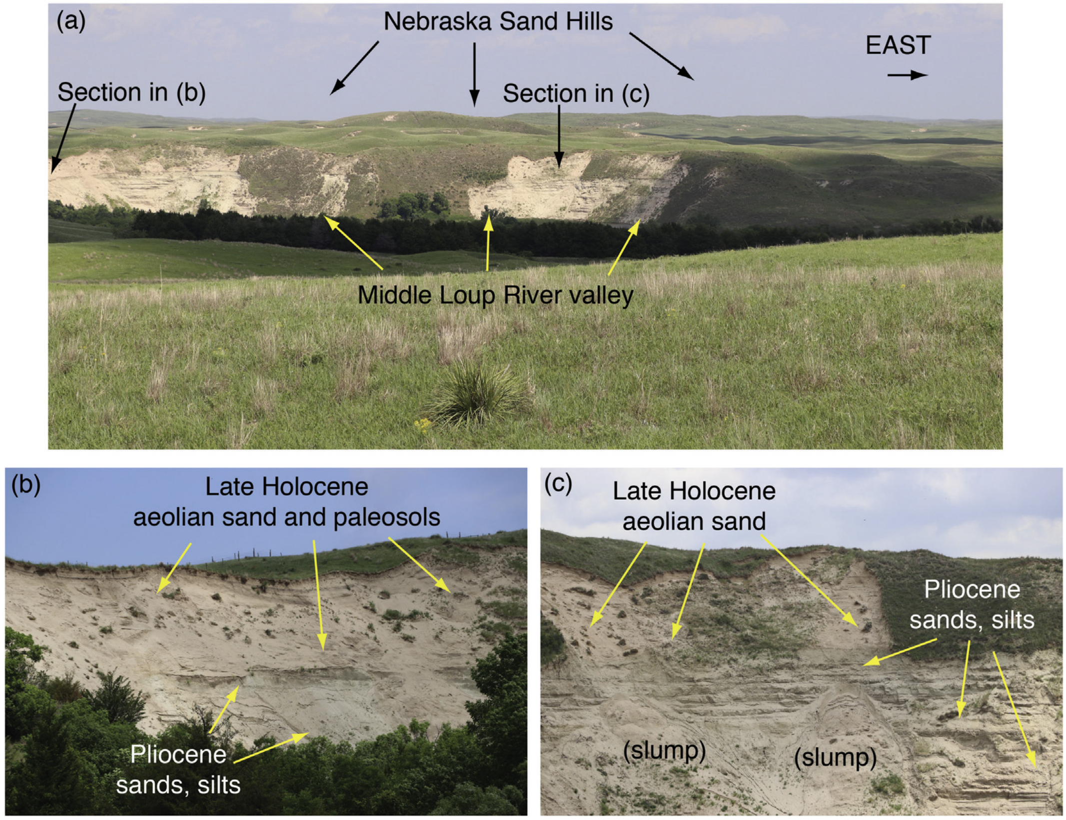

Fig. 15. Exposure of Pliocene sediments underlying Holocene aeolian sand along the Middle Loup River valley at "locality 32" of Ahlbrandt and Fryberger (1980), identical to the "Red Ranch" locality of May et al. (1995), and the "Seneca" localities of Muhs et al. (1997). (a) Long view to north taken from locality at N42°01.868′, W100°48.737′; (b) and (c) closer views showing contact between Pliocene sands and silts and overlying late Holocene aeolian sand, photographed looking north from a locality immediately south of the Middle Loup River at N42°02.414′, W100°48.685′. Note late Holocene paleosols in aeolian sand in (b) and horizontal bedding of Pliocene sediments in (c). Stratigraphy and radiocarbon ages of late Holocene aeolian sand can be found in Muhs et al. (1997). Photographs by D.R. Muhs.

Lincoln, Nebraska) previously studied by Muhs et al. (2008). Four samples from each section, at depths of 150 cm to 350 cm, were analyzed. Results show that Nebraska loess and dune sand define distinct geochemical fields on a K/Ba vs. K/Rb plot, indicating that K-feldspar and/or mica populations were derived from different source rocks (Fig. 23a). On a Sc-Th-La plot, both sediment groups plot, at least

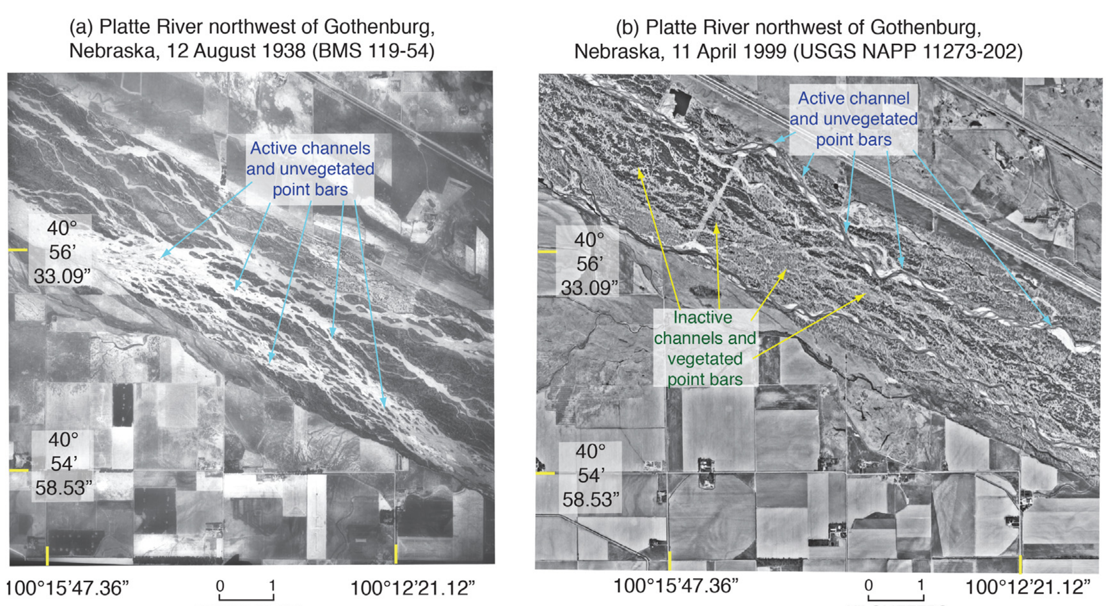

Fig. 16. Comparative aerial photographs showing historical changes in Platte River channel morphology. (a) BMS photograph 119–54 acquired 12 August 1938, northwest of Gothenburg, Nebraska, showing braided channel pattern, with shallow depths and abundant, sand-rich, unvegetated bars. (b) Same area as in (a), but image acquired on 11 April 1999 (U.S. Geological Survey NAPP 11273-202 photograph), showing single main channel and largely vegetated floodplain, former channels, and bars.

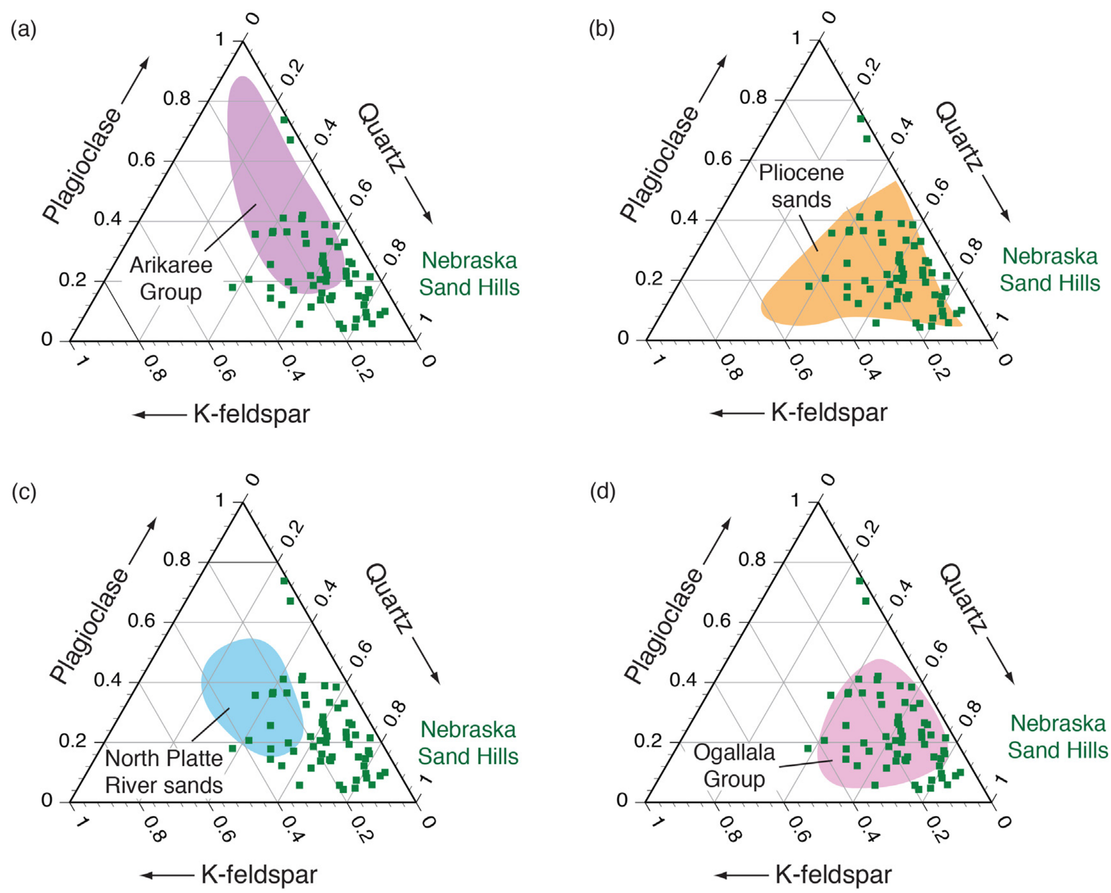

Fig. 17. Ternary diagrams showing *relative* abundances of predominant minerals in late Holocene dune sands of the Nebraska Sand Hills (filled green squares). Relative abundances determined by X-ray diffractogram peak heights for quartz (20.9°, 2-theta), K-feldspar (27.5°, 2-theta), and plagioclase (27.8°, 2-theta). Also shown are compositional fields defining the range of these mineral abundances in dune sand source sediments, determined in the same manner: (a) Arikaree Group; (b) Pliocene sands; (c) North Platte River sands; (d) Ogallala Group sands.

broadly, within the range of average upper continental crust, but loess and dune sand define distinct geochemical fields (Fig. 23b). Similar to loess deposits from many regions (see examples in Muhs, 2018), Nebraska loess samples have REE compositions that fall close to that of average upper continental crust. However, Nebraska loess samples have both lower La_N/Yb_N and Eu/Eu* values compared to dune sediments of the Nebraska Sand Hills (Fig. 23c). Finally, measures of trace element compositions in the heavy mineral fraction, using Fe/Sc and As/Sb, show no overlap between loess and dune sand in Nebraska (Fig. 23d).

4. Discussion

4.1. Source of sediment in the Nebraska Sand Hills: previous hypotheses

Early investigators of the Nebraska Sand Hills did not have access to the tools available today for provenance studies, but they offered hypotheses about the source of sand of this large dune field. Lugn (1939, 1962, 1968) considered that both the Ogallala Group and sediments reworked from it were the sources of both the Nebraska Sand Hills and loess to the southeast of the dune field. Thornbury (1965) articulated the same concept as Lugn for the origin of the Nebraska Sand Hills. In addition, however, Thornbury (1965) stated that the upper part of the Ogallala Group is missing beneath the Sand Hills and the overall elevation of the dune field is lower than that of the High Plains region to the west. This suggested to him that major erosion occurred before the dune field formed. It is important to note, however, that Thornbury (1965) provided no subsurface data to support these claims. In fact, it is not certain that such data even existed at the time he made these statements. Smith (1965) rejected the concept that the Nebraska Sand Hills owed their origins to the Ogallala Group, considering Lugn's (1962) explanation to be oversimplified. Further, Smith (1965) pointed out that the Ogallala Group is indurated in many places and is therefore unlikely to have been a very important source for dune sand. Based on more recent studies, however, it is actually Smith's (1965) statement about induration in the Ogallala Group that is oversimplified. Joeckel et al. (2014) conducted detailed sedimentological studies of the Ash Hollow Formation of the Ogallala Group. These investigators pointed out that very fine to fine-grained sandstone is the predominant facies in this formation and that the sediments are well sorted and only weakly cemented. The observations of Joeckel et al. (2014) are consistent with those made in the present study. To be fair, Smith (1965) did speculate, however, that *reworked* Ogallala Group sediments could be a more likely source for the Nebraska Sand Hills, in agreement with Lugn (1939, 1962, 1968). Smith (1965) also hypothesized that Pleistocene sediments in Nebraska, including the Nebraska Sand Hills, could have had sources farther west. Precisely what "western" sources Smith (1965) was referring to is not clear, nor did he present evidence for this hypothesis. Reed (1968) also considered that unconsolidated Pleistocene sediments, reworked from the Ogallala Group, were a likely source for the Sand Hills. Extending this argument further, Wright Jr. (1970) pointed out that with time, an eroding Ogallala Group surface might have been buried by aeolian sand, and subsequent dune field growth would have to come from sources farther to the northwest, such as the Tertiary White River Group (Fig. 5). Wright Jr. et al. (1985) reiterated the concept of a White River Group source in a later study. Although this idea is intriguing, it is problematic in that the White River

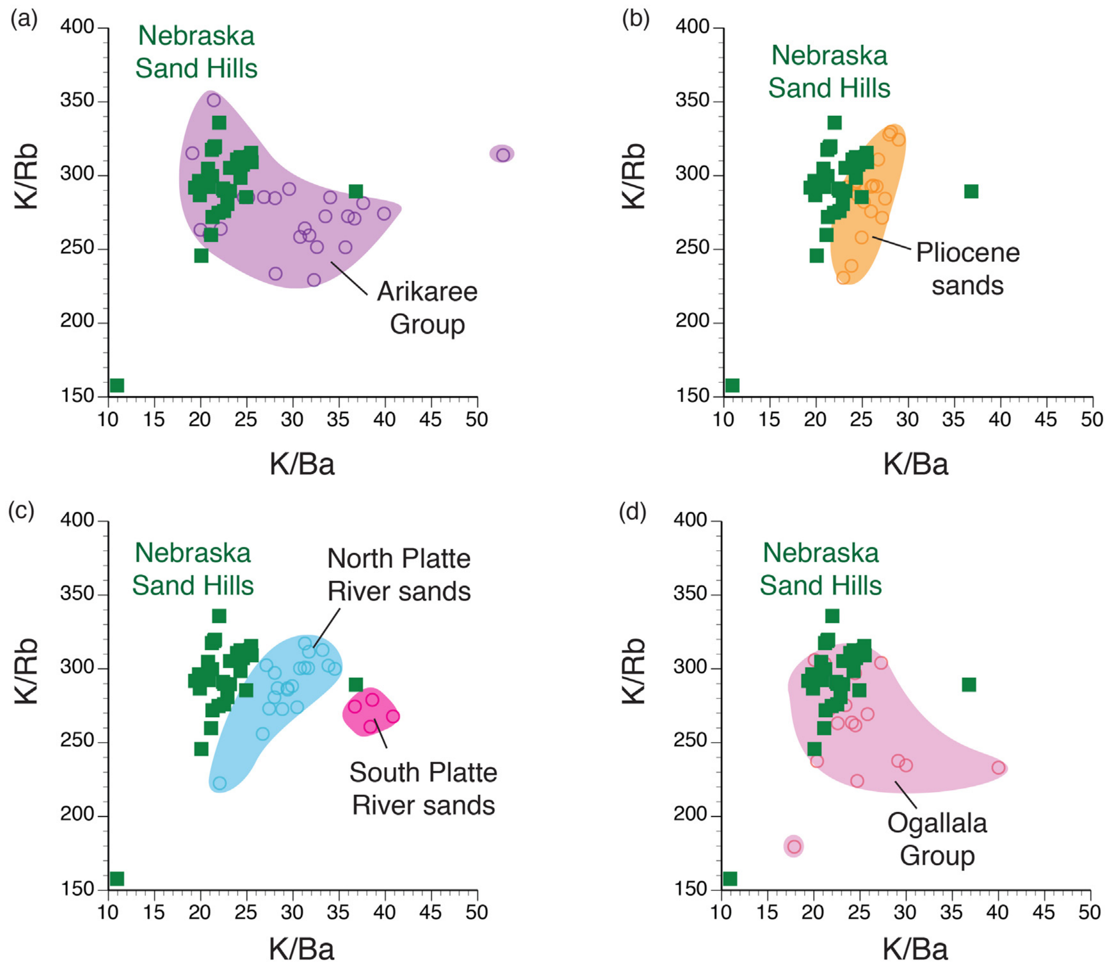

Fig. 18. Bivariate plots of K/Ba and K/Rb for late Holocene dune sands of the Nebraska Sand Hills (filled green squares; localities shown in Fig. 5). Also shown are values for these element ratios for potential source sediments (open circles) and compositional fields (colored areas) for: (a) Arikaree Group sands; (b) Pliocene sands; (c) North Platte and South Platte River sands; (d) Ogallala Group sands. All concentrations of K, Ba, and Rb determined by instrumental neutron activation analysis in this study; note analytical differences in comparison with Fig. 29 of Muhs (2017), where same sample groups were analyzed for K, Ba, and Rb by energy-dispersive X-ray fluorescence (see text for discussion).

Group is dominated by silt, not sand. Aleinikoff et al. (2008) showed that K-feldspars in the White River Group have Pb-isotopic compositions that differ from those of the Nebraska Sand Hills.

Later investigators proposed younger sediments as sources of the Nebraska Sand Hills. Warren (1976) considered, on the basis of particle-size data, that underlying fluvial sands were the source of the dunes, but was not specific as to where these sediments came from. Swinehart (1990) also proposed that fluvial sands of Quaternary and Pliocene age, beneath the Sand Hills, were the primary sources of sand, along with some contributions from the Ogallala Group. Pliocene sediments were also favored by May et al. (1995) as a likely source for the Nebraska Sand Hills. Winspear and Pye (1996) analyzed fluvial sands from beneath the dunes and aeolian sands from the Nebraska Sand Hills for both mineralogy and geochemistry. Their data suggest little difference in composition between the two except that K-feldspar is less abundant in the Nebraska Sand Hills than in the underlying fluvial sands.

As mentioned already, Muhs (2017) evaluated the same four potential source sediments considered in the present study. On the basis of K/Rb and K/Ba, Muhs (2017) concluded that sediments of the Ogallala Group and/or sediments derived from it are the most likely sources for the Nebraska Sand Hills, a return to earlier hypotheses. Nevertheless, contributions from sources other than the Ogallala Group were recognized as possibilities, requiring further study.

4.2. Source of sediment in the Nebraska Sand Hills: geochemistry

A first consideration in evaluating source sediments is mineralogy. Although a potential source of aeolian sand may contain a broader suite of minerals than what is found in the dune field downwind, it obviously must at least contain all of the minerals found in that dune field. Mineralogical data indicate that sediments of all potential sources considered, including the Arikaree Group, Ogallala Group, Pliocene sands, and North Platte River sands, contain the requisite species within the light mineral fraction, which constitutes the majority of particles. Sediments of the Nebraska Sand Hills are dominated by quartz, K-feldspar, and plagioclase. Although the dune sands are more quartz-rich than most of the possible source sediments, all potential sources contain quartz, K-feldspar, and plagioclase (Fig. 17).

Geochemical results support some of the hypotheses of earlier investigators and eliminate others. In a re-evaluation of the K/Rb vs. K/Ba composition (primarily as a proxy for K-feldspar) of source sediments investigated by Muhs (2017), new results presented here show similar ranges of values compared to the earlier study, although offset to lower values, as discussed earlier (Fig. 18). Samples from the Nebraska Sand Hills have minimal overlap with Pliocene sands and almost no overlap with the range of K/Rb and K/Ba values for North Platte River and South Platte River sands. In contrast, samples from the Nebraska Sand Hills show considerable overlap with the ranges of K/Rb and K/Ba values

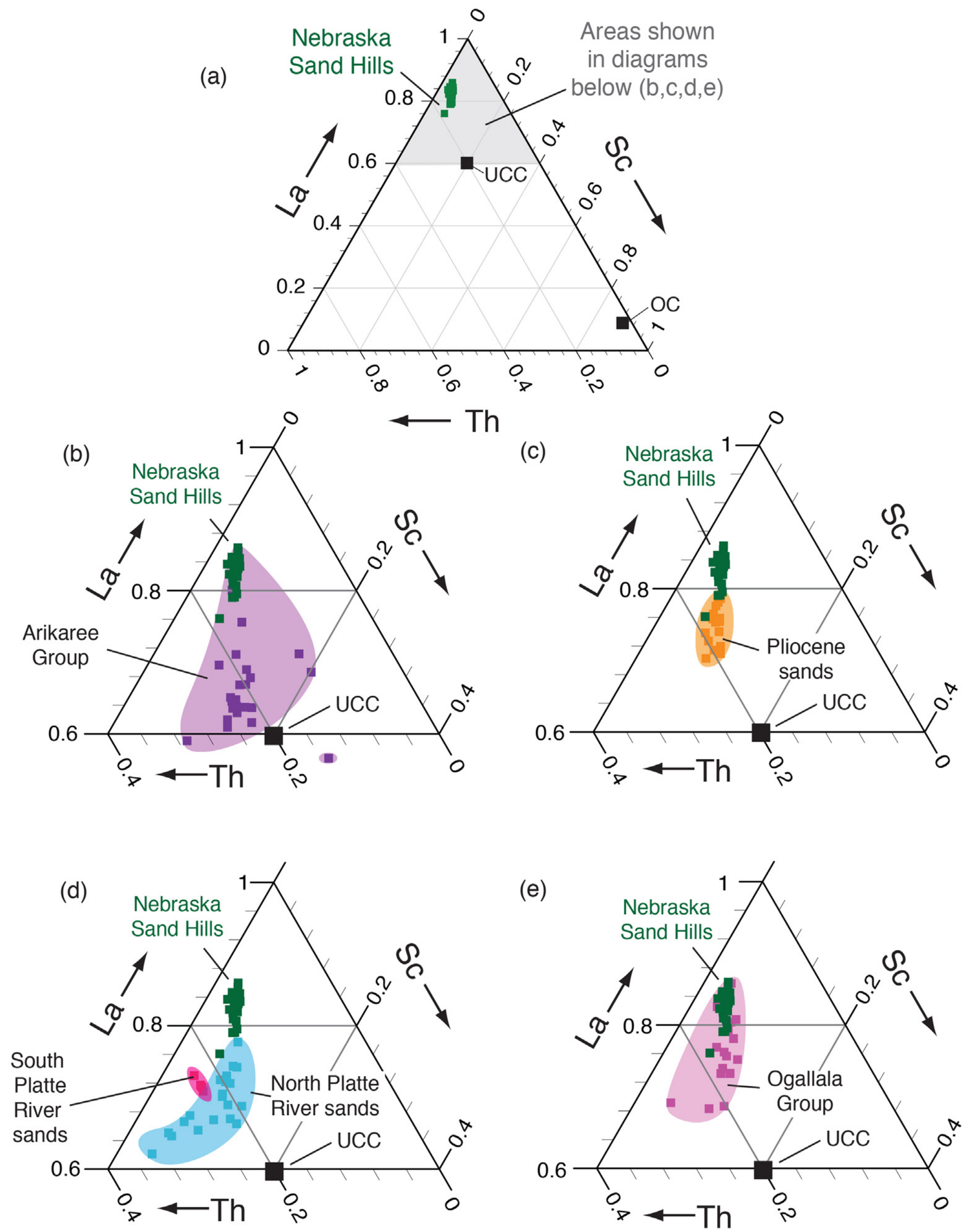

Fig. 19. (a) Ternary diagram of abundances of Sc, Th, and La for late Holocene dune sands of the Nebraska Sand Hills (filled green squares), compared to values for upper continental crust (UCC) and oceanic crust (OC). Also shown are the upper parts of Sc-Th-La ternary diagrams and Nebraska Sand Hills samples compared with sample values (colored squares other than green) and compositional fields for these element ratios in possible source sediments: (b) Arikaree Group sands; (c) Pliocene sands; (d) North Platte and South Platte River sands; (e) Ogallala Group sands. Concentrations of all elements determined by instrumental neutron activation analysis in this study. UCC and OC values from Taylor and McLennan (1985).

for both Arikaree Group and Ogallala Group sands. Thus, either or both of these source sediments could have been important contributors to the Nebraska Sand Hills.

A similar interpretation can be made on the basis of the Sc-Th-La compositions of the various source sediments compared to the samples from the Nebraska Sand Hills. Ternary plots of Sc-Th-La indicate that all of the candidate source sediments plot near the value for average upper continental crustal rocks (Fig. 19). This result is not surprising, as mafic rocks have contributed only minor amounts of material to the source sediments considered here (Stanley, 1976; Swinehart et al., 1985). Pliocene sands show the smallest range in variability and the Arikaree Group shows the greatest range of variability. Sediments of the Nebraska Sand Hills show only slight overlap with the range of Pliocene sands and no overlap with North Platte River or South Platte River sands. However, all samples from the Nebraska Sand Hills fall within the range of values for the Arikaree Group and Ogallala Group sands, permitting an interpretation of either or both of these sediments as sources.

The REE compositions of possible source sediments show considerable variability. The Arikaree Group shows a wide range in Eu/Eu* values and the Ogallala Group shows a wide range in La_N/Yb_N values (Fig. 21). The relatively high Eu/Eu* values in some of the Arikaree Group and Ogallala Group samples could be due to a component of feldspar inputs from the anorthosites of the southern Laramie Mountains (Fig. 2). Anorthosites in these mountains have positive Eu anomalies (Frost et al., 2010). In contrast, other source rocks in southeastern Wyoming and northeastern Colorado, such as granite in the Sherman batholith (Fig. 2), have negative Eu anomalies (Frost et al., 1999). On

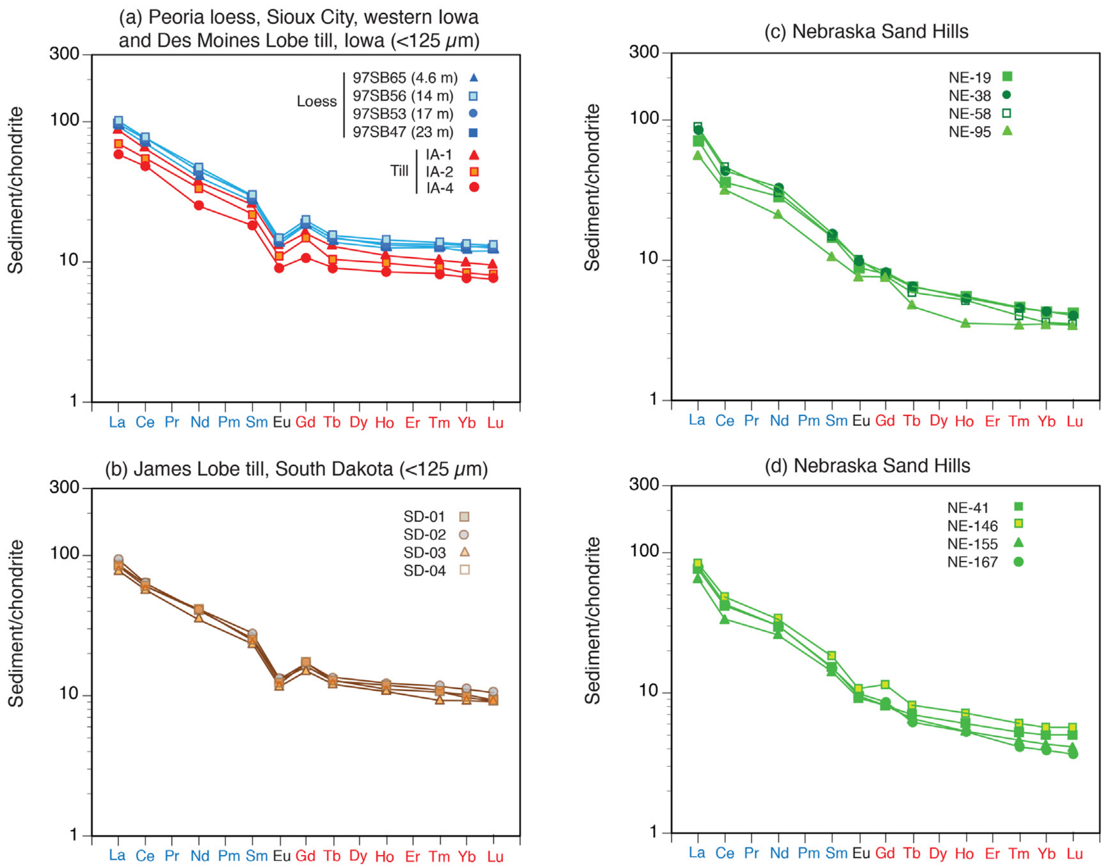

Fig. 20. Chondrite-normalized REE abundance plots for three groups of sediments. Values on vertical axis are measured concentrations normalized to chondritic meteorite compositions, by convention (see text for discussion). On horizontal axes, light REE are labeled in blue; heavy REE are labeled in red. (a) Peoria (last-glacial-aged) Loess from western Iowa and Des Moines Lobe till from central Iowa (see Muhs et al., 2008 for localities); (b) James Lobe (last-glacial-aged) till from southeastern South Dakota (see Muhs et al., 2008 for localities); (c) and (d) late Holocene dune sands from the Nebraska Sand Hills (this study). Note enriched light REE abundances and prominent negative Eu anomalies in (a) and (b), typical of average upper continental crust (Taylor and McLennan, 1985), but less distinct negative Eu anomalies and two positive Eu anomalies in Nebraska San Hills samples in (c) and (d). Concentrations of all elements determined by instrumental neutron activation analysis from this study.

La_N/Yb_N vs. Eu/Eu* plots, Nebraska Sand Hills samples show modest overlap with the ranges of values for Arikaree Group, Pliocene, and North Platte River sediments. However, Nebraska Sand Hills sediments show excellent agreement with the range of values for both La_N/Yb_N and Eu/Eu* observed in sands from the Ogallala Group.

Finally, element ratios representing the heavy mineral fraction, Fe/Sc vs. As/Sb, provide additional support for an Ogallala Group source for the Nebraska Sand Hills (Fig. 22). While the Arikaree Group and Pliocene sands show some overlap with the composition of the Nebraska Sand Hills, North Platte River and South Platte River sands show no overlap. However, the range of Fe/Sc and As/Sb compositions of samples from the Nebraska Sand Hills show excellent agreement with the range of values for sands of the Ogallala Group.

4.3. Source of sediment in the Nebraska Sand Hills: geomorphic considerations

Based on geomorphic and climatic considerations, sand of the North Platte, South Platte, and Platte Rivers would seem to be very likely sources for the Nebraska Sand Hills. These rivers are situated to the west, southwest, south, and southeast of the dune field (Figs. 3–5) and are therefore at present upwind of the sand sea in late spring and summer, when sediments are not frozen or snow-covered (Fig. 4b). Unlike the sediments of the Arikaree and Ogallala Groups, modern sediments of these rivers are uncemented. Furthermore, prior to regulation, the Platte River system, with a broad, sandy, vegetation-free bar-and-channel system may have been an ideal geomorphic setting for aeolian sand input to the Nebraska Sand Hills. Nevertheless, the geochemical data do not indicate that sediments from the Platte River system were important sources for the Nebraska Sand Hills.

Sridhar et al. (2006) and Schmeisser et al. (2010) proposed that during the Medieval Warm Period (~1000 to ~800 yr B.P.) of the late Holocene, there was a seasonal shift in wind regime over the Nebraska Sand Hills, with northwesterly winds dominant during fall, winter and early spring, but southwesterly winds (associated with very warm, dry air masses, and bringing drought) in late spring and summer. This seasonal shift in wind regime is invoked to explain the northwest-to-southeast orientation of linear dunes with bimodal dip directions, found in the southeastern part of the Nebraska Sand Hills. With this sort of shift in wind regime, these would seem to be ideal conditions for transport of sand from the North Platte River or Platte River to the Nebraska Sand Hills. While we do not dispute this scenario, the geochemical data presented here imply that sand inputs during such a wind regime must have been minimal. It is certainly possible, however, that this shift in wind regime during the Medieval Warm Period reworked pre-existing sand into linear dunes, but with little or no new sand input.

The best overall agreement of the geochemistry of the Nebraska Sand Hills is with sediments of the Ogallala Group. The Ogallala Group crops out extensively to the northwest of the Nebraska Sand Hills in western Nebraska (Figs. 5 and 24), as well as in southern South Dakota and eastern Wyoming, which is consistent with the paleowind reconstructions of the dune field, both for the youngest (Holocene) dunes (Fig. 3) and also the much larger and older barchanoid ridges and barchans (Figs. 6-8). It is also possible that widespread, late Tertiary or

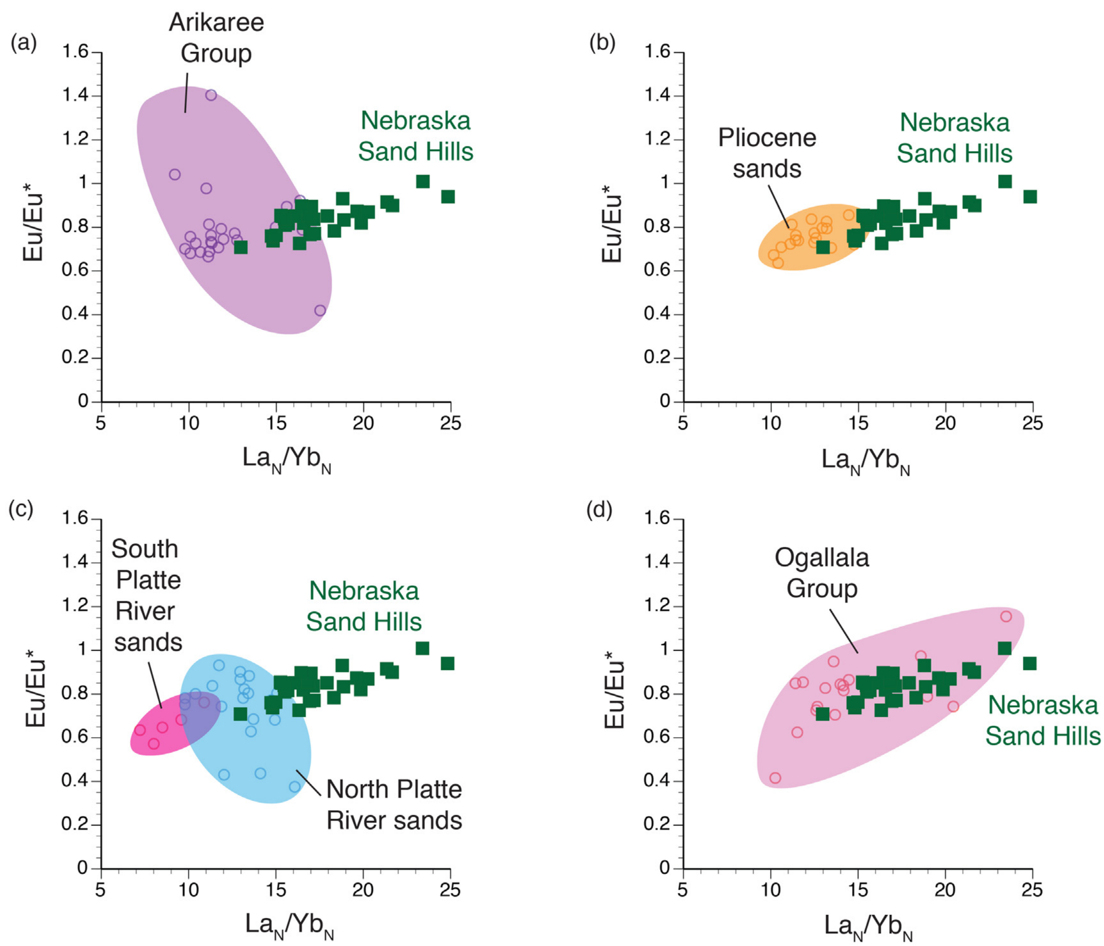

Fig. 21. Bivariate plots of La_N/Yb_N and Eu/Eu* for late Holocene dune sands of the Nebraska Sand Hills (filled green squares). Also shown are values for these element ratios for potential source sediments (open circles) and their compositional fields (colored areas): (a) Arikaree Group sands; (b) Pliocene sands; (c) North Platte and South Platte River sands; (d) Ogallala Group sands. Concentrations of all elements determined by instrumental neutron activation analysis from this study.

early Quaternary stripping of the Ogallala Group, found beneath the present location of the dune field (Swinehart and Diffendal, 1990), could have provided much of the initial sediment that forms the present Nebraska Sand Hills.

Even without such a Tertiary and/or early Quaternary period of erosion, examination of the present geomorphology of western Nebraska permits an interpretation of how Ogallala Group sediments might be delivered to the Nebraska Sand Hills. The surface of the Great Plains is often perceived as a flat, featureless plain. Even relatively recent texts describe it as a "...little dissected, gently east-tilted, flat, plateau surface, underlain, in most areas, by the hard caliche caprock layer that forms the top of the Ogallala formation…" (DiPietro, 2013, p. 125). Indeed, with a widespread calcrete caprock aiding in its preservation as broad mesas, Smith (1965), as noted above, did not consider the Ogallala Group to be a particularly important source for dunes of the Nebraska Sand Hills. When examined at a more detailed scale, however, the landscape of western Nebraska is not really a featureless plain. We mapped the drainages of western Nebraska from USGS 1:250,000-scale topographic maps. While consideration of drainages at this scale may not even include many first-order or even second-order streams, it provides documentation of at least the minimum amount of dissection that has taken place in this region. We superimposed these drainages on the bedrock geology of the region, derived from Swinehart et al. (1985). Although all rock units exhibit stream dissection at this scale, by far the greatest drainage density overall is on the landscapes where the Ogallala Group crops out at the surface (Fig. 24a). Tributaries to the Niobrara River, North Platte River, and Lodgepole Creek have dissected much of the total area where the Ogallala Group is exposed at the surface (Figs. 24b,c; see also Fig. 14). The importance of this is that, contrary to Smith's (1965) proposal, there is a significant amount of area to the northwest and southwest of the Nebraska Sand Hills, where unconsolidated sediments derived from the Ogallala Group could be subject to entrainment by wind during dry periods. Thus, while we agree that little erosion is likely to have taken place from those areas where the calcrete caprock forms a protective cover for the Ogallala Group, there is also a considerable amount of area where this caprock is missing. These parts of the landscape could supply sediment to the Nebraska Sand Hills during any period when the climate was dry enough that a protective vegetation cover was lacking.

4.4. Relation of the Nebraska Sand Hills to loess in central and eastern Nebraska

A recurring question that has occurred in studies of the Nebraska Sand Hills is the relation of this aeolian sand to loess that is found to the east, southeast, and south of the dune field (Lugn, 1939, 1962, 1968; Condra et al., 1947; Smith, 1965; Thornbury, 1965; Reed, 1968; Wright Jr., 1970; Ahlbrandt and Fryberger, 1980). As mentioned earlier, many of the early studies seem to have considered loess to be a downwind, finer-grained facies of the dune sand. An interpretation of a facies relationship between dune sand and loess implies a common source or sources for both sediment groups. This concept is suggested even in recent summaries of the origin of the Nebraska Sand Hills and adjacent loess regions (e.g., DiPietro, 2013, p. 99). Lugn (1939, 1962, 1968) was

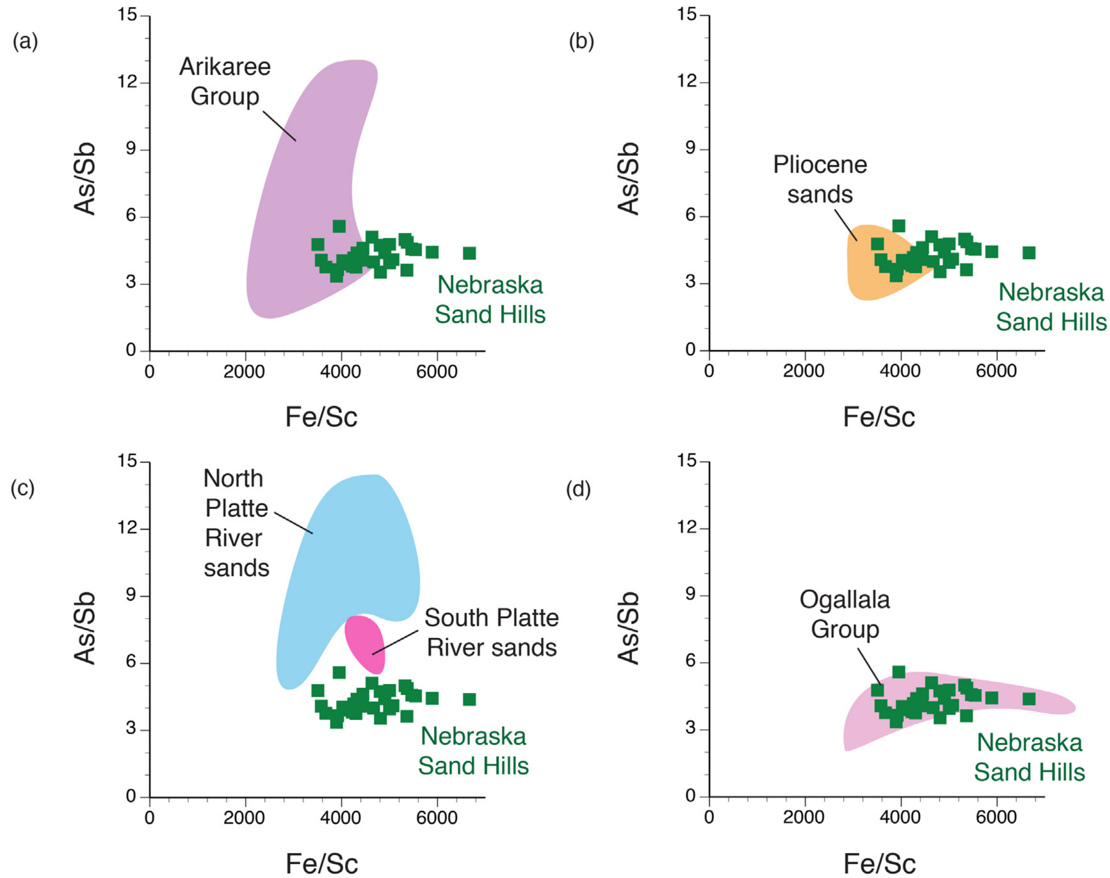

Fig. 22. Bivariate plots of Fe/Sc and As/Sb for late Holocene dune sands of the Nebraska Sand Hills (filled green squares). Also shown are compositional fields for these element ratios in potential source sediments (colored areas): (a) Arikaree Group sands; (b) Pliocene sands; (c) North Platte and South Platte River sands; (d) Ogallala Group sands. Concentrations of all elements determined by instrumental neutron activation analysis from this study.

actually fairly specific about this, and indicated that the Ogallala Group was the ultimate source for both dune sand and loess in Nebraska.

Interestingly, it is now known that the timing of dune formation and loess accumulation in Nebraska is similar. Miao et al. (2007) showed that dune formation in the Holocene matches the timing of accumulation of Bignell Loess to the southeast of the Nebraska Sand Hills. In addition, the largest dunes of the Nebraska Sand Hills, the barchanoid ridges and barchans, were active during the last glacial period (Mason et al., 2011), similar to the timing of loess accumulation southeast of the Nebraska Sand Hills (Roberts et al., 2003; Muhs et al., 2008). A similar timing of both dune activity and loess accumulation during both the late Pleistocene and Holocene does not, of course, require identical sediment sources. It means only that environmental controls on aeolian particle entrainment, transport, and accumulation (sediment supply, climate, vegetation cover) were likely similar for both sand and loess. With regard to Peoria Loess of last-glacial age in Nebraska, Aleinikoff et al. (2008) and Muhs et al. (2008) reported isotopic ($^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$) and geochemical (K/Rb values) evidence to show that dune sands of the Nebraska Sand Hills and loess of central and eastern Nebraska had different sources. The most important source of silt in Peoria Loess of Nebraska is volcaniclastic siltstone of the White River Group.

The trace element geochemical data presented here are consistent with the conclusions of Aleinikoff et al. (2008) and Muhs et al. (2008) that sediments of the Nebraska Sand Hills and Peoria Loess of Nebraska had different sources. Values of K/Rb and K/Ba, Sc-Th-La, Eu/Eu*, La_N/Yb_N, As/Sb, and Fe/Sc all show that the compositions of dune sediments of the Nebraska Sand Hills and Peoria Loess of Nebraska are distinctive (Fig. 23). Peoria Loess of Nebraska has a composition that is close to average upper continental crust, similar to loess found in many other regions of the world. If our interpretation of the Ogallala Group as the main source for the Nebraska Sand Hills is correct, then it is expected that dune sand, derived from this source, and loess, derived from the White River Group, should be compositionally distinct. Detailed petrographic studies by Stanley (1976) indicate that sediments of the Ogallala Group in eastern Wyoming and western Nebraska were derived not only from sources such as the Laramie Range, but also sources west of the Front Range, such as volcanic rocks in the North Park basin of Colorado (see Tweto, 1979). In contrast, the fine-grained volcaniclastic silts of the White River Group are derived from more distal sources (Swinehart et al., 1985), including volcanic centers in southern Colorado and possibly volcanic centers farther west, in the Basin and Range Province (Fig. 1). From all of these considerations, along with the geochemical data reported here, we conclude that the sediments of the Nebraska Sand Hills and Peoria Loess of central and eastern Nebraska had separate sources, though both areas may have been experiencing active sediment transport at the same time. Mason (2001) and Muhs et al. (2008) presented a model showing that silt-sized particles, derived from the White River Group, may have been transported *through* the Nebraska Sand Hills, while the dunes were active, and these particles accumulated as loess farther downwind. In this scenario, however, the dune field contributes little or nothing to the loess itself, but serves merely as a sediment transport pathway. This kind of process is referred to as "sediment bypassing" by Kocurek and Lancaster (1999), although perhaps the phrase "sediment through-passing" is more appropriate. In any case, the general models presented by Mason (2001) and later by

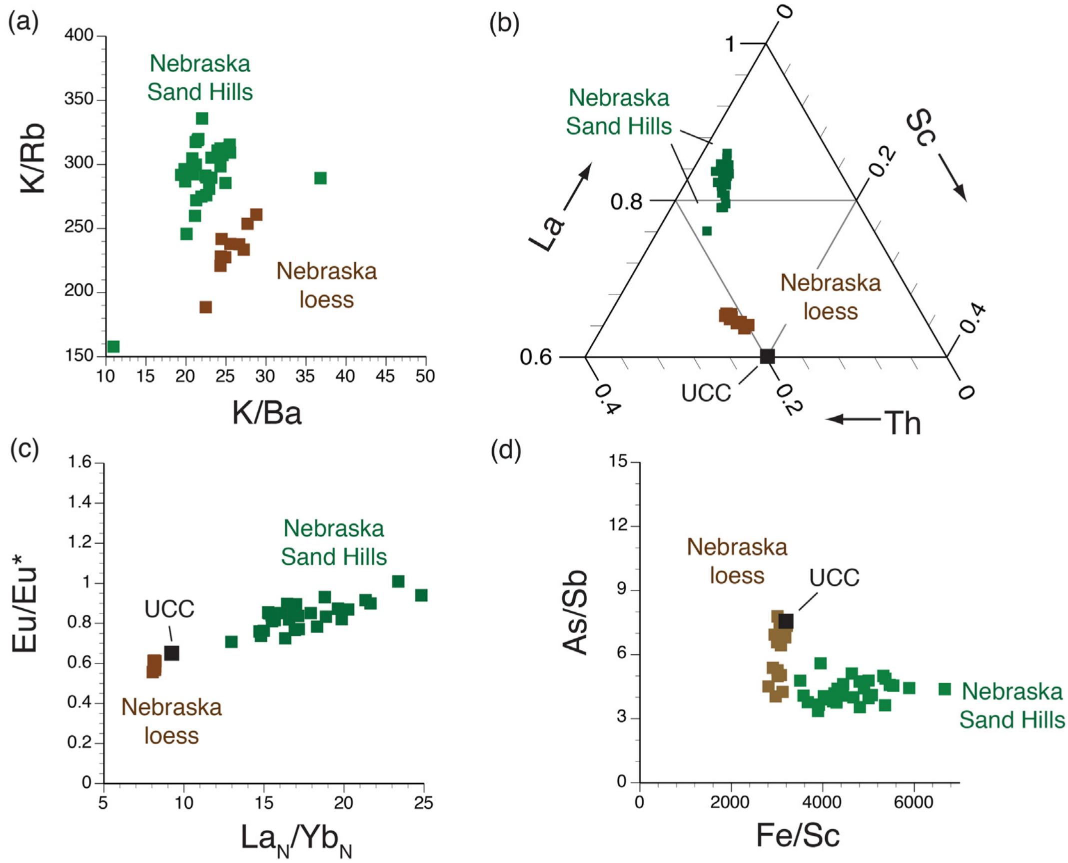

Fig. 23. Bivariate and ternary plots of K/Ba vs. K/Rb, Sc-Th-La, La_N/Yb_N vs. Eu/Eu*, and Fe/Sc vs. As/Sb for late Holocene dune sands of the Nebraska Sand Hills (filled green squares), compared to same data for Peoria Loess (last-glacial-age) of central and eastern Nebraska (Elba and Lincoln, Nebraska localities; see Muhs et al., 2008). Concentrations of all elements determined by instrumental neutron activation analysis from this study. UCC, upper continental crust; values from Taylor and McLennan (1985).

Muhs et al. (2008) still have validity with the data presented here, because they assume that the dunes and loess had separate sources.

5. Summary and conclusions

The Nebraska Sand Hills region is the largest dune field in North America. It hosts a diverse suite of aeolian landforms, including barchanoid ridge, barchan, linear, and parabolic dunes, as well as aeolian sand sheets. Although many of the largest dunes were built during the late Pleistocene, many studies of the past three decades show that Holocene dune activity was widespread in the Nebraska Sand Hills. Furthermore, a minimal degree of soil development in the youngest aeolian sand indicates that virtually all of the dune field has been active during the Holocene, though not necessarily at all localities simultaneously. Modern, sand-moving winds are dominantly from the west, northwest, and north during the fall, winter, and spring, with weaker southerly or southeasterly winds during summer months. Dune morphology indicates that dune-forming winds were dominantly from the northwest during both the late Pleistocene and Holocene.

Identification of the source sediments for the Nebraska Sand Hills has been a challenging problem for the better part of a century. Many investigators have proposed source sediments but with few exceptions, mineralogical or geochemical data to support a specific source or sources have been lacking. Proposed sources include the Arikaree Group and Ogallala Group of Tertiary age, sediments reworked from these units, Pliocene sands that underlie the Nebraska Sand Hills, and fluvial sources such as the Platte River system. We collected representative samples from each of these potential sources, generated separates that approximate the size distribution of the dune sands, and performed mineralogical and geochemical analyses. The mineralogy of the dune sands and all source sediments is dominated by quartz, plagioclase, and K-feldspar, indicating at a broad level of composition, any or all of the hypothesized source sediments could be important.

Trace element geochemistry was performed by high-precision INAA on Holocene dune sediments of the Nebraska Sand Hills and sands from the Arikaree Group, Ogallala Group, Pliocene sediments, and North and South Platte River sediments. K/Rb, K/Ba, Sc-Th-La, Eu/Eu*, La_N/Yb_N, As/Sb, and Fe/Sc all indicate that sediments of the Ogallala Group are the most important sources for the Nebraska Sand Hills. While geochemical evidence indicates that sediment of the Arikaree Group could have been a minor contributor, the highly variable composition of this unit does not always show good compositional agreement with that of the Nebraska Sand Hills. Pliocene sediments are found beneath the Nebraska Sand Hills, and sands of the Platte River system are found to the west, southwest, south, and southeast of the dune field. However, neither of these sediments appear to have been significant sources for the Nebraska Sand Hills. The Ogallala Group is often perceived to be a well-indurated unit, anchored in its upper parts by a cemented calcrete caprock. However, examination of the western Nebraska landscape, both in the field and with topographic maps, shows that a significant amount of the region mapped as the Ogallala Group is quite dissected. Dissected landscapes of western Nebraska not only lack a calcrete-cemented caprock, but in addition host valley sides mantled by unconsolidated sediment derived from the Ogallala Group. Regionally extensive erosion of the Ogallala Group, perhaps envisioned to be widespread, or even uniform stripping of this unit, during pre-Quaternary or early Quaternary time has long been hypothesized to have provided the initial material for formation of the Nebraska Sand Hills. While this may have occurred, the present results also show that

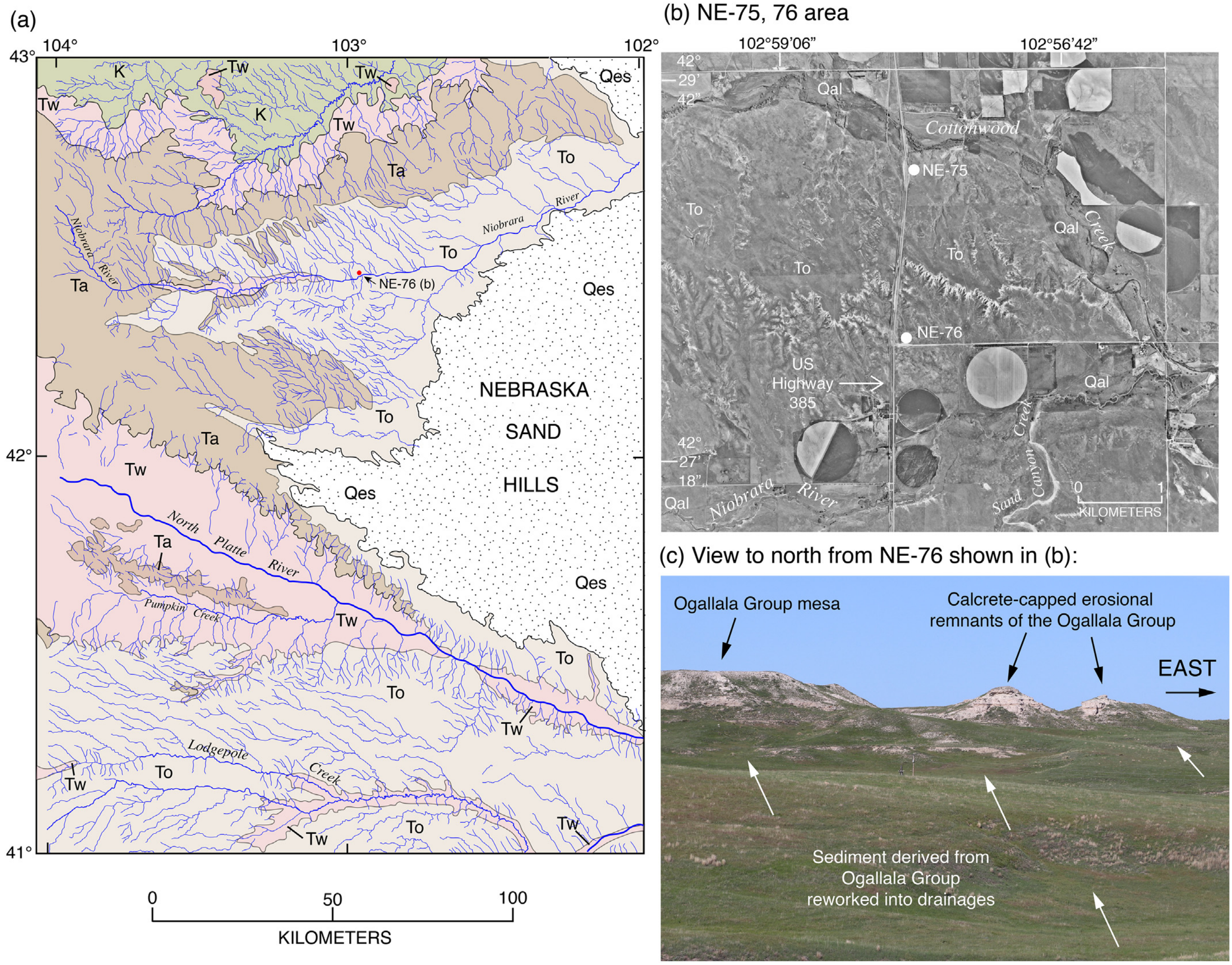

Fig. 24. (a) Map showing drainage systems in northwestern Nebraska, mapped by the authors from the Scottsbluff quadrangle and Alliance quadrangle 1° x 2° USGS topographic maps (scale, 1:250,000). Also shown is bedrock geology of northwestern Nebraska and extent of aeolian sand in the western Nebraska Sand Hills (bedrock simplified from Swinehart et al., 1985; western extent of the Nebraska Sand Hills mapped by the authors from Landsat imagery). Reservoirs, farm ponds, canals and other artificial water bodies are not shown. Rock units: K, Cretaceous rocks, undifferentiated, but largely Pierre Shale; Tw, White River Group; Ta, Arikaree Group; To, Ogallala Group; Qes, Quaternary aeolian sand. (b) U.S. Geological Survey National Aerial Photography Program (NAPP) aerial photograph of the area near sample NE-76 (see (a) for location) showing eroded outcrops of the Ogallala Group rocks north of the Niobrara River. Image number: N10NAPPW11245058, acquired 21 May 1999. To, Ogallala Group rocks; Qal, Quaternary alluvium. (c) ground photograph showing view to north from NE-76 area, showing Ogallala Group mesa, with calcrete-cemented caprock (left) and buttes that are calcrete-capped erosional remnants of the Ogallala Group (right). White arrows point to sediment derived from the Ogallala Group eroded into drainages. Photograph by D.R. Muhs.

an Ogallala Group landscape, if minimally vegetated under drought conditions, could have supplied aeolian sand to the Nebraska Sand Hills once dissection had proceeded to the point where loose sediment became available.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2019.02.023.

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