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Geomorphology 17 (1996) 129–149

GEOMORPHOLOGY

Origin of the late Quaternary dune fields of northeastern Colorado

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Received 28 March 1994; revised 4 January 1995; accepted 20 February 1995

Abstract

Stabilized eolian deposits, mostly parabolic dunes and sand sheets, cover much of the landscape of northeastern Colorado and adjacent parts of southwestern Nebraska in four geographically distinct dune fields. Stratigraphic and soil-geomorphic relations and accelerator radiocarbon dating indicate that at least three episodes of eolian sand movement occurred between 27 ka and 11 ka, possibly between 11 ka and 4 ka, and within the past 1.5 ka. Thus, eolian sand deposition took place under both glacial and interglacial climatic conditions. In the youngest episodes of eolian sand movement, Holocene parabolic dunes partially buried Pleistocene sand sheet deposits.

Late Holocene sands in the Fort Morgan and Wray dune fields, to the south of the South Platte River, have trace element ratios that are indistinguishable from modern South Platte River sands, but different from Ogallala Formation bedrock, which has previously been cited as the main source of dune sand on the Great Plains. Sands in the Greeley dune field, to the north of the South Platte River, have trace element concentrations that indicate a probable Laramie Formation source. Measurements of parabolic dunes indicate paleowinds from the northwest in all dune fields, in good agreement with resultant drift directions calculated for nearby weather stations. Thus, paleowinds were probably not significantly different from present-day winds, and are consistent with a South Platte River source for the Fort Morgan and Wray dune fields, and a Laramie Formation source for the Greeley dune field. Sand accumulated downwind of the South Platte River to form the Fort Morgan dune field. In addition, sand was also transported farther downwind over the upland formed by the calcrete caprock of the Ogallala Formation, and deposited in the lee of the upland on the southeast side. Because of high wind energy, the upland itself served as a zone of sand transport, but little or no sand accumulation took place on this surface.

These studies, which demonstrate the importance of fluvial-source sediments for dune fields in Colorado, may be applicable to other dune fields in North America. Because modern drift potentials in northeastern Colorado are among the highest in the world, the present stability of dunes in the region may be in part a function of the dunes being supply-limited rather than solely transport-limited. Extensive (~ 7700 km^2) late Holocene dunes document that eolian sand in northeastern Colorado is very sensitive to small changes in climate or fluvial source conditions.

1. Introduction

Much of the arid and semiarid landscape in the world is covered by either active or stabilized eolian

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SSDI 0169-555X(95)00100-X

sand. Wind-blown sand and loess are the surficial sediments over a significant portion of northeastern Colorado and adjacent parts of western Nebraska and Kansas, as well as the Nebraska Sand Hills (Lugn, 1968; Warren, 1976; Scott, 1978; Sharps, 1980; Bryant et al., 1981; Wright et al., 1985; Muhs, 1985; Madole, 1994, 1995). The sand dunes and sand sheets of northeastern Colorado are found largely in three distinct dune fields informally named by Muhs (1985) and one informally named here: (1) the Greeley dune field, which is east of the city of Greeley, Colorado and north of the South Platte River; (2) the Fort Morgan dune field, which is actually a series of dune fields to the south, southeast, and east of the South Platte River; and (3) the Wray dune field, which is southeast of, and separated from, the Fort Morgan dune field, and extends eastward into Nebraska (Fig. 1). A fourth dune field, here informally named the Sterling dune field, occurs east of the Greeley dune field and north of the South Platte River (Fig. 1). Madole (1994, Madole (1995) referred to the Greeley, Fort Morgan, and Sterling dune fields collectively as the South Platte eolian sand area. Reconnaissance field studies indicate that most dunes in the Sterling dune field have better developed soils and are probably older than the majority of dunes in the other three fields; studies of the Sterling dune field are not reported here. Loess covers much of the landscape where eolian sand is not at the surface. Elsewhere, weakly consolidated rocks of the Pierre Shale (Cretaceous), Laramie Formation (Cretaceous), White River Group (Oligocene), Arikaree Group (Oligocene–Miocene), and the Ogallala Formation (Miocene) underlie the surface (Scott, 1978).

The sand dunes and sand sheets of northeastern Colorado are at present stabilized mainly by a sand-sage (*Artemisia*) community which includes bunch grass, cactus, and yucca. Actively moving sand is limited to local blowouts near dune crests. Recent studies have shown, however, that the present climatic conditions of northeastern Colorado are near a boundary that separates active from stabilized sand (Muhs and Maat, 1993). Reduction in vegetation cover through a reduction in precipitation and increase in temperature could occur naturally on the Great Plains in the future, as has been the case in the past, or may occur in the near future, because of human causes. Simple numerical experiments using climatically based mobility indexes indicate that

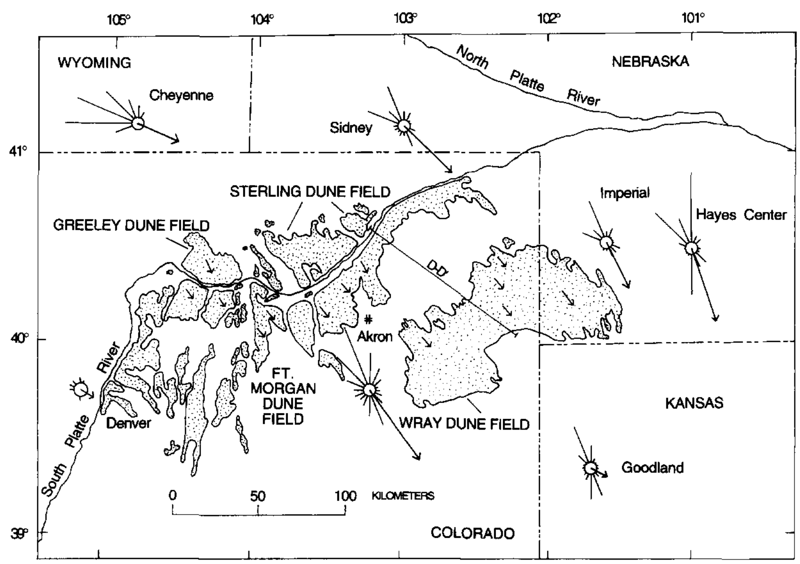

Fig. 1. Map showing distribution of eolian sand in northeastern Colorado and southwestern Nebraska, location of cross-section D–D′ (Fig. 23), orientation of late Holocene paleowinds, and modern sand roses (calculated using the method of Fryberger and Dean, 1979). Eolian sand distribution west of 104° and north of 40° and all areas east of 102° were mapped by the authors; other areas are from Scott (1978), Sharps (1980), and Bryant et al. (1981).

dunes, over a significant portion of the Great Plains including northeastern Colorado, could be reactivated under a future greenhouse climate (Muhs and Maat, 1993). In order to understand better the potential for reactivation of eolian sand, it is crucial to know when eolian sand was active in the past, what the climatic conditions were at the time of sand movement, and what the sources of the sand were.

2. Methods

Eolian sand in parts of northeastern Colorado was previously mapped at 1:250,000 by Scott (1978), Sharps (1980), and Bryant et al. (1981), and at 1:100,000 by Colton (1978), but mapping is available for the whole area only on a reconnaissance basis by Muhs (1985) and Madole (1994, 1995). We remapped those areas not covered by previous workers using high-altitude aerial photographs as a base. These areas include the Greeley and Fort Morgan dune fields west of 104°W and north of 40°N and the Wray dune field east of 102°W; for the former areas, 1:58,000 color infrared aerial photographs taken in 1983 were used as a mapping base and for the latter area, 1:80,000 black-and-white aerial photographs taken in 1981 were used.

Accelerator mass-spectrometric (AMS) radiocarbon ages were determined on carbonate nodules and rhizoliths found in dune sands and eolian sheet sands. For pedogenic carbonate nodules, physical cleaning was followed by an HCl bath, in turn followed by partial dissolution (under vacuum) in phosphoric acid; the gas generated by this reaction was pumped off and discarded. The remaining portion of the sample was then dissolved completely in phosphoric acid and this fraction was graphitized and dated. Radiocarbon ages of secondary carbonates have been controversial, although recent studies have shown that pedogenic carbonate is dominantly derived from soil CO_2, in equilibrium with atmospheric CO_2 (Cerling et al., 1989; Quade et al., 1989). Hence, radiocarbon ages of pedogenic carbonates have the potential to be reliable age estimates. Nevertheless, we recognize that the sources and exchange processes of soil CO_2 can be complex (Wang et al., 1994) and that radiocarbon ages of soil carbonates, such as nodules and rhizoliths, should be interpreted with caution.

The distribution of particle-size in eolian sands within the sand-sized range was determined by sieving 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, standard deviation, and skewness (as defined by Folk, 1974) were calculated for all samples.

Concentrations of trace elements in eolian sands and potential source sediments were measured using the energy-dispersive X-ray fluorescence method. Samples of eolian deposits analyzed included all size fractions. Potential source sediments, whether modern fluvial sediments or bedrock sediments, include a wide range of particle sizes from clays to gravels. Valid geochemical comparisons to eolian sands can only be made on source sediments that are of the same size as those in eolian sands. Therefore, after removal of gravel by sieving, fluvial sediments from the South and North Platte Rivers were treated with Na-pyrophosphate dispersant to allow removal of silts and clays by wet sieving; sand fractions were then concentrated by dry sieving. Samples from the Laramie Formation, Arikaree Group and Ogallala Formation (and Pleistocene deposits derived from it) were first treated by removing carbonate cement with an Na-acetate buffer and then were processed in the same manner as the fluvial sediments. Laramie, Arikaree, and Ogallala samples were checked for complete or nearly complete removal of calcite cement by X-ray diffraction analysis. Because the Arikaree Group and North Platte River sediments were studied as possible distant-source sediments, only the very fine and fine sand (53–250 μm) fractions were analyzed. For sediment sources closer to northeastern Colorado dune fields (South Platte River sediments, Laramie Formation, and Ogallala Formation) the very fine, fine, and most of the medium sand fractions (53–425 μm) were analyzed.

3. Geomorphology, soils, stratigraphy and radiocarbon ages

3.1. Geomorphology and soils

In the Greeley, Fort Morgan and Wray dune fields (Fig. 1), the main eolian deposits are simple parabolic dunes, compound parabolic dunes, and low-relief sand sheets (Fig. 2). In the Fort Morgan dune field, T.S. Ahlbrandt (pers. commun., 1994) also observed rare, isolated transverse and barchanoid-ridge dunes. Muhs (1985) reported parabolic dunes as long as 4 km in some areas, and Forman et al. (1992) later reported parabolic dunes as long as 10 km. The higher-relief parabolic dunes (both simple and compound) alternate with low-relief dunes and interdune sand sheets on the landscape.

Thicknesses of eolian sand are difficult to ascertain in northeastern Colorado because few exposures exist. In the Fort Morgan dune field, we observed outcrop thicknesses of up to ~20 m, and well log data presented by Bjorklund and Brown (1957) indicate thicknesses of up to ~30 m. Based on well log

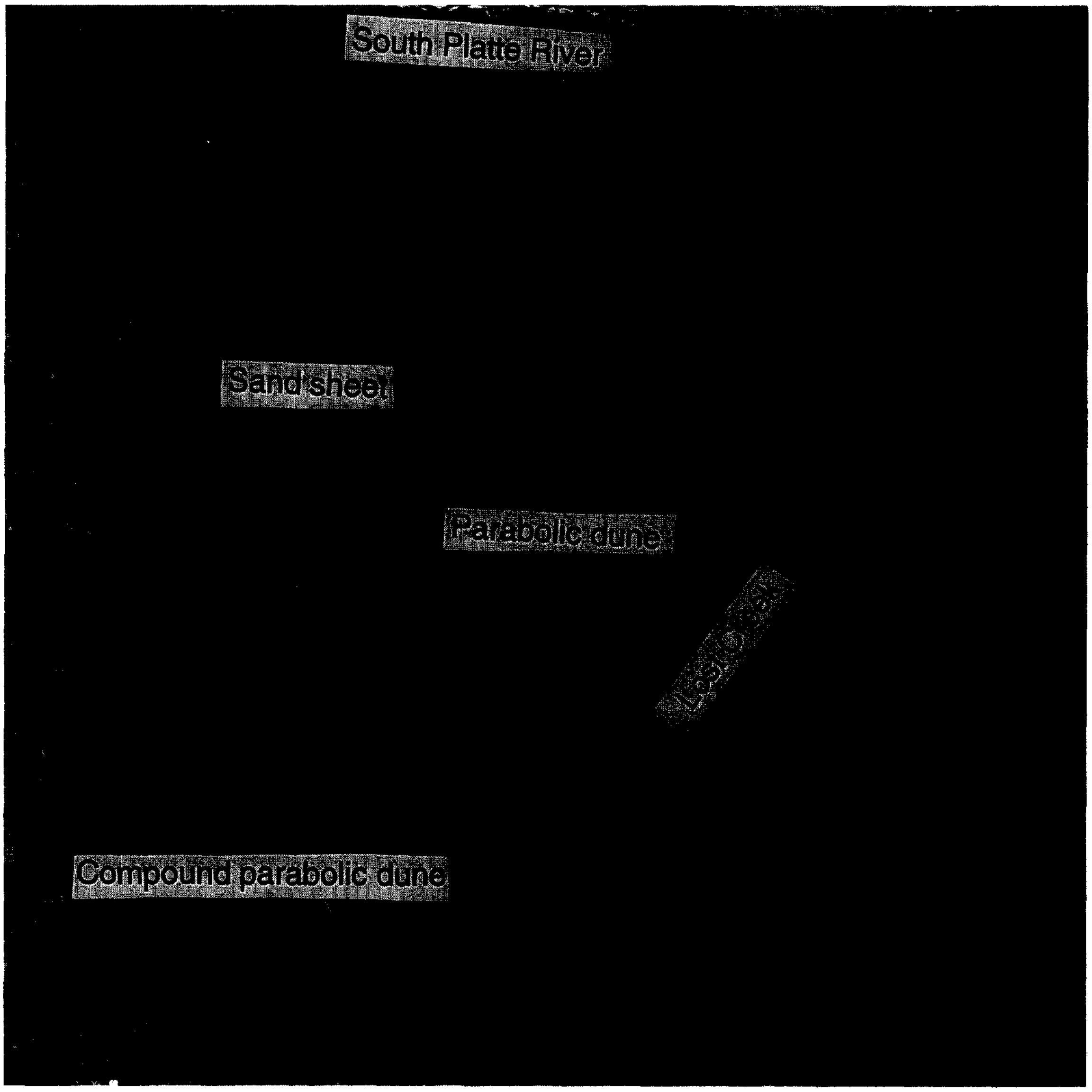

Fig. 2. Aerial photograph of the Lost Creek area south of the South Platte River (near the area mapped in Fig. 3) in the Fort Morgan dune field showing simple parabolic dunes, compound parabolic dunes, and sand sheets.

data reported in Weist (1964), eolian sand in the Wray dune field reaches a maximum thickness of ~ 37 m in places. All thickness estimates from well logs are likely minimum values because wells are typically drilled in topographically low interdune areas and not on the topographically higher dune crests where thicknesses would be greater. In the Greeley dune field, the few outcrops available suggest that on average, thicknesses of eolian sand are less than in the other two dune fields; augering and well log data indicate common thicknesses of ~ 5 m.

Soils on dunes and in interdune positions of the landscape differ markedly (Crabb, 1980; Larsen, 1981; Muhs, 1985; Jorgensen, 1992; Madole, 1995). In the Fort Morgan and Greeley dune fields, for example, soils on high-relief parabolic dunes are mostly in the Valent series (Ustic Torripsamments) and have weakly developed A/AC/C profiles. In contrast, interdune sand sheets have better developed soils of the Vona or Osgood series (both Ustollic Haplargids). Vona and Osgood soils have A/Bt/Bk/C profiles and both have thicker sola than the thin Valent soils. Valent soils are also found on high-relief dunes in the Wray dune field, and four soil series of Haplargids or Argiustolls, with varying degrees of argillic B horizon development, are found in sand sheet deposits in the interdune areas (Larsen, 1981).

3.2. Late Pleistocene eolian sand deposition

In an earlier study, Muhs (1985) suggested that in northeastern Colorado, interdune sand sheets with well-developed soils represent an older landscape that was partially buried by deposition of younger sand when the parabolic dunes formed. In contrast, Jorgensen (1992), who studied soils on dunes in a part of the Fort Morgan dune field, speculated that well-developed interdune soils are the result of landscape position rather than age. Although Jorgensen (1992) did not specify why an interdune position should have better developed soils, we infer from his study that it would be a preferred locus of secondary dust deposition after sand stabilization, which could, therefore, accelerate soil development. We tested these contrasting hypotheses by deep augering at two localities in the Lost Creek area of the Fort Morgan dune field, one ~ 2 km south of the South Platte River (cross-section B–B′ on Fig. 3) and the other ~ 8 km south of the river (cross-section C–C′ on Fig. 3). At both localities, high-relief parabolic dunes

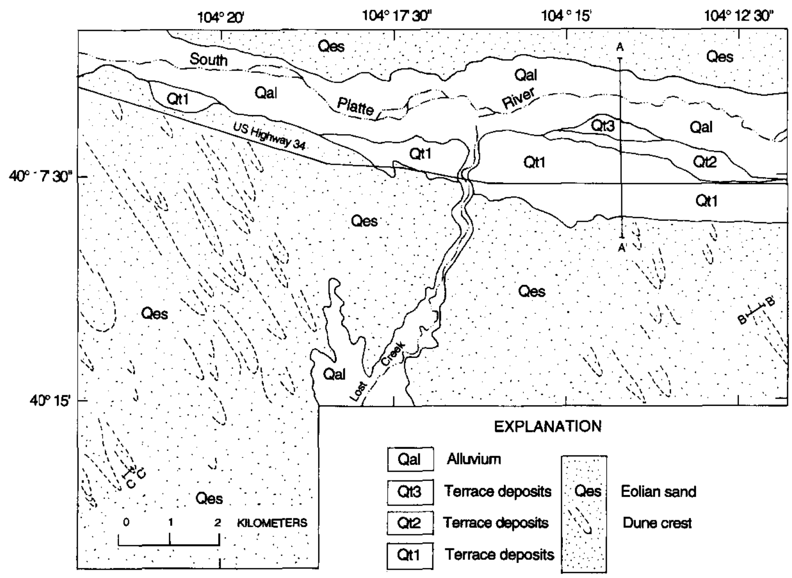

Fig. 3. Surficial geologic map of a portion of the Lost Creek area south of the South Platte River, between Greeley and Fort Morgan, Colorado, with locations of cross-sections shown in Figs. 4, 5 and 8.

with alternating interdune deposits are well expressed geomorphically (Figs. 2 and 3). At cross-section B–B′, an Osgood soil with an A/Bt/Bk/C profile is developed in eolian sheet sand (based on the presence of well-expressed wind ripple strata) in the interdune area, and is underlain by a buried Btk horizon with carbonate nodules at a depth of ~ 3 m (Fig. 4). Augering in the adjacent high-relief dune revealed a buried Osgood-like profile in one borehole, and a thick zone of clay lamellae in another borehole. In the latter borehole, a buried soil with a carbonate nodule zone in the 3Bkb horizon was encountered at a depth of ~ 6 m, and could correlate with the carbonate nodule-bearing paleosol found below the Osgood interdune soil (Fig. 4). At cross-section C–C′, farther from the river, augering also showed that the interdune Osgood soil with its A/Bt/Bk/C profile can be traced in the subsurface beneath an adjacent dune to the northeast (Fig. 5). At this locality, the water table is higher and augering could not be conducted as deeply as at section B–B′; hence, we were unable to determine whether the older buried soil beneath the interdune Osgood soil at section B–B′ is also present farther south. Surface soils at both localities on the high-relief parabolic dunes are Valent soils with A/AC/C profiles. Thus, data from both localities support the original suggestion of Muhs (1985) that younger parabolic dunes partially buried a pre-existing sand sheet landscape.

Soil-geomorphic evidence, along with archaeological data, can provide an age estimate for the sand sheets with A/Bt/Bk/C soil profiles. Along the South Platte River between Kersey and Fort Morgan, we mapped three terraces named, in order of descending elevation, the Qt1, Qt2, and Qt3 terraces. The Qt1 terrace is broad and fairly continuous whereas the Qt2 and Qt3 terraces are of very limited extent (Figs. 3 and 6). On the basis of longitudinal profiles (Fig. 7), we correlate the Qt1 terrace with the Kersey terrace, found just upstream of our study area (Holliday, 1987). The presence of Clovis artifacts within the upper part of deposits of the Kersey terrace indicates that the latest deposition of this alluvium took place around 11,500–11,000 yr BP (Wheat, 1979; Holliday, 1987; Zier et al., 1993). Although soils in both the Kersey-Qt1 terrace sediments and interdune eolian sand sheets show considerable variability, on average soils in the terrace

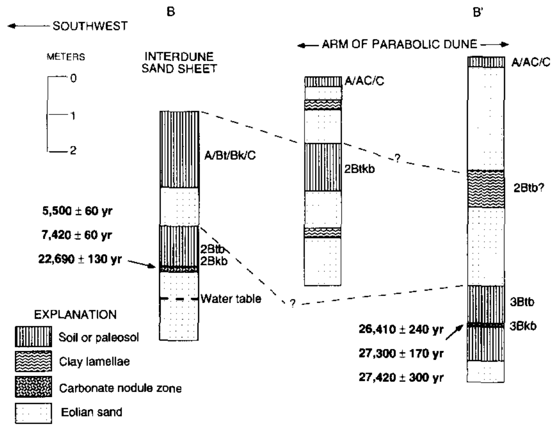

Fig. 4. Cross-section B–B′ through eolian sands in an area south of the South Platte River in the Fort Morgan dune field; ages are from accelerator radiocarbon analyses of carbonate nodules. Location of section shown in Fig. 3.

sands and eolian sands show that the two deposits could be of approximately the same age (Fig. 8). Soils in fine-grained facies of Kersey-Qt1 sediments have well-expressed Bt and Bk horizons, as do the Vona and Osgood soils developed in eolian sheet sands. Therefore, we estimate that deposition of the eolian sand sheets may have ended at ~ 11 ka.

AMS radiocarbon ages provide maximum-limiting ages for eolian sand sheet deposition. At cross-section B–B′ carbonate nodules were recovered from augering at a depth of ~ 6.9 m, under the high-relief dune in the lower part of the lowermost buried soil,

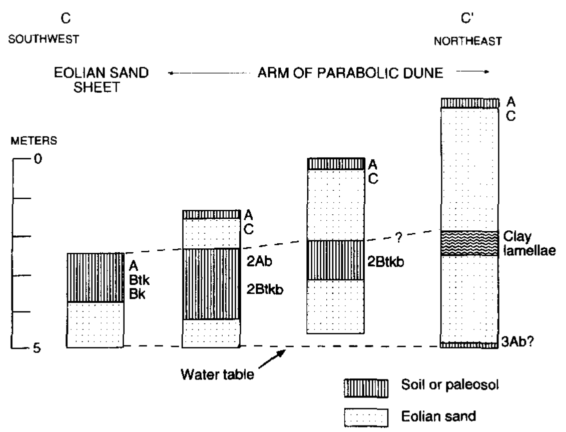

Fig. 5. Cross-section C–C′ through eolian sands in an area south of the South Platte River in the Fort Morgan dune field. Location of section shown in Fig. 3.

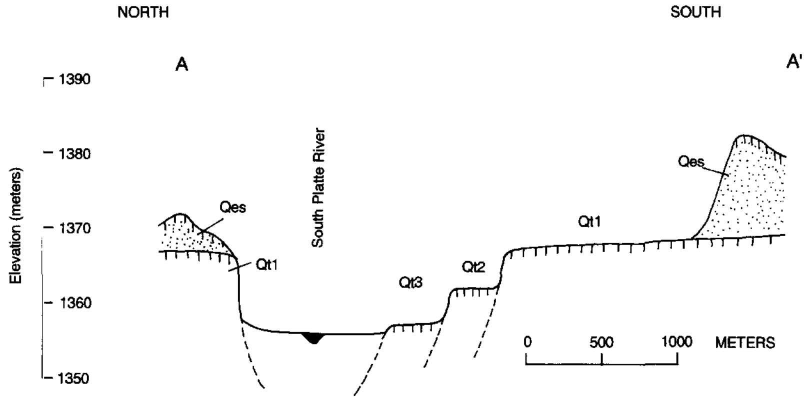

Fig. 6. Cross-section A–A′ north and south of the South Platte River between Greeley and Fort Morgan, Colorado. Location of section shown in Fig. 3.

and at a depth of ~3.7 m in the lower part of the buried soil in the interdune area. AMS radiocarbon ages (all reported in radiocarbon years BP) for three nodules collected under the high-relief dune (Fig. 4) are 27,300 ± 170 yr (CAMS-11339), 27,420 ± 300 yr (CAMS-16612), and 26,410 ± 240 yr (CAMS-16604). Three nodules collected in the interdune area (Fig. 4) gave AMS radiocarbon ages of 5500 ± 60 yr (CAMS-16605), 7420 ± 60 yr (CAMS-11336), and 22,690 ± 130 yr (CAMS-16611). The ages for the three nodules collected under the high-relief dune are in excellent agreement with one another. The nodule ages from the interdune position, however, do not agree with one another. The spread of nodule ages from the interdune position suggests varying degrees of nodule–groundwater interaction, because the water table was encountered ~0.6 m below the zone where the nodules were collected (Fig. 4). Therefore, we reject these three inconsistent radiocarbon ages, but accept the three nodule ages of ~27 ka as a reasonable maximum-limiting age for the overlying eolian sand sheet. The combined AMS radiocarbon and archaeological data indicate, therefore, a maximum-limiting age of ~27 ka and a minimum-limiting age of ~11 ka for eolian sand sheet deposition.

Radiocarbon ages of organic coatings on eolian sand exposed in the Logan County landfill near Sterling in the Fort Morgan dune field show that in addition to eolian sheet sands, some of the earliest dunes may have been deposited prior to ~9500 yr BP, and could correlate with the period of deposition of eolian sheet sand. In the section exposed, basal fluvial sands and gravels (that may correlate with the

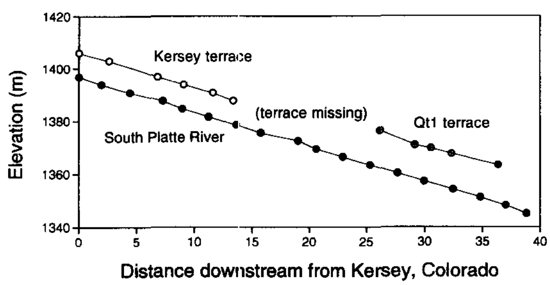

Fig. 7. Longitudinal profiles of the South Platte River and the Kersey and Qtl terraces downstream from Kersey, Colorado. Downstream distances in kilometers.

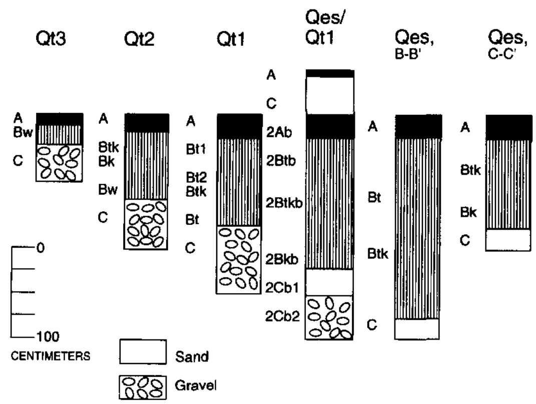

Fig. 8. Soil profile development in terrace alluvium along the South Platte River and in Osgood soils developed in interdune sheet sands south of the South Platte River at localities where cross-sections B–B′ and C–C′ were measured.

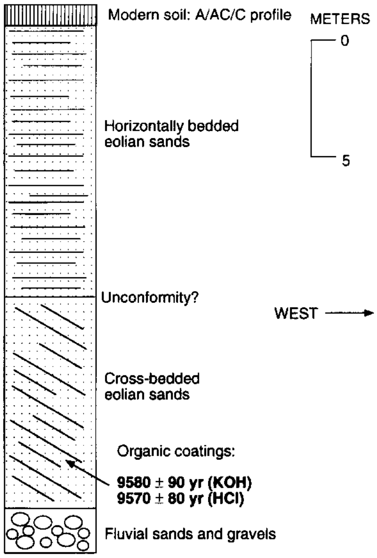

Fig. 9. Eolian sediments exposed in the Logan County landfill near Sterling, Colorado, in the Fort Morgan dune field, and radiocarbon ages of organic coatings on grains found in foreset beds.

~ 11,000 yr BP Qtl terrace) are unconformably overlain by ~ 9 m of cross-bedded sands dipping 25–30° southeast that we interpret to be dune foreset beds (Fig. 9). The cross-bedded sands are in turn unconformably overlain by ~ 10 m of horizontal or gently dipping beds of sand that we interpret to be eolian sand sheets. Immediately above the horizontal beds part of the section is covered, but at least another 3 m of eolian sand caps the section, and has a Valent (A/AC/C profile) soil developed in the uppermost part. About 2.5 m above the contact with the basal gravels, a zone of cross-bedded sands several cm thick occurs where grains have very distinctive dark coatings of organic matter and (or) MnO_2. We tentatively interpret these coatings to be groundwater- or throughflow-water-derived materials that were deposited some time after dune formation. We extracted carbon from two splits of these grain coatings, using a KOH extraction for one split and an HCl extraction for the other split. The KOH extraction gave an AMS radiocarbon age of 9580 ± 90 (CAMS-5307) and the HCl extraction gave an AMS radicarbon age of 9570 ± 80 (CAMS-5308) (Fig. 9). The two ages are in excellent agreement with one another and indicate that dune deposition occurred *before* about 9500 yr BP.

3.3. Holocene eolian sand deposition

On the basis of soil-stratigraphic correlation to radiocarbon-dated eolian sands in the Nebraska Sand Hills, Muhs (1985) inferred that Colorado eolian sands with A/AC/C soil profiles were less than about 3000 yr old. New soil-geomorphic evidence supports this inference. The Qtl terrace discussed earlier is present on both sides of the South Platte River and is covered by eolian sand in places on both sides (Fig. 6). Parts of the Qtl terrace on the south side of the river are not covered with eolian sand (Figs. 3 and 6); however, the degree of soil development in terrace alluvium here is about the same as that on the north side of the river, where eolian sand mantles the Qtl terrace (Fig. 8). This observation indicates that on the north side of the river, pedogenesis in Qtl sediments was ongoing throughout the Holocene until very recently. Therefore, eolian sand which overlies the Qtl terrace, with its A/AC/C soil profile, must have been deposited fairly recently.

In the Greeley dune field on the north side of the South Platte River, a blowout north of Orchard, Colorado exposes ~ 6 m of eolian sand in which

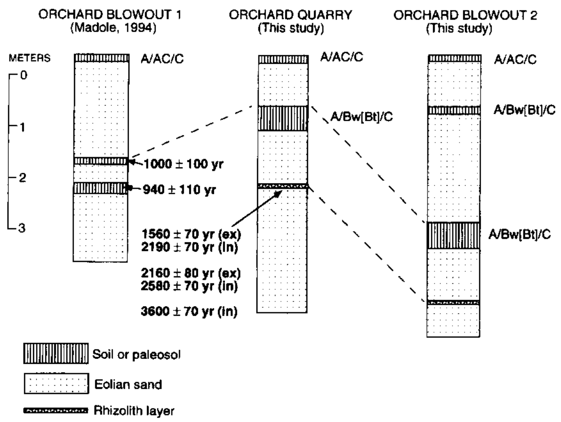

Fig. 10. Eolian stratigraphy exposed in a blowout and quarry exposures north of Orchard, Colorado in the Greeley dune field, showing radiocarbon ages of rhizoliths (this study) and soil organic matter (Madole, 1994).

two buried soils exist (Fig. 10). The oldest eolian sand is at least 2.2 m thick and appears to be a sand-sheet deposit, based on the presence of horizontally bedded ripple strata and the absence of high-angle foreset beds. The upper part of the unit has a paleosol characterized by a Bw or possibly minimal Bt horizon, and small calcium carbonate rhizoliths are present locally below the Bw[Bt] horizon. The thickness, clay content, and structural development in this B horizon is less than that observed in Osgood and Vona soils in the interdune sand sheets of the Fort Morgan dune field. The unit is overlain by ~ 2.3 m of younger sheet sand, characterized by a very thin paleosol that has a Bw or minimally developed Bt horizon. The youngest unit is a thin (~ 70 cm) cap of eolian sand that has an A/AC/C soil profile. A nearby exposure in a quarry and numerous roadcuts along the Weld-Morgan County line road show similar stratigraphy except that the thin A/Bw[Bt]/C paleosol exposed in the upper part of the blowout exposure is not present. Because the degree of soil development in the lower eolian unit is less than that observed in the interdune sand sheets of the Fort Morgan dune field, we estimate that it is significantly younger than ~ 11 ka.

We collected carbonate rhizoliths for AMS radiocarbon dating from the lower part of the soil developed in the oldest eolian unit at the quarry locality. The interiors of three individual rhizoliths gave ages of 3600 ± 70 yr (CAMS-6378), 2580 ± 70 yr (CAMS-8235), and 2190 ± 70 yr (CAMS-8236); the exteriors of the latter two rhizoliths gave ages of 2160 ± 80 yr (CAMS-8233) and 1560 ± 70 yr (CAMS-8234), respectively (Fig. 10). The 'exteriors' are the first CO_2 fraction taken off after acid dissolution and the 'interiors' are the final CO_2 fraction taken off after acid dissolution. The ages are in correct stratigraphic order for individual rhizoliths because younger carbonate would have accumulated on the exterior of earlier-formed carbonate as rhizolith growth proceeded. Because no evidence exists of significant contemporary carbonate accumulation in the eolian sand above the buried B horizon, we interpret the rhizoliths to have formed during a period of pedogenesis after deposition of the lowermost eolian unit. Thus, the oldest interior radiocarbon age is a minimum age for the lowermost unit, indicating that deposition of this sand took place some time before 3600 yr BP. The radiocarbon data, combined with the relative degree of soil development in this unit, leads us to conclude that the lowermost eolian sand sheet was deposited between ~ 11 ka and ~ 4 ka.

The radiocarbon data also provide limits on the age of the youngest eolian sand, with its A/AC/C profile. The youngest rhizolith exterior radiocarbon age from the lower unit is a maximum age for the overlying eolian sand, and indicates that deposition of this unit took place sometime after ~ 1500 yr BP. The maximum-limiting age of ~ 1500 yr BP for the uppermost eolian sand is in excellent agreement with a radiocarbon age on soil humus of 1000 ± 100 yr BP, derived from what we interpret to be a correlative paleosol, exposed in a blowout (referred to as 'Orchard blowout 1' in Fig. 10) 1–2 km north of our locality (Madole, 1994). In the Fort Morgan dune field, several localities with maximum-limiting radiocarbon ages of ~ 1000 yr BP support the interpretation that eolian sands with A/AC/C profiles are very young (Madole, 1994).

4. Sedimentology

We collected latest Holocene eolian sands (those with A/AC/C soil profiles) from all three dune fields for detailed sedimentological analyses. Most samples analyzed are moderately sorted, medium and fine sands (Fig. 11). Sands in the Fort Morgan dune field are coarsest (overall mean = 1.85 ± 0.25 phi) and Wray sands are finest (overall mean = 2.13 ± 0.26 phi), with the Greeley sands having intermedi-

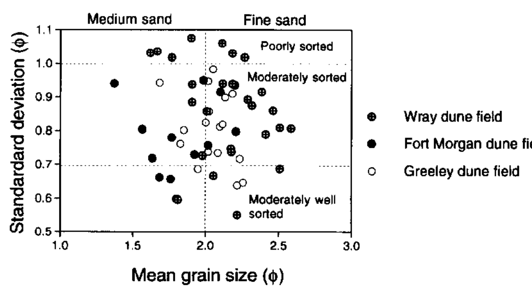

Fig. 11. Mean grain size and sorting values for eolian sands from three dune fields in northeastern Colorado.

ate values (overall mean = 2.04 ± 0.15 phi). The generally finer mean grain size of sands in the Wray dune field compared to the Greeley and Fort Morgan dune field suggests either a different source sediment or a greater distance of transport. Generally, sheet sands are coarser and more poorly sorted than dune sands (Pye and Tsoar, 1990), although Breed et al. (1987) found that eolian sand sheet deposits of the Sahara had a bimodal distribution, with modes in the very coarse sand and fine sand–very fine sand fractions. We found no significant differences between grain size distributions of Holocene dunes and Holocene sand sheets (Fig. 12). Most samples of the dunes and the sand sheets of northeastern Colorado are neither fine nor coarse-skewed, but symmetrical.

Northeastern Colorado dune sands are generally coarser and not as well sorted as sands in other dune fields (Ahlbrandt, 1979), including the nearby Nebraska Sand Hills (Ahlbrandt and Fryberger, 1980). This comparison indicates that the distributions of grain size in eolian sands in the Great Plains may be distinctive from dune field to dune field and could be a function of differences in source sediments, distance of transport, average wind strength at the time of dune building, or number of reworking cycles. On a global basis, most dune sands are fine grained and moderately well sorted (Ahlbrandt, 1979). This suggests that the coarser and more poorly sorted Colorado sands have perhaps not traveled as far from the source regions as have other dune sands.

A distinctive aspect of dune sands in northeastern Colorado is the relatively high content of silt and clay. During sampling, we were careful to collect

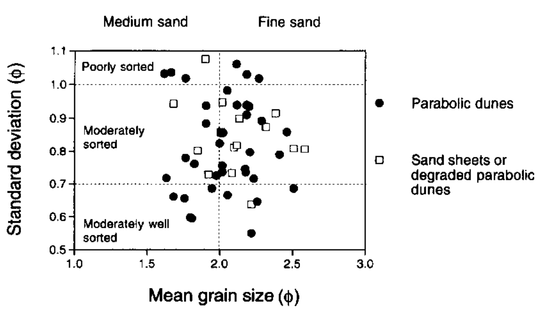

Fig. 12. Comparison of mean grain size and sorting values for parabolic dunes and eolian sand sheets in northeastern Colorado.

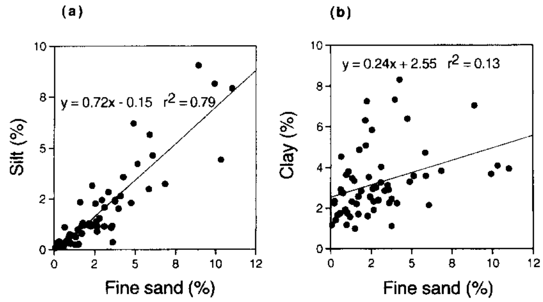

Fig. 13. Plots of silt content as a function of fine-sand content, and clay content as a function of fine-sand content in eolian sands in northeastern Colorado.

sediments well below the zone of pedogenesis and we avoided clay lamellae that sometimes occur in Great Plains eolian sands (cf. Ahlbrandt and Fryberger, 1980; Jorgensen, 1992). Despite these precautions, silt contents in our samples range from less than 1% to as high as 13%; clay contents range from 1% to 7%. Muhs (1985) reported silt contents as high as 20% in some Valent soils of northeastern Colorado and speculated that the relatively high silt and clay contents result from secondary dust accumulation and infiltration after stabilization of the dune. If the silt and clay are primary deposits that are transported with the sand fraction, then they should show a positive correlation with the finest sand fractions. If the silt and clay are secondary dust additions, then the concentrations should be unrelated to the finest sand content. We tested these hypotheses by comparing silt and clay contents with the finest sand fraction (63–88 μm) contents. Results indicate that silt probably accumulates at the same time as fine sand, whereas clay content shows no correlation with fine sand content and thus may result from secondary dust additions (Fig. 13). An alternative explanation is that clay may be transported as a coating on sand grains that form part of the primary dune sediments (Walker, 1979), in which case clay content may or may not be systematically related to the fine-sand content. If clay in these dunes is externally derived from airborne dust, our data show that it can accumulate quickly and may be the primary source of clay in the buildup of Bt horizons.

5. Trace element geochemistry and sources of eolian sand

In a summary of over 35 years of study of the eolian history of the Great Plains, Lugn (1968) stated categorically that the Miocene Ogallala Formation was the main source of Pleistocene and Holocene eolian sand for the entire region, from Nebraska to Texas, including northeastern Colorado. Hunt (1986) also proposed that dunes in northeastern Colorado were derived from 'Tertiary formations', which we interpret him to mean the Ogallala Formation, but in contrast to Lugn (1968), Hunt also thought there could have been contributions from the South Platte River during glacial times. In northeastern Colorado and southwestern Nebraska, the Ogallala Formation is a dominantly fluvial deposit that is composed of silt, sand, and gravel derived from granitic, sedimentary, and volcanic rocks, and locally contains volcanic ash beds (Scott, 1978). The Ogallala Formation forms broad, flat uplands in part because of cementation in its upper part by calcium carbonate. Despite the presence of the calcrete caprock on the upland surface, sideslopes are largely uncemented and provide unconsolidated sediment to first-order drainages in northeastern Colorado. This slopewash-derived sediment has the potential of being deflated by the wind. Other potential source rocks, particularly for the Greeley dune field, are sediments from the North Platte River, the Laramie Formation, which crops out extensively in northern Colorado (Braddock and Cole, 1978), and the Arikaree Group, which crops out extensively in eastern Wyoming and western Nebraska (Love and Christiansen, 1985; Swinehart et al., 1985). Other pre-Quaternary bedrock units in northeastern Colorado, such as the Pierre Shale and the White River Group, contain largely clay- or silt-sized particles and probably are not important sources of eolian sand. In addition to the Ogallala Formation, however, a potential source in northeastern Colorado and southwestern Nebraska is the South Platte River. This river has abundant sand in the form of bar sediments in its present channel, derived largely from the Front Range. The river had an even wider, braided, and more sand-rich channel in the 19th and early 20th centuries (Nadler and Schumm, 1981; Eschner et al., 1983). The cross-section shown in Fig. 6 shows that during the time of Qt1 terrace deposition about 11,500–11,000 yr ago, the South Platte River floodplain was considerably wider (at least 4 km in places) than it is at present. We tested Lugn's (1968) and Hunt's (1986) hypothesis of the Ogallala Formation being the main source of eolian sand in northeastern Colorado by conducting detailed mineralogical and geochemical studies.

The mineralogy of northeastern Colorado and southwestern Nebraska dune sands is dominated by quartz, plagioclase, K-feldspar, rock fragments, and lesser amounts of heavy minerals. Using X-ray diffraction analysis of powdered sand samples, we found no significant differences in quartz, plagioclase, and K-feldspar contents between sands from the three dune fields and sands from the South Platte River and the Ogallala Formation. Because mineralogical data do not distinguish the three dune fields or the potential sources, we used trace element concentrations, to 'fingerprint' the potential source sediments and compare them to eolian sands from the three dune fields, following an approach used by Muhs et al. (1995) for the Algodones dunes of southeastern California. Concentrations of Rb, Sr, Ti, and Zr can all be measured with relatively high precision by X-ray fluorescence spectrometry. Ba and Rb substitute for K and are, therefore, found in K-feldspar and biotite. Because of its higher charge, Ba tends to be enriched in early-formed K-bearing minerals, whereas Rb, because of its larger ionic radius, tends to be enriched in later-formed K-bearing minerals. Ba is also found to a much lesser degree in plagioclase. Sr substitutes for Ca and is present mostly in plagioclase, but can be found in some K-bearing minerals as well. Ti is found mainly in ilmenite and Zr is present almost exclusively in zircon.

Trace element concentrations found in light and heavy minerals show that dune fields in northeastern Colorado may have different sources. The Greeley dune field has significantly lower Rb and Sr concentrations and, on average, higher Ti/Zr values than the Fort Morgan and Wray dune fields (Fig. 14). In all three dune fields, however, Ti content shows a positive linear correlation with Zr content, which would be expected in eolian sediments, because both elements are found in heavy minerals. Concentrations of trace elements also show that within a dune field, source sediments may not have changed over

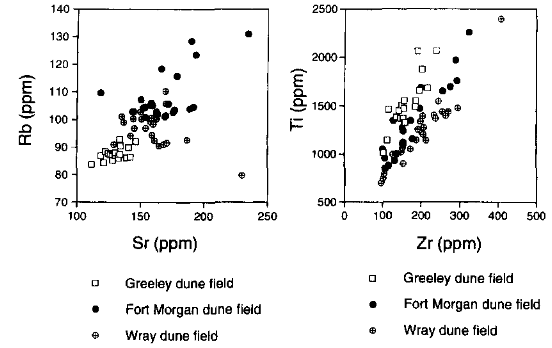

Fig. 14. Plots of Rb, Sr, Ti, and Zr contents for sands of the three dune fields in northeastern Colorado.

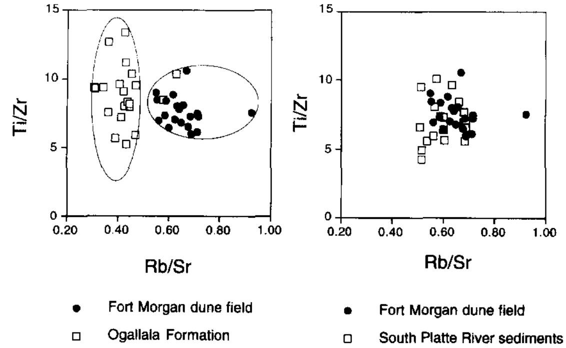

Fig. 16. Plots of Ti/Zr and Rb/Sr values for sands from the Fort Morgan dune field, the Ogallala Formation, and the South Platte River.

time, or alternatively, younger sediments may have been reworked from older sediments. In the Fort Morgan dune field, Rb, Sr, Ti, and Zr contents in late Pleistocene sand sheet deposits are not significantly different from those in late Holocene dunes (Fig. 15).

The Fort Morgan dune field parallels the south side of the South Platte River and it is apparent from this geomorphic setting alone that river sediments are a potential source of eolian sand for this dune field, whereas the Ogallala Formation is not present at the surface immediately upwind of the Fort Morgan dune field. Fort Morgan dune field sands and South Platte River sands show no significant differences in Rb/Sr or Ti/Zr values (Fig. 16). Ti/Zr values in Ogallala Formation sands are, however, significantly more variable than those in Fort Morgan dune field sands, and Rb/Sr values are significantly higher in Fort Morgan dune field sands. Thus, based on both trace elements found in feldspars (Rb and Sr) and trace elements in heavy minerals (Ti and Zr), we conclude that South Platte River sediments are the most likely source of Fort Morgan dune sands.

The source of sands for the Wray dune field is not as apparent as for the Fort Morgan dune field, at least on the basis of geomorphic setting (Fig. 1). Eolian sands could be derived from the Ogallala Formation, which underlies the area northwest of the Wray dune field, although uncemented sand is not abundant on the surface of this caprock-controlled upland. Wray dune sands, like Fort Morgan dune sands, however, have Ti/Zr values that are much less variable than Ogallala Formation sands, and Rb/Sr values that are higher than Ogallala Formation sands (Fig. 17). In contrast, Wray dune sands

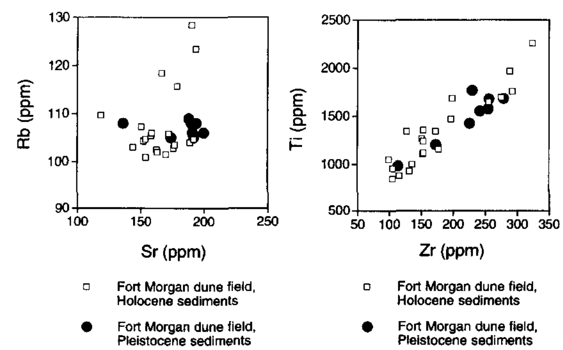

Fig. 15. Plots of Rb, Sr, Ti, and Zr contents for Holocene vs. Pleistocene eolian sands from the Fort Morgan dune field.

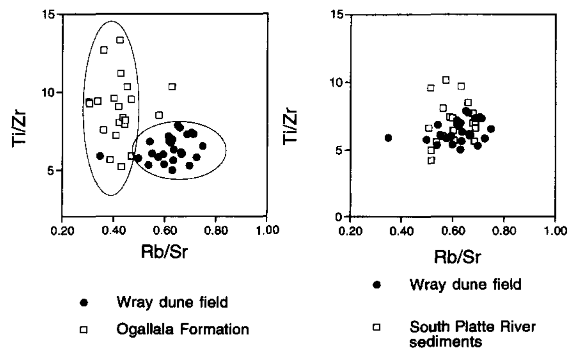

Fig. 17. Plots of Ti/Zr and Rb/Sr values for sands from the Wray dune field, the Ogallala Formation, and the South Platte River.

have Ti/Zr and Rb/Sr values that are not significantly different from South Platte River sediments. We conclude from these data that the Wray dune sands are also derived from the South Platte River. This conclusion is supported by particle size data, which show that Wray dune sands, farther downwind from the South Platte River, are generally finer than Fort Morgan dune sands, close to the South Platte River (Fig. 11).

Numerous potential bedrock units are present to the north or northwest of the Greeley dune field, including the Ogallala Formation, the Arikaree Group, the White River Group, the Laramie Formation, and the Fox Hills Sandstone. In addition, the North Platte River is found to the north of the Greeley dune field, and is a potential distant source of sand. As discussed earlier, formations of the White River Group can be eliminated as potential sand sources because these formations are mostly siltstones and contain little sand. The Fox Hills Sandstone has a very limited areal extent near the Greeley dune field, and where we observed it, it is very well cemented. Secondary calcite, abundant in the Fox Hills Sandstone, is absent in the Greeley dune sands, and, thus, the Fox Hills Sandstone can be eliminated as an important source.

The long-distance transport of sands from either the Arikaree Group or the North Platte River in Wyoming and western Nebraska could be the sources of sediment for the Greeley dune field. Ti and Zr contents and Ti/Zr values for both of these sources are not significantly different from those in the Greeley dune field. Ba/Sr and Rb/Sr values, however,

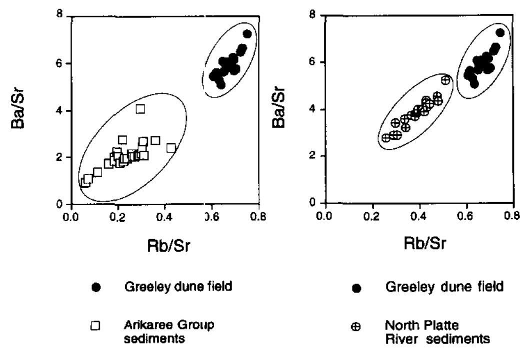

Fig. 18. Plots of Ba/Sr and Rb/Sr values for sands from the Greeley dune field, the Arikaree Group, and the North Platte River.

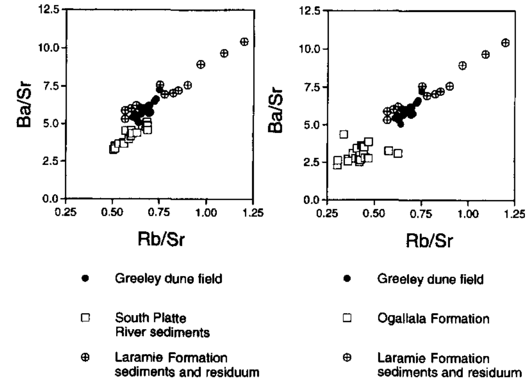

Fig. 19. Plots of Ba/Sr and Rb/Sr values for sands from the Greeley dune field, the Laramie and Ogallala Formations, and the South Platte River.

are significantly higher in the Greeley dunes than they are in either the Arikaree or North Platte sediments (Fig. 18). For sources closer to the Greeley dune field, Ogallala Formation sediments and South Platte River sediments also have significantly lower Ba/Sr and Rb/Sr values than the Greeley dunes (Fig. 19). Laramie Formation sediments and residuum show a greater range of variability for both Ba/Sr and Rb/Sr compared to Greeley sands, but overlap the range for the dunes and many have higher values. From all of these data we conclude that two possibilities exist: (1) the Laramie Formation is the dominant source of the Greeley dunes, or (2) some combination of the Laramie Formation and any other source could explain the composition of the Greeley dunes.

6. Dune forms and wind regimes

Most late Holocene parabolic dune arms in the Fort Morgan dune field and in the Colorado portion of the Wray dune field point ~ N35°W, indicating paleowinds that came from the northwest (Muhs, 1985). In the present study, we measured orientations of approximately 200 late Holocene dunes in the Greeley dune field and the Nebraska portion of the Wray dune field, in addition to approximately 300 late Holocene dunes measured by Muhs (1985). These data show results similar to those of the earlier study and indicate northwesterly paleowinds in the Nebraska portion of the Wray dune field. The mean orientation of dune arms in the Greeley dune field is

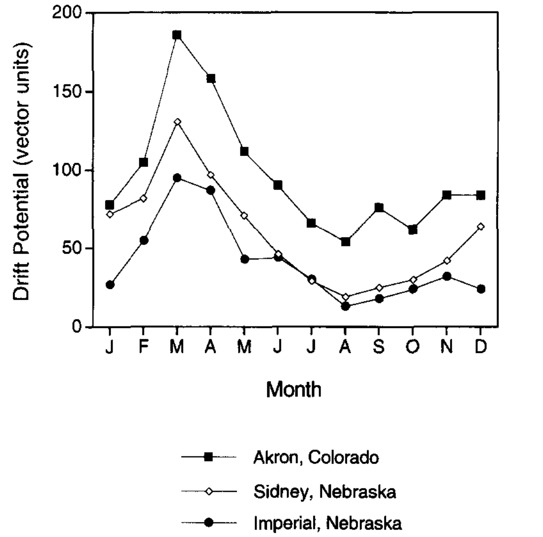

Fig. 20. Plot of monthly values of drift potential (DP) for three localities adjacent to northeastern Colorado dune fields.

N27°W (Fig. 1). It is pertinent to see if our conclusions about source sediments are consistent with paleowind data and to compare both with modern wind data.

Wind regimes as they apply to the formation of sand dunes and sand sheets are best defined in terms of sand-moving potential, expressed graphically as sand roses (Fryberger and Dean, 1979). Fryberger and Dean (1979) define several parameters from sand rose data: drift potential (DP), which is the scalar sum of all sand-moving winds, regardless of direction; resultant drift potential (RDP), which is the vector sum of all sand-moving winds and will always be less than or equal to DP; and resultant drift direction (RDD), which is the net direction of sand movement. Calculation of DP, RDP, and RDD require fairly detailed wind data. We were able to find data for only six weather stations that surround the three dune fields in northeastern Colorado and southwestern Nebraska (Fig. 1). Periods of record vary greatly and are not long for any of the stations. Akron, CO; Imperial, NE; and Sidney, NE, have only 5-year records from the early 1950s, whereas Goodland, KS, and Cheyenne, WY, have records from 1965 to 1978. Hays Center, NE, has a record of slightly less than three years, from 1948 to 1950. All stations can be considered to be in high-energy wind regimes. The drift potentials of these localities in the Great Plains are among the highest of those reported for anywhere in the world (Fryberger and Dean,

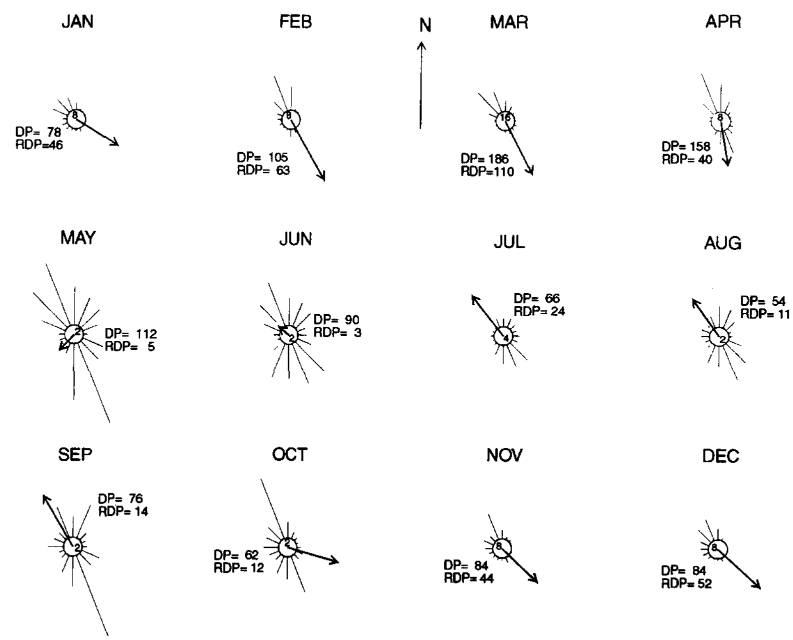

Fig. 21. Monthly sand roses for Akron, Colorado.

1979). Drift potentials are highest in the spring months of March, April, and May and lowest in the late summer and early fall (Fig. 20). Paleowinds from the northwest, inferred from dune orientations, are in generally good agreement with RDDs derived from the sand roses; a general northwest-to-southeast drift of sand is implied for all stations surrounding the three dune fields (Fig. 1).

Dune orientations, dune field distribution, and source areas identified by trace element geochemistry are in good agreement with RDD data for all dune fields. Concentrations of trace elements of sands in the Fort Morgan dune field are consistent with a South Platte River source, which is expected given the geographic location of the dune field, dune orientations, and modern RDD data. Geochemical data also indicate a South Platte River source for the Wray dune field, which is consistent with dune orientations and RDD data. The Greeley dune field, based on trace element concentrations, is derived solely or mostly from the Laramie Formation, which occurs mainly to the north and northwest of the dune field, and is consistent with dune orientations indicating paleowinds from the northwest. In all dune fields, summer winds are associated with a monsoonal flow of air from the southeast. Sand rose data show that southeasterly summer winds on the central Great Plains are at present sufficiently strong to move sand-sized particles (Figs. 1, 20 and Fig. 21). Northwesterly winds during the fall, winter, and spring, however, appear to have been the dominant sand-moving winds, based on dune orientations.

7. Discussion

7.1. Glacial vs. interglacial times of dune formation

A number of investigators have asserted or assumed that dune fields on the Great Plains, particularly the Nebraska Sand Hills, were last active in the Pleistocene, during full-glacial time (Watts and Wright, 1966; Wright, 1970; Warren, 1976; Sarnthein, 1978; Wells, 1983; Kutzbach and Wright, 1985). Wright et al. (1985) hypothesized that the principal dune forms in the Nebraska Sand Hills are Pleistocene, but that intensive Holocene reactivation may have occurred in some areas. All of these investigators based their interpretations on few or no radiocarbon ages. In contrast, Ahlbrandt et al. (1983) and Swinehart and Diffendal (1990) reported numerous radiocarbon ages which show that dune activity was extensive during the Holocene, particularly the late Holocene, in the Nebraska Sand Hills. Holocene radiocarbon ages for dunes and eolian sand sheets have also been reported by Johnson (1991) for the Great Bend Sand Prairie area south of the Arkansas River in Kansas, and for eastern Colorado by Forman and Maat (1990), Forman et al. (1992), and Madole (1994). Thus, an important question that arises is whether eolian sand in northeastern Colorado, and the Great Plains in general, is a predominantly glacial or interglacial phenomenon.

Stratigraphic, radiocarbon, and soil-geomorphic evidence from our study indicates at least three episodes of eolian sand deposition in northeastern Colorado. The maximum-limiting carbonate nodule radiocarbon ages of ~ 27 ka and the minimum-limiting Clovis-age artifacts of ~ 11 ka for sand sheet deposition agree well with the timing of late Wisconsin (Pinedale) glaciation in the Colorado Front Range, estimated to be ~ 30 ka to ~ 12 ka (Madole, 1986a). This age estimate is consistent with minimum-limiting radiocarbon ages of ~ 9600 yr BP for cross-bedded eolian sands in the Fort Morgan dune field. Radiocarbon and thermoluminescence ages reported by Madole (1986b), Forman and Maat (1990), and Forman et al. (1992) indicate possible eolian activity in the mid-Holocene, although data from the latter study are based on a single, isolated section outside of the Fort Morgan dune field, and may not be representative of eolian history within the main part of the dune fields studied here. In the Greeley dune field, an eolian sand sheet deposit with a weak Bt horizon is probably younger than ~ 11 ka, and has a minimum-limiting radiocarbon age of 3.6 ka. This sand sheet was probably deposited during the early or middle Holocene. The youngest episode of eolian deposition is represented by parabolic dunes and sand sheets with A/AC/C profiles; based on radiocarbon data presented here and in Madole (1994), eolian sand in these areas was active in the past 1500–1000 yr. Thus, eolian sand deposition apparently took place between 27 ka and 11 ka, sometime between 11 ka and ~ 4 ka, and during the past 1.5 ka. These periods of eolian sand deposition correspond fairly closely to Madole's (1995) scheme of three allostratigraphic units of eolian sand for eastern Colorado, based on bedform type, topographic expression of dunes, and degree of soil development. Based on a compilation of data from modern soil surveys, older eolian sands, which include all those deposits with Bt horizons, regardless of thickness (soil of the Vona, Osgood, Julesberg, Haxton, Manter, and Truckton series) cover ~4800 km^2 in the Greeley, Fort Morgan, and Wray dune fields. Based on the same soil surveys, dunes and sand sheets with A/AC/C soil profiles cover ~7700 km^2. Thus, latest Holocene eolian activity was also extensive in northeastern Colorado and southwestern Nebraska.

General circulation models (GCMs) provide data on possible climatic conditions at the time of eolian sand deposition in northeastern Colorado. Based on the COHMAP GCM simulations at 18 ka, the central Great Plains (which, in this GCM, covers a region including all of Colorado, Kansas, and Nebraska, most of Wyoming, and small parts of adjacent states to the east and south) had paleoclimatic conditions significantly different from the present (Thompson et al., 1993). At full-glacial time (~18 ka), summer and winter temperatures were significantly cooler than at present, summer and annual precipitation was less than at present, and summer and annual precipitation-minus-evaporation was lower than at present. These model results are consistent with other evidence for the region. For example, fossil insects from the Lamb Spring site near Denver have AMS radicarbon ages of ~17 ka and are interpreted to indicate a cold, dry grassland or steppe environment at the Pinedale glacial maximum (Elias and Toolin, 1990). Just to the north of our study area, in southeastern Wyoming, Nissen and Mears (1990) report ice-wedge casts and sand-wedge relics of probable late Wisconsin age that are evidence for much colder, but not necessarily wetter, conditions during the last glacial maximum; overall, they interpret the wedges to indicate a windswept, permafrost environment with thin or minimal snow cover. Numerical experiments by Leonard (1989) have demonstrated that Pinedale glaciers in the Colorado Front Range could have been maintained with an 8–9°C temperature decrease without any increase in precipitation. With even greater temperature decreases, Pinedale glaciers could be maintained with a *decrease* in precipitation. All these lines of evidence suggest that eolian sand sheets in northeastern Colorado could have been deposited in a cold, arid environment during Pinedale time, with sediment supplied by glacial outwash. Péwé (1983) defines a periglacial environment as one characterized by permafrost, with mean annual air temperatures of 0°C or colder. Present mean annual air temperatures in the dune fields of northeastern Colorado are 9.0–9.5°C, so *if* Leonard's (1989) estimated temperature lowering for the Colorado Front Range can be applied to the Great Plains to the east, then it is possible that eolian sand sheets in northeastern Colorado were deposited in a periglacial environment. Whether or not periglacial conditions existed at this time cannot be determined by present evidence, but the late Wisconsin eolian sand sheet deposits of northeastern Colorado invite comparison with late Wisconsin, periglacial, outwash-derived, eolian sand sheet deposits reported for Alaska (Lea, 1990; Lea and Waythomas, 1990; Waythomas et al., 1993), Greenland (Dijkmans and Törnqvist, 1991), and northwestern Europe (Schwan, 1988).

In an earlier summary, Kutzbach (1987) reported that in the early-to-mid-Holocene (9–6 ka), GCM simulations indicate that north-central North America was warmer, had higher evaporation, and lower precipitation than the present. The more recent GCM summary by Thompson et al. (1993), however, indicates that the only statistically significant differences from the present would be warmer-than-present summer temperatures. Some of the eolian sand may have accumulated in the early or mid-Holocene under conditions where vegetation cover was diminished because of greater evaporation and lower precipitation. As described earlier, however, field evidence for a major period of eolian sand deposition during this time period is not abundant, and must await further study.

A significant conclusion from our studies is the observation that eolian sand has been active in the past ~1500 yr over an area of ~7700 km^2 in northeastern Colorado and adjacent Nebraska. Tree-ring data for drought-sensitive cedars in western Nebraska indicate that numerous droughts occurred in the past 800 yr, some of considerably greater duration than the intense 1930s and 1950s droughts (Weakly, 1962). During such droughts, vegetation

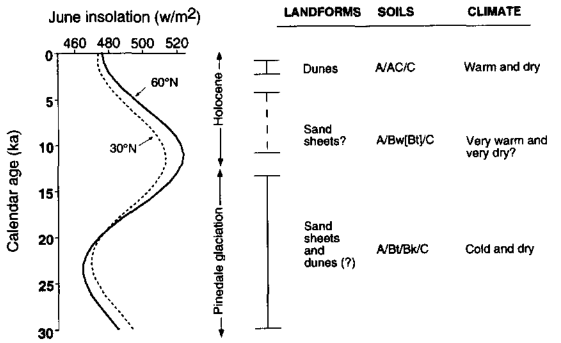

Fig. 22. Estimated times of eolian sand deposition in northeastern Colorado, inferred climates at the times of sand deposition and comparison to June insolation at the top of the atmosphere for latitudes bracketing the study area. Insolation data from Berger and Loutre (1991).

cover on dunes would be greatly diminished, and previously stabilized sand could be reactivated. We conclude, therefore, as did Muhs and Maat (1993) and Madole (1994), that northeastern Colorado is, at present, very near a climatic boundary that separates active from stable sand.

Based on this evidence, the deposition of eolian sand in northeastern Colorado can take place under a variety of climatic conditions (Fig. 22). Common to all conditions is aridity, but sand movement can occur under warm or cold temperatures, and it is likely, though not proven, that under both climatic conditions vegetation cover is minimal and winds are strong. We conclude that eolian sand activity in the region is neither an exclusively glacial nor interglacial phenomenon.

7.2. Dune field evolution

Most detailed studies of large dune fields have concentrated on low-latitude, warm-desert sand seas (Breed et al., 1979; Fryberger and Ahlbrandt, 1979; Lancaster, 1989; Pye and Tsoar, 1990) because fewer mid-latitude, cool-climate sand seas exist (some in Europe and North America are reviewed in Koster, 1988). The observations made in this study have important implications for the origin of sand seas and evolution in a semi-arid, mid-latitude environment.

The origin and subsequent degree of activity of northeastern Colorado dune fields are closely tied to the characteristics of the South Platte River. In contrast to the suggestions of Lugn (1968) and Hunt (1986), bedrock does not appear to be a significant source of sediment for dune fields in northeastern Colorado, with the exception of inputs of Laramie Formation sediments to the Greeley dune field. This conclusion is consistent with observations made by investigators who have studied low-latitude sand seas and sand sheets, where fluvial and (or) lacustrine sources of sediment are thought to be more important than bedrock sources (Wilson, 1971, Wilson, 1973; Breed et al., 1979, 1987; Lancaster, 1989; Pye and Tsoar, 1990), although examples of warm-desert sand seas can be found where no immediate fluvial source is apparent (Fryberger and Ahlbrandt, 1979).

Because trace element data presented here show that the South Platte River is the major sediment source for the dune fields, new inputs of sediment must, therefore, be controlled to some degree by fluvial activity. Shallow, braided, sandy channels can result from stream aggradation because of inputs of glacial outwash. Under warm and dry climatic conditions, however, river systems have highly variable flood flow conditions, which also results in wide, braided, sandy channels, and frequent days of no flows. Either of these climatic regimes, through effects on the South Platte River, could increase sediment supplies to dune fields or sand sheets. Historic evidence shows that the South Platte River had a wide, shallow, braided, sandy channel system in the 19th century compared to the present, largely because of human influences (Eschner et al., 1983). Thus, northeastern Colorado dune fields may be inactive today because of climatic conditions that stabilized vegetation cover and because the sand supply is limited. The observations made here may apply to other Great Plains sand seas and dune fields, such as those along the Arkansas, Cimarron, North Canadian, Canadian, and Pecos rivers.

Field evidence presented in this study and by Madole (1995) show that the latest Pleistocene eolian sands are commonly sand sheet deposits, whereas latest Holocene deposits are commonly dunes. One possible explanation for this difference is that topographically higher dunes may have been deposited during the latest Pleistocene, but were largely reworked by Holocene winds. Pleistocene sand sheet deposits, because of topographically subdued expressions and protected locations, may have escaped reworking by Holocene winds. Alternatively, if periglacial conditions existed in northeastern Colorado during full-glacial time, sand sheet deposition may have been dominant because of limitations on sand transport, and, therefore, dune-building, because of ice cementation, seasonally high water tables, and snow cover, similar to what has been described for Alaskan sand sheets of late Wisconsin age (Lea and Waythomas, 1990). Although some dunes formed in Colorado during full-glacial time (based on the evidence at the Logan County landfill shown in Fig. 9), the possible extent of full-glacial dune formation is not known.

It could be argued that Holocene dune-building is primarily the result of reworking of Pleistocene sand sheet deposits, with little or no addition of new sand. Lea and Waythomas (1990) have presented persuasive arguments in favor of this hypothesis for many Alaskan dune fields, and Castel et al. (1989) have shown that Holocene dunes in northwestern Europe were reworked from late Wisconsin sheet sands ("cover sands") as a result of human disturbances in the past ~ 2000 yr. It is likely that some reworking of Pleistocene sand sheets occurred in Colorado during the Holocene. The latest Holocene parabolic dunes, with arms pointing to the northwest, however, are often found immediately downwind of the South Platte River. Because no older sand sheet deposits occur upwind of the late Holocene dunes, the South Platte River must have been the direct source of sediments to build the dunes. Evidence compiled from observations by early explorers elsewhere in the Great Plains indicates that some historic dunes were built directly from river sediment sources (Muhs and Holliday, 1995).

Portions of the landscape in northeastern Colorado serve as corridors for sand transport, but are not loci of sand accumulation. The best example of this is the large area between the Fort Morgan and Wray dune fields (Fig. 1), where the Ogallala caprock forms a high upland surface, and no significant amount of eolian sand has accumulated. The key pieces of evidence that this broad upland serves as a sand-transport corridor are the trace element data which show that the Wray dune field is most likely derived from the South Platte River, and Wray dune orientations, which indicate a northwesterly paleowind. We hypothesize that wind speeds are probably lower upwind and downwind of the Ogallala upland, as has also been reported for the southern High Plains by McCauley et al. (1981). The locus of deposition is, therefore, upwind of and in the lee of the upland surface. The Fort Morgan and Wray dune fields have resulted from this topographic control (Fig. 23). This explanation is supported by a comparison of wind data for Akron, Colorado, upwind of the Wray dune field, and Goodland, Kansas, downwind of the same dune field (Fig. 1). Although DP is high at both localities (Akron DP = 1087; Goodland DP = 554), RDP is lower at Goodland (62 vs. 322 for Akron), in part because of greater directional variability of wind at Goodland (Fig. 1). Fryberger and Ahlbrandt (1979) used a similar mechanism as part of the explanation for the geography of the Grand Erg Oriental in Algeria. Accumulations of eolian sand upwind of and in the lee of major bedrock topographic barriers have also been illustrated in the Sahara in western Mauritania and in the Ala Shan Desert of the People's Republic of China (Breed et al., 1979).

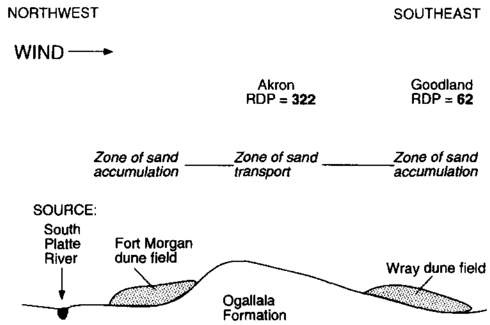

Fig. 23. Schematic cross-section D–D′ (location shown in Fig. 1) from the South Platte River near Sterling, Colorado, to the Wray dune field near Wray, Colorado, showing locations of dune fields relative to the Ogallala caprock upland, and RDP values for selected localities.

8. Conclusions

Stratigraphic relations, soil-geomorphic data and AMS radiocarbon dating allow recognition of at least three periods of eolian sand deposition in northeastern Colorado. Eolian sand sheet deposits have well developed A/Bt/Bk/C soil profiles, and can be traced below adjacent high-relief parabolic dunes with minimally developed soils. Sand sheet sediments, deposited between ~ 27 ka and ~ 11 ka, were probably derived from Pinedale glacial outwash of the South Platte River, possibly under periglacial conditions. During warmer and drier conditions of the early and middle Holocene, sand sheet sediments may also have been deposited, based on relative degrees of soil development and minimum-limiting radiocarbon ages. The record of eolian deposition during this period, however, is not well constrained geochronologically and not well expressed geomorphically. Late Holocene dune deposition is well documented by extensive parabolic dunes with minimally developed A/AC/C or A/C soil profiles and maximum-limiting radiocarbon ages of 1000–1500 yr BP. Thus, eolian activity is not limited to glacial conditions, as hypothesized by many previous workers, nor strictly to interglacial conditions. It is not known if Pleistocene and Holocene episodes of eolian sand movement were synchronous among the three dune fields, except to the extent that all dune fields had extensive activity during the latest Pleistocene, and again in the past 1500–1000 yr.

Previous generalizations have concluded that eolian sands on the Great Plains were derived mainly from Ogallala bedrock. Ratios of trace elements and particle size data, however, indicate that the Fort Morgan and Wray dune sands are derived from the South Platte River, even though the two dune fields are separated by a large, sand-free caprock upland underlain by the Ogallala Formation. Northwesterly winds apparently transported sand over the escarpment on the northwestern side of the upland, and sand accumulated in the lee of the upland on its southeast side. Ratios of trace elements indicate that the Laramie Formation is the most likely source for sands in the Greeley dune field, which occurs to the north of the South Platte River. Sediment sources are consistent with estimated paleowind directions, based on dune orientations, and do not differ significantly from the directions of modern winds that are capable of moving sand-sized particles. Dunes in northeastern Colorado demonstrate the importance of river sediments as sources of eolian sand. It follows, therefore, that because present drift potentials in the region are among the highest in the world, the present inactivity of the dunes may be a function of supply limitations as well as sparse cover of vegetation.

Acknowledgements

This study was supported by the U.S. Geological Survey's Global Change and Climate History Program. We thank the Logan County Landfill, the Lost Creek Cattle Company, Eagle's Nest Ranch, and the National Hog Farms for cordial access to their land. The radiocarbon measurements were made using the accelerator at Lawrence Livermore National Laboratory. The National Climatic Data Center, Asheville, NC provided data needed to generate sand roses. We thank J. Aleinikoff and C. Hedge for helpful discussions of trace element geochemistry, and E. Leonard for helpful discussions of paleoclimate. T. Ahlbrandt, D. Loope, R. Madole and C. Breed read an earlier version of the paper and made constructive comments for its improvement.

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