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Distribution of Late Quaternary Wind-Deposited Sand in Eastern Colorado

By Richard F. Madole, D. Paco VanSistine, and John A. Michael

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(Facing page, top) Sand sage (*Artemisia filifolia*) is the dominant species of sagebrush in eastern Colorado. As its common name implies, this small shrub thrives on sand, and thus it is particularly abundant in the deposits shown on the map. The vegetation shown in figure 1A on the map sheet is typical sand sage prairie. *Drawing by Carol Quesenberry, USGS.*

(Facing page, bottom) View across the Cimarron River valley near the Oklahoma–Colorado border. Typical vegetation of the short-grass prairie covers the upland in the distance, whereas more luxuriant vegetation covers the valley floor. Wind power is harnessed to lift groundwater to the stock tank in the foreground. Most streams in eastern Colorado, including several that are called rivers, are ephemeral (do not flow year round). Consequently, over much of the region, groundwater is relied on to meet agricultural and domestic needs. *Photograph by Craig Brunstein, USGS.*

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Introduction

This map is a product of a study of the geomorphology and stratigraphy of sand sheets and dune fields in eastern Colorado. The study was made to obtain information about the number, frequency, and spatial extent of droughts, especially those that predate historical and instrumental records. The study also sought to identify areas that have drought-related land and resource management issues. Although droughts cannot be prevented, an improved understanding of drought frequency and magnitude allows society to adopt strategies to mitigate their negative socioeconomic consequences.

Eolian sediment blankets about 60 percent of Colorado east of the Rocky Mountains (Madole, 1995a). Of this eolian cover, about 30 percent is sand and 70 percent is loess. The presence of eolian sand imposes limits on land use, especially where deposits are thicker than 1 m. Most eolian sand in eastern Colorado is stable at present, but it can be destabilized easily by land-use practices that disturb vegetation (fig. 1 on map sheet). The sand is stable now, in spite of strong winds, primarily because of the vegetation cover. Moisture and the presence of vegetation dramatically increase the threshold velocity at which wind entrains sand grains.

A windstorm in February 1977 eroded as much as 600 tons of sediment per acre in parts of southeastern Colorado in a 24-hour period. This amount of sediment is considered to be equivalent to that removed during 30 years of typical erosion (Curry, 1977, in McCauley and others, 1981). Severe windstorms and sediment erosion have occurred in this region before. During the "dirty 30s," a term used to describe the 1930s drought, similar severe dust storms were referred to as "black blizzards" (see photograph of a dust storm in fig. 2 on map sheet).

The February 1977 windstorm also impacted southwestern Kansas and areas along the Texas–New Mexico border. Certain land-use practices in this region clearly contributed to the extreme wind erosion caused by this storm. McCauley and others (1981) described these land-use practices, which among other things involved attempts to produce crops on irrigated sand dunes, plowing and planting crops parallel to the prevailing wind, removing natural vegetation from rangeland on eolian sediment and converting it to grain production, installing center-pivot irrigators on fields that included bare sand, and removing wind breaks and shelter belts (trees planted after the 1930s drought) to facilitate installation of center-pivot irrigators.

Little bluestem (*Andropogon scoparius*), a perennial grass found on plains and mountain areas of Colorado. *(Drawing by Margaret Austin, USDA.)*

Blue grama (*Bouteloua gracilis*), the State grass of Colorado, is symbolic of the short-grass prairie. (*Drawing by Jennifer Shoemaker, USGS.*)

Why the Map Was Made

The map was made because the project required a regional overview of the distribution of eolian sand, and previously published maps did not meet this need. The 1:500,000-scale geologic map of Colorado (Tweto, 1979) does not distinguish eolian sand from loess, and it under represents the amount of loess and eolian sand in eastern Colorado (Madole, 1995a). Eolian deposits on the State geologic map were compiled from small-scale maps (mostly 1:250,000), which are the only sources of geologic data for much of the region. These maps depict dune sand accurately, but commonly omit large areas of sheet sand. In some places on the maps, sheet sand may have been omitted intentionally to emphasize bedrock geology, particularly in areas where eolian sand is extensive but thin. In other areas, however, eolian sheet sand probably was not recognized because it lacks distinctive geomorphic expression and exposures are scarce. Also, distinction of eolian sand from sheetwash alluvium and sandy residuum can be difficult.

How the Map Was Made

The distribution of eolian sand shown on this map is a synthesis of information from county soil maps and geologic maps, supplemented in some places by photogeologic mapping and field study. County soil maps were the principal sources of information in about 75 percent of the map area because they are published at large scales (1:15,840 to 1:31,680) and are available for most of the region. Geologic maps were secondary sources of information, except in Kit Carson, Lincoln, and Las Animas Counties, where county soil maps were not available, and in parts of northwestern Elbert County, northern Douglas County, westernmost Arapahoe and Adams Counties, and El Paso County that are underlain by the Dawson Formation (fig. 3), which produces large amounts of sandy surficial material of diverse origins (residuum, alluvium, and eolian sand). The genesis of sandy surficial materials in areas where the Dawson Formation is the surface bedrock can be difficult to determine even in the field.

Some soil series are closely related to specific surficial geologic units. For example, with few exceptions, the Valent series (Ustic Torripsamments) is developed in Holocene eolian sand, and the Vona series (Ustollic Haplargids) is developed in Pleistocene eolian sand (table 1). However, other soils, such as the Bijou series (Ustollic Haplargids) and Bresser series (Aridic Argiustolls), developed in both alluvial and eolian sand, and soils of the Truckton series (Aridic Argiustolls), formed in an even wider range of sandy parent materials that include alluvium, eolian sand, and residuum (Crabb, 1980; Larsen and Brown, 1971; Sampson and Baber, 1974; and Larsen, 1981).

Figure 3. Generalized geologic map of eastern Colorado (modified from Tweto, 1979). Knowledge of bedrock geology is essential to interpret the sandy surficial deposits in eastern Colorado. *(See p. 6 for a discussion of bedrock geology and sandy surficial deposits.)*

Table 1. Soil series developed in eolian sand and sandy alluvium in eastern Colorado counties.

[Soil series are described in County soil reports. See Sources of Map Data for references. A, alluvium; ES, eolian sand; ESb, eolian sand buried by another deposit; ESt, eolian sand, thin cover only; L, loess; Lb, loess buried by another deposit; sdy, sandy; *, initially mapped as the Tivoli series, a name now restricted to soils developed in a warmer climate; forward slash (/) indicates one unit overlying another—unit to left of slash overlies unit to right of slash]

Knowledge of regional bedrock geology is essential to interpret surficial geology from soil maps. Identification of sandy surficial deposits on county soil maps usually is easy in areas of eastern Colorado that are underlain by the Pierre Shale or by shale and claystone of the Laramie Formation. Those rocks constitute the surface bedrock in much of the region (fig. 3). Most residuum derived from the Pierre Shale is clayey. Consequently, sandy soils in areas underlain by this formation generally indicate the presence of allochthonous material (material formed elsewhere and transported to its present location). However, in some places, sandstone beds in the upper part of the Pierre Shale produce sandy residuum. The same is true of the Dawson Formation, parts of the Fox Hills Sandstone, and some sandstone beds in the Laramie Formation. Still, except for the Dawson Formation, the residuum developed from the sandstone beds in these formations typically is thin (1 meter or less), and the soils developed in it are not likely to be confused with those developed in either eolian sand or sandy alluvium.

It is particularly difficult to identify the genesis of surficial deposits from soil maps in areas where soil parent materials are derived from thick sections of arkosic (feldspar rich) sandstone and very fine pebble conglomerate in the Dawson Formation. This formation and correlative strata in the Denver and Arapahoe Formations (fig. 3) consist of clastic material, nearly 1 kilometer thick, that was deposited in the Denver Basin when the Southern Rocky Mountains were being elevated during Laramide time, about 70–45 Ma (Tweto, 1975).

During the late Cenozoic, all Laramide basin-fill strata were eroded from the northernmost part of the Denver Basin. However, in the southern part of the basin, between Denver and Colorado Springs, only the upper part of the Dawson Formation was eroded. Thus, a nearly complete section of the Dawson Formation remains on the higher (western) part of the interfluve between the South Platte and Arkansas Rivers. Much of the sandstone and conglomerate of the Dawson Formation is weakly cemented. Consequently, that formation is the source of large quantities of sandy residuum and alluvium. Alluvium derived from the Dawson Formation was the dominant source of the eolian sand in the Black Squirrel and Big Sandy areas south and southeast of the Palmer Divide, the local name for the western part of the South Platte River–Arkansas River drainage divide. It also was the principal source of belts of eolian sand shown on the map along the small valleys (Box Elder, Kiowa, and Bijou Creeks) that drain from the Palmer Divide north to the South Platte River.

Arkosic sand is also the parent material of the Bijou, Bresser, and Truckton soils, the principal soil series in the map area that developed in sandy material of more than one origin (table 1). In spite of their polygenetic parent materials, soil series, such as the Bijou, Bresser, and Truckton, can be used to identify the origin of surficial deposits. Three criteria are used to determine whether these soil series are developed in eolian sand, alluvium, or residuum: (1) position in the landscape, (2) shape and orientation of bodies of sandy material on soil maps, and (3) associated soil series.

The position of sandy soils in the landscape is a particularly important clue to the likely genesis of the parent material. Except for old alluvial deposits that are inverted in the landscape and are not related to present-day streams, the distribution of alluvial parent materials parallels existing drainage systems. In contrast, the trend of eolian sand deposits parallels the direction of the dominant sand-transporting wind. Generally, it is at a high angle to, if not orthogonal to, the trend of stream channels that were the sources of most of the eolian sand (figs. 4 and 5). Unlike alluvium, eolian sand ascends hillslopes from valley floors to adjacent interfluves, but it tends not to do so equally on both sides of a valley. It is widespread on the leeward side of valleys, but is sparse or absent on the windward side (figs. 4 and 5). If the soil series on valley side-slopes and adjacent interfluves differ from those on late Pleistocene terrace deposits in the same area, they probably are developed in eolian sediment. For example, if soils of the Bresser series extend across interfluves between valleys in which the Nunn or Manzanola soil series are developed in terrace deposits, the parent material of the Bresser series is probably eolian. In contrast, if soils of the Bresser series or, more commonly, the Bijou series, parallel streams, they probably are developed in Pleistocene stream-terrace deposits. However, eolian sand caps Pleistocene stream terraces in some places.

The shape and orientation of bodies of sandy material on soil maps also help to identify parent material genesis. Eolian deposits tend to be elongated in the direction of the dominant sand-transporting winds, and narrow bands of different soil series alternate repetitively in a direction normal to the dominant wind direction (fig. 5). The bands reflect differences in parent materials, slope and topography, drainage, and vegetation related to eolian bed forms. In addition, the upwind and downwind edges of eolian sand deposits tend to be scalloped, and the axes of apices and re-entrants along deposit margins tend to parallel the direction of the dominant sand-transporting winds. The margins of the South Platte and Wray sand areas (see map) reflect this pattern on a regional scale. These areas also illustrate the fact that deposits of eolian sand are most extensive and are elongated on the downwind sides of sandy stream channels, especially where the channels are at nearly right angles to the prevailing wind.

Contours (in meters) drawn on the top of Precambrian rock define the extent and depth of the Denver Basin (after Hansen and Crosby, 1982, U.S. Geological Survey Professional Paper 1230). Shaded areas are Precambrian rock-cored mountains that bound the west edge of the basin. Mountains in western Colorado are not shown. During late Cenozoic time, Laramide basin-fill sediment (Denver, Arapahoe, and Dawson Formations) was eroded completely from the northern part of the Denver Basin, but not the southern part of the basin (*see fig. 3*).

(Facing page) Physiographic subdivisions of eastern Colorado. Eastern Colorado encompasses all of the Colorado Piedmont section and parts of the High Plains and Raton sections of the Great Plains physiographic province (Fenneman, 1931). The High Plains are defined as that part of the Great Plains underlain by Miocene fluvial rocks (Ogallala Formation). The Colorado Piedmont section is distinguished by having been stripped of Miocene rocks by the South Platte and Arkansas Rivers and their tributaries and by having a surface that, along its boundaries, is topographically lower than the adjoining regions, except where the Arkansas and South Platte rivers leave it. Prominent bluffs separate the Colorado Piedmont from the High Plains of Wyoming to the north, and lower, less definite escarpments separate it from the High Plains to the east. Similar escarpments are lacking, however, in most places between the Colorado Piedmont and the Raton section. Over much of this area, the boundary is mostly arbitrary as slopes ascend gradually across a transition zone that is as much as 30–40 kilometers wide. The Raton section is distinguished by several extensive lava-capped mesas that stand much higher than the terrain in the other sections of the Great Plains.

In addition to Miocene rocks, older Cenozoic rocks (Paleocene, Eocene, and Oligocene) also have been eroded from the Colorado Piedmont, except on the higher, western part of the interfluve between the South Platte and Arkansas Rivers. Much of the Colorado Piedmont is underlain by Upper Cretaceous shale, claystone, and siltstone that have been eroded into low and rolling topography. Maximum relief is about 450 meters, which is the maximum height of the divide between the South Platte and Arkansas Rivers. As much as 300 meters of relief exists between the South Platte River and the line of bluffs that forms the northern boundary of the region.

Figure 5. Block diagram showing relations between bedrock, surficial deposits (eolian sand and alluvium), and soil series in Otero County south of the Arkansas River (after Larsen and others, 1972). The soils series form in the uppermost part of the eolian sand and alluvium. Most eolian sand in eastern Colorado is noncalcareous. However, the parent material of the Dwyer soil is calcareous because it was derived from calcareous alluvium and was not blown far enough for the $CaCO_3$ coatings on grains to be removed by impact and abrasion during transport.

Figure 4 (facing page). Soil and geologic map of an area in Adams County just north of Denver (modified from Sampson and Baber, 1974). Note that soils on the windward (northwest) side of the river are developed in bedrock residuum, whereas on the downwind side most soil is developed in eolian sand. Also note the general linearity of soil units and their orientation with respect to the river valley and dominant paleowind direction. The eolian sand was derived from the flood plain of the South Platte River. The last major episode of eolian sand deposition in this area was during the late Pleistocene.

Map Accuracy and Reliability

Inaccuracies in the data sources used to make this map and in the compilation of those data are small compared to inaccuracies imposed by the map scale (1:700,000). Isolated outliers of eolian sand that are less than 1 kilometer wide cannot be shown at the scale of this map, regardless of their length. Likewise, narrow, elongate re-entrants or inliers of bedrock, residuum, loess, and alluvium in small valleys within larger areas of eolian sand cannot be shown on the map. Many small deposits of eolian sand that are beyond the mapped margins of the main bodies of eolian sand are omitted, as are small areas of noneolian materials within large areas of eolian sand. In many places, especially Baca County, groups of small sand deposits are mapped as a single deposit. Also, contacts are drawn through areas of noneolian materials in order to include as many small, discontinuous deposits of eolian sand as possible, rather than to omit them because they are too small to show separately. The small scale of the map requires that highly intricate and irregular contacts be generalized (smoothed). It also precludes showing different ages of eolian sand separately, because many deposits are small and, in most areas, units of different ages are interspersed in complex patterns.

Eolian sand probably is depicted less accurately in Kit Carson, Lincoln, and Las Animas Counties than in other areas because large-scale soil maps of those counties had not been published when this map was compiled. Small-scale (1:250,000) geologic maps were the primary data sources for most of Lincoln and Kit Carson Counties (see "Index Showing Sources of Map Data" in this pamphlet), and STATSGO map data were relied on for the distribution of most eolian sand in Las Animas County. The Natural Resources Conservation Service compiled the STATSGO (State Soil Geographic Data Base) units at a scale of 1:250,000. Typically, individual units include several soil series and, thus, are not as closely related to geologic units as the individual soil series on county soil maps. The differences in detail available from county soil maps, compared to STATSGO maps, explains why the boundaries of deposits in Baca County are more intricate than the boundaries in Las Animas County. The limits of eolian sand in Baca County are from McLaughlin's (1954) 1:62,500-scale geologic map, rather than the published county soil map of Woodyard and others (1973). The distribution of eolian sand on McLaughlin's map was compiled from an older, unpublished soil map on which windblown sand was shown in more detail than on the map of Woodyard and others.

Drought Frequency

Historic and Protohistoric—The term "Dust Bowl" was introduced in the 1930s to describe an area of nearly 100 million acres in the Great Plains where drought is frequent and wind erosion is particularly severe (Hurt, 1981). Much of eastern Colorado is within the Dust Bowl (fig. 6 on map sheet). Some part of the Dust Bowl has experienced drought in nearly every decade since instrumental weather data began to be recorded systematically in the late nineteenth century. Particularly severe droughts impacted the region during the 1930s, 1950s, and, to a lesser degree, the 1970s. Accounts in diaries and newspaper articles indicate that severe droughts also occurred in the nineteenth century (Rosenberg, 1980; Muhs and Holliday, 1995), prior to establishment of weather stations. Dendrochronologic (tree-ring) data from areas outside of Colorado, but along or relatively near the margin of the Great Plains, reveal a pattern of recurring drought that extends back several centuries (Fritts, 1983; Stockton and Meko, 1983; Blasing and Duvick, 1984; Stahle and others, 1985; Stahle and Cleaveland, 1988; Cleaveland and Duvick, 1992; Meko, 1992; Sieg and others, 1996).

Prehistoric Droughts—Deposits of windblown sand are indicators of prehistoric droughts. Widespread wind erosion of sand coincides with times of persistent drought that minimized soil moisture and severely reduced plant cover. As soil moisture and vegetation decline, so does the threshold velocity required for wind to mobilize sand grains. Unlike instrumental and dendrochronological measurements, deposits of windblown sand only record droughts that persisted long enough to develop conditions that were conducive to extensive mobilization of sand by wind. None of the historic droughts were that severe, although sand was reactivated locally during the 1930s drought (Muhs and Maat, 1993) and, presumably, also during earlier droughts (historic and prehistoric) of similar magnitude.

Conditions necessary to generate new dune fields or to cause existing dune fields to migrate apparently require what Woodhouse and Overpeck (1998) referred to as "megadroughts." At least three megadroughts occurred in eastern Colorado during the past 1,300 years. Woodhouse and Overpeck (1998) discuss a variety of data that indicate megadroughts occurred in the thirteenth and sixteenth centuries, and as discussed later, geomorphic and stratigraphic data indicate that wind mobilized sand on a regional scale between A.D. 675 and 1020 and again between A.D. 1250 and 1650. The latter interval includes the droughts of both the thirteenth and sixteenth centuries.

During the droughts of the past 1,300 years, sand was mobilized in about two-thirds of the approximately 26,370 square kilometers of eolian sand (table 2) in eastern Colorado. Model simulations of atmospheric circulation indicate that average surface temperature and estimated annual precipitation varied only slightly in the region during the past 1,300 years (Kutzbach, 1987). Given that climate has changed little during a time that wind has mobilized sand over large areas suggests that under the present climate, eastern Colorado is near the threshold of widespread mobilization of sediment by wind. This underscores the need to carefully manage land uses that disturb the deposits shown on this map.

Table 2. Size, thickness, and mineralogy of eolian sand deposits in eastern Colorado.

Eolian Sand Sources, Transport Directions, and Properties

Sediment Sources

Gilbert (1896), working along the Arkansas River and in the Black Squirrel sand area, was the first to conclude that stream deposits were the primary source of eolian sand in eastern Colorado. Since then, many studies have reached this conclusion (Fisher, 1906; Toepelman, 1924; Hunt, 1954; Scott, 1962, 1982; Smith and others, 1964; Coffin, 1967; Reheis, 1980; Shroba, 1980; Muhs, 1985; Madole, 1994, 1995a; Muhs and others, 1996). The conclusion is based primarily on the fact that eolian sand is most widespread on the leeward sides of valleys, and it tends to be thickest near the valley (its source) and become progressively thinner downwind from the valley. Some studies have documented this relation more rigorously by examining sand mineralogy and geochemistry, and by showing that grain size decreases systematically downwind from valley-floor sediment sources (Coffin, 1967; Reheis, 1980; Shroba, 1980; Muhs, 1985; Muhs and others, 1996; Muhs and others, 1999). Although streams were a principal source of eolian sand, they were not the only source. In some places, eolian sediment also was derived from residuum of Upper Cretaceous and Tertiary sedimentary rocks.

Paleowind Directions

Conclusions about paleowind directions are based chiefly on dune form and orientation. The shape and orientation of individual eolian sand areas shown on the map reflect the direction of the dominant sand-transporting winds. The paleowind directions shown on the map (arrows) were determined primarily from the orientation of middle and late Holocene parabolic dunes. North of the Arkansas River, the dominant sand-transporting winds were northwesterly; south of the river they were southwesterly. The location and geometry of sand sheets indicate that paleowind directions in latest Pleistocene time were similar to those in the Holocene (Madole, 1995a; Madole, Muhs, and Holliday, 1996).

At present, prevailing winds over most of northeastern and east-central Colorado and adjoining parts of Kansas and Nebraska are northwesterly from October to April and southeasterly from June through September (Muhs and others, 1996). Southeasterly winds bring moisture inland from the Gulf of Mexico and are the reason why 70–80 percent of the annual precipitation in eastern Colorado presently is received between April and September (Berry, 1959).

During latest Pleistocene time, the South Platte and Arkansas Rivers looked much like this present-day Alaskan river. Then, the valleys of the South Platte and Arkansas Rivers were not incised, as they are today, and they had flood plains that were many times wider than their present flood plains. Broad, braided streams occupied these valleys, and during winter months, the streams shrank to rivulets, leaving large expanses of bare, dry sand exposed to wind erosion. *Photograph courtesy of U.S. Geological Survey Photographic Library.*

(Facing page, top) The valley floor of the present South Platte River is typically 6–12 meters lower than late Pleistocene terrace deposits, and the width of its flood plain is only a small fraction of Pleistocene flood-plain widths. Diversions and returns of water used for irrigation have altered the character of the present channel and flood plain. Channel narrowing has allowed gallery forests composed primarily of plains cottonwood to develop along the channel sides. *Photograph by R.F. Madole*.

(Facing page, bottom) View of plains south of Lamar, Colorado, in Prowers County, showing examples of old and new devices for harnessing wind power. Windmills have been used to pump water in this region since the late nineteenth century, and wind farms, of which the wind turbines shown here are a part, have been supplying electricity to Colorado commercially since March 1998. The Great Plains are one of the windiest regions in the United States (Gillette and Hanson, 1989), and present-day wind velocities in most areas exceed what is required to erode loose, dry, bare sand 30–60 percent of the time (Muhs and Maat, 1993). At present, wind erosion of sand in eastern Colorado is minimal primarily because of the vegetation growing on it. Moisture and the presence of vegetation dramatically increase the threshold velocity required for wind to mobilize sand grains. Thus, land-use practices that disturb vegetation can trigger serious wind erosion. Model simulations of atmospheric circulation indicate that, under the present climate, eastern Colorado is near the threshold of widespread mobilization of sediment by wind. *Photograph by Craig Brunstein, USGS.*

Sediment Properties

Deep exposures of eolian sand are comparatively rare in eastern Colorado. Consequently, statements about deposit thickness, mineralogy, and texture are based on observations at a relatively small number of localities. Deposit thickness is particularly difficult to assess because even in deep exposures the bottom contact generally is not well exposed. Eolian sand commonly overlies fluvial sand, and the contact between the two is difficult to distinguish, if not much of the fluvial sand is exposed. The maximum thicknesses reported in previous publications (table 2) are based primarily on borehole data from water-supply investigations. Some of the reported thicknesses may include sand of noneolian origin. Nevertheless, the maximum eolian sand thicknesses reported in previous publications are similar to estimates based on the assumption that maximum sand thickness is comparable to the topographic relief within dune areas, or, in other words, dune heights equal maximum sand thickness.

The maximum thickness of eolian sand in most areas of eastern Colorado probably is between 20 and 40 meters. However, except for parts of the Wray dune field, the Black Squirrel area, and the eastern part of the South Platte sand area, the typical thickness of eolian sand is probably between 3 and 10 meters. The most extensive areas of thick sand and high dunes are in the Wray dune field and the easternmost part of the South Platte sand area.

Quartz is the dominant mineral in all eolian sand areas, and feldspar also is present in quantities that vary with sediment source. For example, in the South Platte sand area, feldspar is more abundant in eolian sand south of the South Platte River than in eolian sand north of the river (Muhs, 1985; Muhs and others, 1996). In some places south of the river, potassium feldspar is reported to be so abundant that it colors the sand reddish-orange (McGovern, 1964). The eolian sand south of the South Platte River was derived chiefly from the river flood plain, which contains feldspar-bearing sediment from two sources. One source is the feldspar-bearing Precambrian crystalline rock that underlies the headwaters of the drainage basin in the Front Range. The other source is the sediment received from tributaries that head in thick arkosic (feldspar-rich) sandstones of the Dawson Formation (Upper Cretaceous, Paleocene, and Eocene) on the South Platte–Arkansas River drainage divide (fig. 3). The arkosic sandstones in the Dawson Formation were derived from the same Front Range Precambrian rocks as much of the flood-plain deposits of the South Platte River.

(Right) Leaves and flowers of cottonwood (*Populus deltoides subsp. monilifera*). *From "An Illustrated Flora of the Northern United States, Canada and the British Possessions," by N.L. Britton and A. Brown, published in 1913*.

(Facing page) ***A***, Mature stand of plains cottonwood (*Populus deltoides subsp. monilifera*), probably more than 100 years old, flanks Kiowa Creek near the town of Kiowa. Valley-floor gallery forests like this are common along plains streams, which are subject to large floods generated by intense summer thunderstorms. Cottonwoods readily germinate on bare sediment exposed or deposited by flooding. *Photograph by Craig Brunstein, USGS*. ***B***, Four age classes of plains cottonwoods grow along West Bijou Creek near Byers, Colorado. These woodlands commonly are tiered, and the different levels relate to major floods. The waist-high plants adjacent to the channel are a few years old. The saplings in the foreground appear to be about 10 years old. The dense trees in the background on the left are about 15 years old, and the trees on the terrace at the right are mostly over 100 years old. Because many cottonwoods germinated at about the same time after large floods and grew at similar rates, trees on a given surface are usually similar in age and height. *Age data and photograph provided by Jonathan Friedman, USGS*. ***C***, Gallery forest of plains cottonwood and peachleaf willow (Salix amygdaloides) along the Arikaree River north of Idalia. This forest became established following a large flood in 1935. The swath of vegetation from the distant center to the lower left corner of the photograph is the Arikaree River flood plain. Except for the South Platte and Arkansas Rivers, most of the rivers in eastern Colorado are dry in some places for at least part of the year, and their channels are markedly underfit (disproportionately smaller than their valleys). Rock of the Ogallala Formation, the distribution of which defines the High Plains Section of the Great Plains (see map of physiographic subdivisions), crops out on the right side of the photograph. *Photograph by Jonathan Friedman, USGS*.

Figure 7. Diagram of late Holocene eolian sand stratigraphy near Hillrose, Colorado (map locality 14), showing stratigraphic units, soil horizons, ^{14}C ages of buried soils, IRSL ages of sand units, ^{13}C values of selected horizons, and percentages of sand, silt, clay, and organic matter in stratigraphic units. Cal yr B.P. age ranges are for the 2-sigma (95% probability) confidence interval. *Photograph of this section is shown in figure 12.*

Table 3A. Percentages of sand, silt, and clay in late Holocene eolian sand units.

Table 3B. Grain-size distribution in the sand fraction of late Holocene eolian sand units.

The eolian sand north of the South Platte River came from a different source than that south of the river. The eolian sand north of the river came chiefly from small drainage basins underlain by Upper Cretaceous sandstone, siltstone, and shale, which were deposited in marine environments that predate the Laramide uplift of the Front Range. The differences between the coarser grained, relatively young Cenozoic basin-fill sediments, derived from a rising Front Range, and the older pre-Laramide Upper Cretaceous marine rocks, capped by the Fox Hills Sandstone (fig. 3), explain most of the similarities and differences in mineralogy and trace-element geochemistry between dune fields, as discussed by Muhs and others (1996).

Fine and medium sand are the dominant grain sizes in most dunes (Muhs and others, 1996; and table 3). However, all sand sizes from very fine to coarse generally are present in eolian sand, and, in some places, most notably the Black Squirrel area, very coarse sand is common, primarily because the sand sources consist chiefly of sediment derived from the Dawson Formation. In addition, most deposits contain a small percentage (typically less than 10 percent) of silt and clay (table 3). Muhs (1985, table 2) reported grain-size distributions for A/C and A/AC/C soil profiles in eolian sand at two localities in the Wray dune field and 12 localities in the South Platte area between Julesburg and Fort Lupton. The silt and clay percentages in table 2 of Muhs (1985) are similar to those in table 3 of this publication. Muhs found that at 8 of 14 localities the combined content of silt and clay was less than 8 percent, quantities comparable to those determined in this study (table 3). In contrast, silt and clay are the dominant sizes in buried soils in late Holocene sand (fig. 7).

Few data are available with which to evaluate how sand size varies with local source area or deposit age. Size does, however, tend to decrease systematically downwind away from the South Platte River (Shroba, 1980; Muhs, 1985; Muhs and others, 1999). The roundness and sorting of sand grains appear to vary with sediment source. Grains derived from the flood plains and channels of large streams, such as the South Platte and Arkansas Rivers, tend to be rounded and well sorted, whereas a high percentage of the grains derived from small tributaries to these rivers commonly are subangular and poorly sorted.

(Facing page, below) Short-horned lizard (*Phrynosoma douglassi*), often referred to as a horned toad even though it is not an amphibian, is one of several reptiles common to eastern Colorado. This specimen is 11 centimeters long (about 4.5 inches). In spite of the numerous spines on its head and back and the large pointed scales along its sides, this small reptile is harmless and tolerates handling, if it is done gently. This creature is uniquely adapted to life in places that are hot and dry. Its scaly, spiny skin minimizes evaporative loss of moisture and serves as camouflage. The lizard blends so well with rocks and soil that it is difficult to see until it moves. *Photograph courtesy of the University of Colorado Museum.*

Figure 9. Vertical aerial photograph of an area southwest of Hillrose, Colorado, showing, from northwest (top, left) to southeast, a succession of three eolian deposits that vary in topographic expression, dune type, and deposit form. The succession consists of (1) younger topographically rough compound parabolic dunes (CP rough), (2) older topographically smooth (subdued) compound parabolic dunes (CP smooth), and (3) hairpin U-shaped simple parabolic dunes (SP). *Army Map Service aerial photograph taken September 1953.*

Dune Forms

Most dune sand is currently stable and covered with vegetation. Parabolic dunes are dominant throughout northeastern and central Colorado, whereas blowout dunes are the most common type in areas south of the Arkansas River. Both dune types are controlled primarily by vegetation and (or) moisture that partially stabilize sand rather than by wind strength and direction (McKee, 1979). Parabolic dunes approximate a parabola in plan view, and they have a convex front that faces downwind and arms that trail upwind toward the open end of the parabola. Blow out dunes are circular or bowl-shaped features of deflation (see diagrams of dune types on map). Except for the dune belt flanking the south side of the Arkansas River, dune fields are few, small, and widely scattered in southeastern Colorado.

Two types of parabolic dunes deserve mention because they are widespread and represent two extremes in form and topographic expression. One type consists of long, low, topographically subdued, U-shaped (hairpin) simple parabolic dunes, whereas the other type consists of relatively high, topographically rough, compound parabolic dunes (fig. 8 on map sheet; fig. 9). The arms of the U-shaped simple parabolic dunes are notably straight and commonly 2–3 kilometers long, but they are only about 5 meters higher than surrounding terrain. These forms are conspicuous on aerial photographs because of the length and linearity of dune arms, but they are inconspicuous on the ground because of their low height. In some places, only the arms of this dune type are preserved; the concentric leading edge is often missing due to continued wind erosion.

(Above) Black-tailed jackrabbit (*Lepus californicus*) on grasslands of Otero County. During the past century the black-tailed jackrabbit, which is the dominant species in the southern Great Plains, expanded its range northward into areas formerly occupied only by white-tailed jackrabbits. The black-tailed jackrabbit is now found throughout the eastern plains of Colorado. This species is well suited to survival in areas where drought and confined grazing have disturbed or degraded the vegetation of the short-grass steppe. *Photograph by Craig Brunstein, USGS.*

Coyote pup (*Canis latrans*) seated next to yucca (*Yucca glauca*). The pup is a member of a litter that probably was born between early April and the middle of May. The barking and howls of coyotes are common during the evening and night in eastern Colorado, even near urban areas. The adaptability and cunning of this remarkable canine and its ability to live in close proximity to humans, together with the demise of the wolf, have allowed it to expand its range during the past century. *Photograph courtesy of the University of Colorado Museum.*

Figure 10. Diagram showing typical soil profiles in eolian sand in the South Platte and Wray sand areas. Column widths denote soil texture according to three classes identified at bottom. Soil structure of A horizons is generally weak and that of Bt horizons ranges from weak to moderate. Textures of A horizons vary; soils of the Julesburg and Vona series include both sandy loam and loamy sand, and the A and AC horizons of the Valent series range from sand to loamy sand.

Most compound parabolic dunes consist of clusters of small parabolic forms and elongated blowouts that are superposed on larger parabolic masses of sand (fig. 8 on map sheet). Within the clusters of small parabolic forms, individual dunes tend to be aligned in rows and often overlap in en echelon (in an orderly steplike arrangement) or telescoping patterns. The main parabolic sand masses are generally 1 kilometer or more long and have steep flanks that rise 10–20 meters above the surrounding terrain. The smaller parabolic forms are about as wide as they are long, which is typically 75–150 meters, and they have relatively sharp crests that are 5–10 meters high. Compound parabolic dunes are conspicuous both on aerial photographs and on the ground because of their height, surface roughness, and the patterns formed by clusters of individual dunes. Compound parabolic dunes are especially widespread in the South Platte and Wray sand areas.

Eolian Sand Stratigraphy

The eolian sand deposits of eastern Colorado can be divided into three age groups on the basis of relative-dating criteria. The criteria include (1) topographic expression of dunes (fig. 9), (2) differences in degree of soil development (fig. 10), (3) superposition and crosscutting relations of deposits and landforms (fig. 9), and (4) dune types (fig. 8 on map sheet; fig. 9). Numerical ages indicate that the three age groups are late Holocene (here defined as 4–0 ka), middle Holocene (8–4 ka), and late Pleistocene. Numerical ages also indicate that each of the three groups includes deposits of more than one age, some widely spaced in time. Unfortunately, relative-age criteria do not distinguish between deposits resulting from different episodes of sand reactivation within each age group, except where the deposits are separated by buried soils.

Differences in the degree of development of surface soils are used to help establish the relative ages of eolian sand deposits, and buried soils within sand deposits are used to decipher how these deposits relate to one another. Degree of soil development refers to attributes such as thickness, soil structure, quantities of translocated clay or calcium carbonate present, depth of leaching, and so forth. On stable surfaces (those not significantly modified by either erosion or deposition), soil development tends to produce more complex and generally thicker soil-horizon sequences with time (fig. 10).

Buried soils are particularly useful to decipher the stratigraphic record because they provide a means to (1) visually distinguish windblown-sand deposits of different ages and (2) determine when the sand was deposited by radiocarbon dating of soil organic matter. Although wind erosion may eliminate surface soil in some places, drifting sand may also bury, and thus protect, uneroded soil in other places. A buried soil records two things. First, it demonstrates that there was a period of land-surface stability during which the soil formed. Second, the degree of soil development provides an estimate of the length of time that the land surface was stable based on what is known about the rates at which certain soil properties form.

Organic matter in a buried soil is the source of ^{14}C ages that provide estimates of when the soil formed. However, the age of a buried soil may or may not date the time when the soil parent material (windblown sand in this case) was deposited. Because organic matter is continually added to soil and lost (by chemical and biological processes) from soil while it is at the land surface, over time, the ^{14}C age of the soil may become progressively younger than the age of the sand in which it is developed. Commonly, the ^{14}C age of a buried soil dates the time of burial more closely than it dates the time its parent material was deposited. The ^{14}C age of a buried soil is a maximum age for the overlying sand and a minimum age for the sand in which it is developed.

Luminescence dating, including thermoluminescence (TL) and optical dating (Huntley and others, 1985), can determine the time elapsed since buried mineral grains were last exposed to sunlight or intense heat. Optical dating is also called optically stimulated luminescence (OSL) or photon-stimulated luminescence. Optically stimulated luminescence is an umbrella term for luminescence (light caused by the release of electrons trapped in mineral-grain defects) resulting from stimulation by photons of any wavelength (Aitken, 1998). In practice, most studies have relied on stimulation by visible wavelengths (green and blue light) and infrared (commonly referred to as IRSL). In-depth discussions of the principles and applications of optical dating are available in several publications; see, for example, Wintle (1993), Berger (1995), Prescott and Robertson (1997), and Aitken (1998).

Like ^{14}C ages of buried soils, luminescence ages measure the time elapsed since sand was buried. However, unlike ^{14}C dating, luminescence dating is not based on radioactive decay. Also unlike radiocarbon dating, which requires the presence of organic carbon, luminescence dating can be applied to almost any eolian sand of Quaternary age. Inheritance, which refers to signal or luminescence resulting from electrons that were not released prior to burial because of incomplete bleaching in sunlight or incomplete heating, is less of a problem with OSL methods than with the TL method. OSL requires short exposure times (only seconds) to sunlight to “zero” a previously acquired signal, which makes it considerably more useful for determining the ages of late Pleistocene and Holocene deposits than TL dating.

Thus far, numerical ages of eolian sand have been obtained at 16 different localities in eastern Colorado (see map and table 4). Except for late Holocene deposits, age control is sketchy. Consequently, most of the following discussion is about late Holocene deposits.

Late Holocene

Two buried soils separate three units of late Holocene eolian sand (figs. 7, 11, and table 4) at several localities in the South Platte sand area. Calibrated ^{14}C ages of the buried soils and optical ages (OSL and IRSL) of the sand units suggest the following sequence of late Holocene events, discussed here from youngest to oldest.

1. Upper Sand Unit—The upper sand unit (unit 3c, fig. 11), where sampled, was deposited between about 700 and 300 years ago (A.D. 1250 and 1650) (fig. 11). This time span includes the megadroughts of the thirteenth and sixteenth centuries (Woodhouse and Overpeck, 1998) and is mostly within the time of the Little Ice Age. Lamb (1985) placed the onset of the Little Ice Age at A.D. 1300–1310, but considered the main phase of this interval of generally cooler climate to have occurred between A.D. 1550 and 1700, and the end of the interval to have been about A.D. 1880–1900.

2. Upper Buried Soil—The upper buried soil is estimated to have formed primarily between about 930 and 700 years ago (A.D. 1020 and 1250). This time span is bracketed by the limits of IRSL ages of the upper and middle late Holocene sand units, and it includes a large part or all of the 2-sigma range of six calibrated ^{14}C ages of the upper buried soil (fig. 11). The interval is approximately coincident with the peak of the European Medieval Warm Period. Lamb (1985) notes that the climax of this warm interval “was not quite contemporaneous everywhere,” but “in the heartland of North America, as in European Russia and Greenland, the warmest times may be placed between about A.D. 950 and 1200.”

Brown eolian sheet sand overlies reddish-brown pebbly alluvium on the Kersey terrace about 12 kilometers south-southwest of Greeley. Light-colored areas in the alluvium are secondary $CaCO_3$. The soil developed in eolian sand (Julesburg series) is representative of soils developed in late Pleistocene sand deposits (see also figs. 10 and 12 for comparison). The A horizon and uppermost part of the Bt horizon developed in alluvium apparently were eroded prior to deposition of eolian sand. Vertical part of ruler spans 1 meter. *Photograph by R.F. Madole, April 1992.*

Table 4. Numerical age control for eolian sand units in eastern Colorado.

Figure 11. Diagram summarizing numerical ages of late Holocene eolian sand units in the South Platte River area.

Figure 12. Late Holocene buried soils in barrow pit near Hillrose, Colorado (map locality 14). View looking southeast. White ruler is 2 meters long. Material properties and ages of this section are shown in figure 7. *Photograph by R.F. Madole*.

Whether or not eastern Colorado warmed between A.D. 1020 and 1250 is unknown, but it is likely that precipitation increased. The upper buried soil, which is simply a 15-centimeter-thick, weakly developed A horizon, has two noteworthy attributes: (1) enough organic matter to be visible (fig. 12) and (2) an exceptionally high content of silt and clay (fig. 7), especially for soil developed in a parent material that is 90 percent (or more) sand in most places (table 3). The moisture retention and bonding produced by an abundance of silt and clay explain why this soil survived subsequent episodes of wind erosion when soils that formed in eolian sand at other places and other times in the Holocene did not survive.

The formation of a 15-centimeter-thick, relatively humus-rich interval in just a few centuries suggests that the climate of that time was effectively wetter and the vegetation denser than at present. An influx of dust probably was critical to the development and preservation of this soil, as was the presence of vegetation to trap the dust and enough annual precipitation to translocate it into the soil profile. The channel and flood plain of the South Platte River were likely dust sources, particularly during late autumn and winter when low flows exposed areas that were inundated during spring and summer.

3. Middle Sand Unit—The middle sand unit (unit 3b, figs. 7, 11) was deposited between about 1275 and 930 years ago (A.D. 675 and 1020). These limits are the approximate maximum and minimum ages of the buried soils underlying and overlying the middle sand. Also, sand grains collected about 10 centimeters above the base of the middle sand at Friehauf Hill (archeological site name) and 20 centimeters above the base of the unit at Hillrose (map localities 13 and 14) have IRSL ages of 1065 ± 125 and 1060 ± 95 yr B.P., respectively (Clarke and Rendell, 2003).

4. Lower Buried Soil—The lower soil ceased to develop when it was buried, which, on the basis of two calibrated ^{14}C ages of the upper 10 centimeters of the buried soil and two IRSL ages of sand in the middle unit (unit 3b, fig. 11), is estimated to have occurred about 1,275 yr B.P. (A.D. 675). The duration of landscape stability that allowed this soil to develop is unknown. However, the lower buried soil is more strongly developed than the upper buried soil, thus it probably represents a longer period (many centuries) of landscape stability.

Stratigraphic relations and ^{14}C ages of the Piney Creek Alluvium, named for deposits along a small tributary to Cherry Creek southeast of Denver (Hunt, 1954), suggest that this period of landscape stability may have begun between about 2,300 and 2,000 cal yr B.P. (table 5). Furthermore, the properties and stratigraphy of the alluvium suggest that soil formation coincided with a period when the water table was higher than today.

The Piney Creek Alluvium is widespread in the Colorado Piedmont, and it is well exposed in cut banks of incised channels in many small valleys that originate on the piedmont. It underlies low terraces (typically 2–5 meters higher than channel level) along the larger valleys in the region, and it floors small, shallow (unincised) first-order channels on uplands. The Piney Creek Alluvium differs from other Holocene alluvium in most places. Most notably, it is distinctly grayer (generally gray to dark gray) than both younger and older Holocene alluvial units, which typically are pale brown. Also, the Piney Creek Alluvium is finer grained (chiefly silt and very fine sand) and more poorly sorted than other Holocene alluvium. Commonly, it contains beds of massive silty sand in which a small percentage of fine gravel, mostly 2–15 millimeters in size, is widely dispersed. Locally, it contains stratified organic-rich alluvium that resembles a soil A-horizon. However, pedogenesis destroys stratification, thus the organic matter (which consists of coatings on mineral grains) in the stratified alluvium probably was derived from an organic-rich sediment source rather than having formed in place by pedogenic processes. In some places, most notably the Jimmy Camp Creek watershed just east of Colorado Springs, the unit contains several discontinuous, thin beds of very dark grayish brown, organic-rich silty and clayey sand, which appear to be thin buried soils and wetland deposits that formed on an aggrading flood plain.

Table 5. Radiocarbon ages of late Holocene alluvium in the Colorado Piedmont

In the Jimmy Camp Creek drainage basin, aggradation of the Piney Creek Alluvium and formation of sequences of thin beds of organic-rich sediment required a shallow water table. Today, the water table in this area is 4.5–8.0 meters lower than the valley floor in most places (Jenkins, 1961, 1964). Jimmy Camp Creek originates on the south flank of the drainage divide between the South Platte and Arkansas Rivers, and, in the middle and lower parts of its course southward to Fountain Creek, it flows over alluvium that is 15–30 meters thick. Except during infrequent large floods, most of the channel is dry year-round. Jimmy Camp Creek seldom flows as far as 6 kilometers from the valley head before being lost entirely to infiltration and evaporation. These were not the conditions under which the Piney Creek Alluvium and its multiple beds of organic-rich sediment aggraded.

Collectively, the properties of the Piney Creek Alluvium suggest it (1) was derived in part from organic-rich sediment during a time of high water table, (2) was delivered to valley floors primarily by sheet flow and low-energy streams, and (3) aggraded slowly. A conventional ^{14}C age of 2,210 ± 60 yr B.P. of organic-rich sediment in the lowermost part of the Piney Creek Alluvium along Cottonwood Creek (map locality 19) indicates that it began to aggrade between about 2,340 and 2,050 cal yr B.P. (table 5). Similarly, ^{14}C ages of the upper 10 centimeters of buried soils at the top of the Piney Creek Alluvium provide an estimate of when aggradation ended. These ^{14}C ages range from 1,470 ± 60 yr B.P. to 1,110 ± 70 yr B.P. (table 5), and include an age of 1,110 ± 70 yr B.P. (uncorrected for isotopic fractionation) obtained at the type locality of the Piney Creek Alluvium (Madole, unpub. data, 1989).

The older ^{14}C ages of the buried soil at the top of the Piney Creek Alluvium are similar to the ^{14}C ages of the lower buried soil in eolian sand in the South Platte sand area (tables 4 and 5). Furthermore, Plains Woodland artifacts, similar to those in the lower buried soil at Friehauf Hill, are common in the Piney Creek Alluvium (Hunt, 1954). The widespread use of the area by Plains Woodland people appears to have coincided with aggradation of the Piney Creek Alluvium. Selected ^{14}C ages of Plains Woodland sites in Colorado reported by Cassells (1997) range from 1,780 ± 150 to 880 ± 180 yr B.P.

5. Lower Sand Unit—The lower sand unit (unit 3a, fig. 7) is poorly dated. Deposition of eolian sand is assumed to have ceased before 2,300 cal yr B.P., the inferred beginning of aggradation of the Piney Creek Alluvium. Also, sand grains near the top of the late Holocene lower eolian sand at Friehauf Hill (map locality 13) have an IRSL age of 2,370 ± 210 (unit 3a, table 4). Exactly when deposition of the lower sand unit began has not been determined.

A ^{14}C age of dark-gray to black interdunal pond sediment from near the edge of the South Platte River valley at Sterling, Colorado (map locality 15), indicates that eolian sand was deposited there sometime after about 2,900 cal yr B.P. However, the pond sediment is both underlain and overlain by eolian sand, and it is not clear whether the overlying sand is the late Holocene middle or lower sand unit. In order for a pond to exist on porous eolian sand, the water table had to have been higher than the bottom of the pond. At present, the water table is lower than the pond deposit. The pond deposit is assumed to correlate with a time when an effectively wetter climate maintained a higher water table, and that such a climate would have been unfavorable for eolian erosion and transport of sand. More stratigraphic sections and numerical ages are required to determine whether or not the section at Sterling has regional significance.

Gambel oak (*Quercus gambelii*). In the map area, this oak is typically a tall shrub that grows along the higher margins of the Colorado Piedmont (western and southern edges), but only in areas south of Denver. It is common on slopes in a zone between the lower boundary of ponderosa pine forest and the upper boundary of grasslands or, in some places, piñon-juniper woodlands. It extends onto the foothills of the Southern Rocky Mountains and over slopes that rim mesas capped by volcanic rock in the Raton Section of the Great Plains (see map of physiographic subdivisions). *Drawing by Hermione Dreja, USDA.*

Figure 13. Diagram of stratigraphy exposed at map locality 4 (after Madole, 1995a). Forman and others (1992) also described a section in this area. However, the buried soil that provided their ^{14}C age of 4,765 ± 305 yr B.P. was not observed in the section shown here, although a ^{14}C age of 920 ± 80 (1,010 ± 90 ^{14}C yr when corrected for isotopic fractionation; table 4) presumably was obtained from the same buried soil for which they reported an age of 920 ± 260 ^{14}C yr B.P. The soil developed in middle Holocene sand near its west edge is similar to that developed in late Holocene sand, which suggests that on the west, the upper part of the middle Holocene sand was eroded prior to or during deposition of late Holocene sand.

Middle Holocene

Middle Holocene eolian sand is the least extensive of the three age groups (late Holocene, middle Holocene, late Pleistocene) at the surface. However, it probably underlies late Holocene sand in some places. Middle Holocene sand is most widespread near the downwind margins of dune fields, but it is also present in linear tracts between late Holocene dunes and is preserved locally upwind of younger dunes. All U-shaped simple parabolic dunes examined thus far appear to be middle Holocene. Topographically rough compound parabolic dunes of late Holocene age overlap subdued compound parabolic dunes (fig. 9) that we infer to be of middle Holocene age. Locally, the subdued compound parabolic dunes overlap U-shaped simple parabolic dunes. The apparent superposition and crosscutting relations of these two dune types give the impression that they are of different ages. However, differences in weathering and soil development between them are minor; thus, in this report, they are included in the same age group.

Optical dates indicate that eolian sand was deposited at different times during the middle Holocene. Thus far, however, neither the beginning nor the end of different episodes of middle Holocene sand reactivation is well dated, although ^{14}C ages of buried soils developed in late Pleistocene sand provide a minimum date of about 7,000 cal yr B.P. for the onset of eolian sand deposition in the middle Holocene (table 4). An OSL age of 6,940 ± 2,100 of sand in a U-shaped parabolic dune near Hardin (map locality 6) and an IRSL age of 4,850 ± 325 of sand near Hillrose (map locality 14) may date separate intervals of sand reactivation.

Forman and others (1992) obtained measured ^{14}C ages (as contrasted to conventional ^{14}C ages, table 4) of buried soils at map locality 4 that bracket deposition of about 3.5 meters of middle Holocene sand. Deposition of this sand began after about 5,515 ± 410 ^{14}C yr B.P. and ended prior to about 4,765 ± 305 ^{14}C yr B.P. (table 4). These ^{14}C ages apparently were not corrected for isotopic fractionation. Had they been corrected for isotopic fractionation, the conventional ^{14}C ages probably would have been a little older given the dominance of C_4 grasses (see glossary and illustration of blue grama on map margin for explanation of C_4 and C_3 plants) in the region (compare columns in table 4 showing measured ^{14}C ages, $\delta\ ^{13}C$ values, and conventional ^{14}C ages). The older ^{14}C age is of a 20–30-centimeter-thick, slightly humus-rich sand that overlies a well-defined buried soil developed in late Pleistocene sand (fig. 13). The upper 10 centimeters of the well-defined buried soil has a 2-sigma calibrated age range of 11,250–10,800 cal yr B.P. (map locality 4, table 4).

The timing of middle Holocene eolian events is poorly understood primarily because it is difficult to recognize either the upper or lower contacts of superposed deposits of different ages. In most places, evidence of unconformities, particularly buried soils, is lacking, and a scarcity of exposures in which to observe stratigraphy compounds the problem. Although age differences among deposits of middle Holocene eolian sand are suggested in some places by crosscutting dunes and differences in the sharpness of dune topography, soil development on these same deposits does not differ significantly. The small differences that do exist could result from differences in topography, microclimate, and vegetation instead of differences in duration of soil development.

The surface soil in middle Holocene eolian sand is not much more developed than the surface soil in late Holocene eolian sand (fig. 10). The similarity of these soils is likely due to the removal in many areas of soil developed in middle Holocene eolian sand, primarily by wind erosion, during or just prior to late Holocene time. In other words, the surface soils in middle Holocene and late Holocene eolian sand probably are of similar age, even though the parent materials are of different ages.

The amount of silt and clay in the soil profile is the key to preservation of soil developed in eolian sand. Given that the soil parent materials typically are more than 90 percent sand (table 3, fig. 7), most of the silt and clay must have been added to the soil profiles after the eolian sand was deposited. Presumably, not enough dust (silt and clay) accumulated in most areas during soil formation in the middle Holocene to make soils resistant to erosion. Distance from the principal dust source, the river channel in this case, probably determines whether enough dust is deposited and then translocated downward into the soil to make it resistant to wind erosion. Deposits of middle Holocene sand are mostly downwind of late Holocene eolian sand and are farther from river channels.

Late Pleistocene

Late Pleistocene eolian sand is more extensive than Holocene eolian sand. It extends several kilometers downwind beyond the limits of the middle and late Holocene units, and, in some places, it is at the surface upwind from the younger units. It also is present in linear tracts between and within groups of younger dunes. Much late Pleistocene eolian sand was either reactivated to form younger eolian deposits or was buried by younger eolian sand.

Radiocarbon and optical ages indicate that late Pleistocene eolian sand approximately coincides in time with glacial deposits of Pinedale age (last glaciation) in the nearby Front Range (Madole, 1995b; Muhs and others, 1996). Deposition of eolian sand, primarily in sheets, may have begun as early as 30,000 cal yr B.P. and continued, probably intermittently, until perhaps as late as 13,000 cal yr B.P. The maximum date estimated for the onset of sand deposition is based on the average of three ^{14}C ages of $CaCO_3$ nodules from the Bkb horizon of a soil overlain by late Pleistocene eolian sand at map locality 8 (Muhs and others, 1996). The 30,000 cal yr B.P. date is the approximate calendar-year equivalent of the mean age (27,280 ^{14}C yr B.P.) of the three carbonate nodules according to the calibrations of Hughen and others (2004).

Archeological data indicate that deposition of late Pleistocene eolian sand ended prior to occupation of the area by Folsom people, a culture that existed between about 10,900 and 10,400 ^{14}C yr B.P. (Dennis Stanford, oral communication, 2005), dates that are equivalent to about 12,700 and 11,300 cal yr B.P., according to the calibrations of Hughen and others (1998). Numerous Folsom projectile points were found at the Fowler-Parrish site, a bison kill site in an area of late Pleistocene eolian sand just north of map locality 7. Also, the Powars site, which is in late Pleistocene eolian sand near Kersey, Colorado (map locality P), is a Folsom camp or habitation site that contained abundant cultural materials equivalent to those at the famous Lindenmeier site farther north (map locality L). In addition, a Clovis projectile point was found near the top of eolian sand just south of the Powars site (Lou Klein, oral communication, 1995), and Clovis points were found at the nearby Klein site (map locality K), which is on Pleistocene terrace alluvium. The Clovis Culture existed between about 12,000 and 10,600 ^{14}C yr B.P. (Dennis Stanford, oral communication, 2005), dates that are equivalent to about 13,000 and 12,300 cal yr B.P., according to Hughen and others (1998).

Radiocarbon ages of buried soils in the uppermost part of late Pleistocene eolian sand at map localities 4, 11, and 15 (table 4) range from 11,250 to 9,415 cal yr B.P. These ages are the mean age of organic matter that formed over an interval of unknown duration; therefore, the soils could be much younger than the sand in which they are developed. In any case, the soil ages indicate that the time between 11,250 and 9,415 cal yr B.P was favorable for soil formation, and, therefore, was an unlikely time for extensive erosion and deposition of eolian sand. Furthermore, the $\delta\,^{13}C$ values of these buried soils (see column 6, table 4) show that they formed under vegetation that included a higher proportion of C_3 grasses than exist today. C_4 grasses thrive in hotter and drier conditions than C_3 grasses; hence, an increase in C_3 grasses suggests a shift toward a cooler and, therefore, probably an effectively wetter climate. The ranges of $\delta\,^{13}C$ values of C_3 and C_4 plants do not overlap; the values of C_4 plants range from –17 ‰ to –9 ‰ and those of C_3 plants range from about –32 ‰ to –20 ‰.

View of the Lindenmeier archeological site in the Lindenmeier valley near the Colorado–Wyoming State line (map locality L). This famous Folsom habitation site was discovered in 1924. However, it did not draw much attention until a Colorado Museum of Natural History expedition found a fluted projectile point (like those found in the Lindenmeier valley) embedded in bone of an extinct species of bison near the town of Folsom in northeastern New Mexico in 1926 (*Photograph by Kevin Black, Colorado Historical Society*).

View of large mammoth tusks embedded in late Pleistocene alluvium in an arroyo bank near the Arkansas River southwest of Caddoa, Colorado, in Bent County. This scene recalls a time when hairy elephants, long since extinct, roamed the plains of eastern Colorado. *Photograph by Junius Henderson, September 1922, courtesy of the University of Colorado Museum.*

Summary

Most of eastern Colorado is in a region that, since the 1930s, has been referred to as the Dust Bowl (Hurt, 1981). This part of North America has a long history of recurring drought. Diaries and newspaper articles show that severe droughts occurred here before establishment of weather stations, and tree-ring data reveal a pattern of recurring drought that extends back several centuries. An even longer record of extreme drought is recorded in deposits of windblown sand that form extensive dune fields and sand sheets.

Dune fields and sand sheets cover nearly 30 percent of eastern Colorado. Most of this sand is stable at present, in spite of frequent strong winds, primarily because of the vegetation cover. However, sand can be easily destabilized by land-use practices that disturb vegetation. Evidently, under the present climate, much of eastern Colorado is near the threshold at which wind can erode and transport sediment. The conditions that control climate in eastern Colorado have remained nearly the same over the past 1,000 years, and, according to model simulations of atmospheric circulation (Kutzbach, 1987), average surface temperature and estimated annual precipitation in the region have varied only slightly. Nevertheless, a variety of climate-proxy data (Woodhouse and Overpeck, 1998) indicate that some droughts during this time have been more severe than the worst droughts of the past century, which, of course, included the "dirty 30s" drought that gave rise to the term Dust Bowl.

The sand in dune fields and sand sheets in eastern Colorado came primarily from stream channels and flood plains; stream terraces and residuum of Cretaceous and Tertiary rocks were secondary sources. Dune orientations and the distribution of windblown sand with respect to source areas show that the dominant sand-transporting winds were northwesterly in northeast and east-central Colorado and southwesterly in southeast and south-central Colorado. Eolian sand stratigraphy indicates that paleowind directions in latest Pleistocene time were similar to those in the Holocene.

The largest dunes and dune fields are in the northern part of the region. Here, parabolic dunes are the dominant type and are present in forms that range from simple long, low, hairpin U-shaped dunes to compound dunes consisting of small parabolic dunes formed on masses of sand that are themselves parabolic in outline. South of the Arkansas River, dunes and dune fields are smaller and blowout dunes are the most common type of dune.

Typically, eolian sand is 3–10 meters thick, but in parts of the Wray dune field, the eastern South Platte sand area, and the Black Squirrel sand area, it is as much as 20–40 meters thick. Quartz is the principal mineral in all areas, and potassium feldspar is the next most abundant mineral. Grain size, sorting, and roundness vary with sediment source. Fine and medium sand are dominant in most dunes, but generally all sand sizes and some silt and clay are present also.

Eolian sand deposits can be divided into at least three age groups on the basis of relative-dating criteria (primarily differences in topographic expression of dunes and degree of soil development). Numerical ages indicate that the three age groups are late Holocene (4–0 ka), middle Holocene (8–4 ka), and late Pleistocene. Each group may include deposits that were emplaced at different times, but which are indistinguishable solely by relative-dating criteria, except where the deposits are separated by buried soils.

Late Holocene eolian sand is particularly widespread in northeastern Colorado. Over much of the South Platte River area, three units of late Holocene eolian sand are recognized because they are separated by buried soils. Calibrated ^{14}C ages of the buried soils and optical ages (OSL and IRSL) of the three sand units indicate that (1) the upper sand unit was deposited between about 700 and 300 cal yr B.P., (2) the middle sand unit was deposited between about 1,275 and 930 cal yr B.P., and (3) deposition of the lower sand unit may have begun sometime between 3,500 and 2,800 cal yr B.P. and ceased prior to 2,340 cal yr B.P.

Preservation of the late Holocene buried soils is attributed primarily to a content of silt and clay that is unusually high for eolian sand. Several numerical ages indicate that the upper buried soil formed between about 930 and 700 cal yr B.P., and two calibrated ^{14}C ages of buried soil and two IRSL ages of sand in the middle unit indicate that the late Holocene lower soil probably was buried about 1,275 cal yr B.P.

Middle Holocene eolian sand is the least extensive and most poorly dated of the three age groups. The eolian history of this time is vague because good exposures of middle Holocene sand are few and evidence of unconformities between superposed deposits is difficult to discern. Optical ages indicate that eolian sand was deposited at different times, but neither the beginning nor the end of any episode of sand reactivation has been determined. Calibrated ^{14}C ages of buried soils developed in Pleistocene eolian sand, which underlies middle Holocene sand at a few localities, suggest a minimum date of about 7,000 cal yr B.P. for the onset of eolian sand deposition in middle Holocene time (table 4). Two optical ages provide meager evidence that eolian sand was deposited during at least two intervals during the middle Holocene.

Late Pleistocene eolian sand is more extensive than Holocene eolian sand, although much of it was remobilized into younger eolian deposits during the Holocene or was buried by Holocene eolian sand. It is present primarily in sheets that extend several kilometers downwind beyond the limits of middle and late Holocene units. Radiocarbon and optical ages suggest that late Pleistocene eolian sand is approximately coeval with glacial deposits of Pinedale age (last glaciation) in the nearby Front Range. Deposition of eolian sand may have begun as early as 30,000 cal yr B.P. and continued, probably intermittently, until about 13,000 cal yr B.P.

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References

1. Aitken, M.J., 1998, An introduction to optical dating—The dating of Quaternary sediments by the use of photon-stimulated luminescence: Oxford, Oxford University Press, 267 p.

2. Berger, G.W., 1995, Progress in luminescence dating methods of Quaternary sediments, *in* Rutter, N.W., ed., Dating methods for Quaternary deposits volume 2: Geological Association of Canada, Geotext, p. 81–104.

3. Berry, J.W., 1959 (revised and reprinted, 1968), Climates of the States, Colorado: U.S. Department of Commerce, Environmental Services Administration, Environmental Data Service, Climatography of the United States No. 60–5, 20 p.

4. Bjorkland, L.J., and Brown, R.F., 1957, Geology and ground-water resources of the lower South Platte River valley between Hardin, Colorado, and Paxton, Nebraska: U.S. Geological Survey Water-Supply Paper 1378, 106 p.

5. Blasing, T.J., and Duvick, D.N., 1984, Reconstruction of precipitation history in North American corn belt using tree rings: Nature, v. 307, p. 143–145.

6. Bryant, Bruce, McGrew, L.W., and Wobus, R.A., 1981, Geologic map of the Denver 1° × 2° quadrangle, north-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1163, scale 1:250,000.

7. Cardwell, W.D.E., and Jenkins, E.D., 1963, Ground-water geology and pump irrigation in Frenchman Creek basin above Palisade, Nebraska: U.S. Geological Survey Water-Supply Paper 1577, 128 p.

8. Carroll, C.J., and Crawford, T.A., 2000, Geologic map of the Colorado Springs quadrangle, El Paso County, Colorado: Colorado Geological Survey Open-file Report 00–03, scale 1:24,000.

9. Cassells, E.S., 1997, The archaeology of Colorado, 2nd ed.: Boulder, Colorado, Johnson Books, 325 p.

10. Clarke, M.L., and Rendell, H.M., 2003, Late Holocene dune accretion and episodes of persistent drought in the Great Plains of northeastern Colorado: Quaternary Science Reviews, v. 22, p. 1051–1058.

11. Cleaveland, M.K., and Duvick, D.N., 1992, Iowa climate reconstructed from tree rings: Water Resources Research, v. 28, p. 2607–2615.

12. Coffin, D.L., 1967, Geology and ground-water resources of the Big Sandy Creek valley, Lincoln, Cheyenne, and Kiowa Counties, Colorado: U.S. Geological Survey Water-Supply Paper 1843, 49 p.

13. Colton, R.B., 1978, Geologic map of the Boulder-Fort Collins-Greeley area, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–855–G, scale 1:100,000.

14. Crabb, J.A., 1980, Soil survey of Weld County, Colorado, southern part: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agriculture Experiment Station, 135 p.

15. Curry, W.N., 1977, Farm county of 7600 loses millions to wind and blizzard: Washington Post, no. 111 (March 26, 1977), p. 1–2.

16. De Voto, R.H., 1968, Quaternary history of Rocky Mountain Arsenal and environs, Adams County, Colorado: Quarterly of the Colorado School of Mines, v. 63, p. 113–127.

17. Fenneman, N.M., 1931, Physiography of western United States: New York, McGraw–Hill, 534 p.

18. Fisher, C.A., 1906, Description of the Nepesta quadrangle: U.S. Geological Survey Geologic Atlas, Folio 135.

19. Forman, S.L., and Maat, P., 1990, Stratigraphic evidence for late Quaternary dune activity near Hudson on the piedmont of northern Colorado: Geology, v. 18, p. 745–748.

20. Forman, S.L., Goetz, A.F.H., and Yuhas, R.H., 1992, Large-scale stabilized dunes on the High Plains of Colorado—Understanding the landscape response to Holocene climates with the aid of images from space: Geology, v. 20, p. 145–148.

21. Forman, S.L., Olgesby, R., Markgraf, V., and Stafford, T., 1995, Paleoclimatic significance of late Quaternary eolian deposition on the piedmont and High Plains, central United States: Global and Planetary Change, v. 11, p. 35–55.

22. Forman, S.L., Olgesby, R., and Webb, R.S., 2001, Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: megadroughts and climate links: Global and Planetary Change, v. 29, p. 1–29.

23. Fritts, H.C., 1983, Tree-ring dating and reconstructed variations in central plains climate: Transactions of the Nebraska Academy of Science, v. 11, p. 37–41.

24. Fullerton, D.S., Bush, C.A., and Pennell, J.N., 2003, Map of surficial deposits and materials in the eastern and central United States (east of 102° west longitude): U.S. Geological Survey Geologic Investigations Series Map I–2789, scale 1: 2,500,000.

25. Gilbert, G.K., 1896, The underground water of the Arkansas Valley in eastern Colorado: U.S. Geological Survey 17th Annual Report, pt. 2, p. 551–601.

26. Gillette, D.A., and Hanson, K.J., 1989, Spatial and temporal variability of dust production caused by wind erosion in the United States: Journal of Geophysical Research, v. 94, p. 2197–2206.

27. Hershey, L.A., and Schneider, P.A., Jr., 1972, Geologic map of the lower Cache la Poudre River basin, north-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–687, scale 1:62,500.

28. Hill, D.R., and Tompkin, J.M., 1953, General and engineering geology of the Wray area, Colorado and Nebraska: U.S. Geological Survey Bulletin 1001, 64 p.

29. Hughen, K.A., Overpeck, J.T., Lehman, S.J., Kashgarian, M., Southon, J.R., and Peterson, L.C., 1998, A new ^{14}C calibration data set for the last deglaciation based on marine varves: Radiocarbon, v. 40, p. 483–494.

Hughen, K., Lehman, S., Southon, J., Overpeck, J., Marchal, O., Herring, C., Turnbull, J., 2004, ^{14}C activity and global carbon cycle changes over the past 50,000 years: Science, v. 303, p. 202–210.

30. Hunt, C.B., 1954, Pleistocene and Recent deposits in the Denver area, Colorado: U.S. Geological Survey Bulletin 996–C, 140 p.

31. Huntley, D.J., Godfrey–Smith, D.I., and Thewalt, M.L.W., 1985, Optical dating of sediments: Nature, v. 313, p. 105–107.

32. Hurt, R.D., 1981, The Dust Bowl: An agricultural and social history: Chicago, Nelson–Hall, 214 p.

33. Hussey, K.M., 1953, A possible implication of the dune topography of the southern Colorado Piedmont: The Scientific Monthly, v. 7, p. 250–254.

34. Jenkins, E.D., 1961, Records, logs, and water-level measurements of selected wells and test holes and chemical analyses of ground water in Fountain, Jimmy Camp, and Black Squirrel valleys, El Paso County, Colorado: Colorado Water Conservation Board and U.S. Geological Survey Ground Water Series, Basic Data Report No. 3, 25 p.

35. Jenkins, E.D., 1964, Ground water in Fountain and Jimmy Camp Creek valleys, El Paso County, Colorado: U.S. Geological Survey Water-Supply Paper 1583, 66 p.

36. Johnson, R.B., 1969, Geologic map of the Trinidad quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–558, scale 1:250,000.

37. Jorgensen, D.W., 1992, Use of soils to differentiate dune age and to document spatial variation in eolian activity, northeast Colorado, U.S.A.: Journal of Arid Environments, v. 23, p. 19–34.

38. Kutzbach, J.E., 1987, Model simulations of the climatic patterns during the deglaciation of North America: Boulder, Colorado, Geological Society of America, Geology of North America, v. K-3, p. 425–446.

39. Lamb, H.H., 1985, Climate history and the future: Princeton University Press, 835 p.

40. Larsen, L.S., 1981, Soil survey of El Paso County area, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 212 p.

41. Larsen, L.S., and Brown, J.B., 1971, Soil survey of Arapahoe County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 78 p.

42. Larsen, R.J., Martin, D.R., McCullough, M.B., 1972, Soil survey of Otero County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 83 p.

43. Lindvall, R.M., 1980, Geologic map of the Commerce City quadrangle, Adams and Denver Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1541, scale 1:24,000.

44. Lindvall, R.M., 1983, Geologic map of the Sable quadrangle, Adams and Denver Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1567, scale 1:24,000.

45. Madole, R.F., 1994, Stratigraphic evidence of desertification in the western Great Plains within the past 1000 yr: Geology, v. 22, p. 483–486.

46. Madole, R.F., 1995a, Spatial and temporal patterns of late Quaternary eolian deposition, eastern Colorado, USA: Quaternary Science Reviews, v. 14, p. 155–177.

47. Madole, R.F., 1995b, Origin of Pleistocene eolian sand sheets on the west-central Great Plains, Colorado: Geological Society of America Abstracts with Programs, v. 27, no. 3, p. 70.

48. Madole, R.F., 2003, Geologic map of the Falcon NW quadrangle, El Paso County, Colorado: Colorado Geological Survey Open-File Report 03–08, scale 1:24,000.

49. Madole, R.F., Burdett, J.W., Rye, R.O., and Cummings, L.S., 1996, Phytoliths and $\delta^{13}C$ values of sediment as indicators of Holocene climatic change on the Great Plains: Geological Society of America Abstracts with Programs, v. 28, no. 3, p. 53–54.

50. Madole, R.F., and Cummings, L.S., 1994, Paleoclimatic significance of phytoliths and buried soils in deposits of late Holocene sand in northeastern Colorado: Abstracts, 13th Biennial meeting, American Quaternary Association, p. 228.

51. Madole, R.F., Muhs, D.R., and Holliday, V.T., 1996, Regional patterns of latest Pleistocene and Holocene sand-transporting winds in the central and southern Great Plains: Geological Society of America Abstracts with Programs, v. 28, no. 1, p. 51.

52. Madole, R.F., and Stokes, S., 1992, Preliminary chronology of dune and sheet sand south and east of the South Platte River near Greeley, Colorado: Abstracts, 12th Biennial meeting, American Quaternary Association, p. 71.

53. Madole, R.F., and Thorson, J.P., 2003, Geologic map of the Elsmere quadrangle, El Paso County, Colorado: Colorado Geological Survey Open-File Report 02–02, scale 1:24,000.

54. McCauley, J.F., Breed, C.S., Grolier, M.J., and MacKinnon, D.J., 1981, The U.S. dust storm of February 1977, *in* Péwé, T.L., ed., Desert dust—Origin, characteristics, and effect on man: Geological Society of America Special Paper 186, p. 123–147.

55. McGovern, H.E., 1964, Geology and ground-water resources of Washington County, Colorado: U.S. Geological Survey Water-Supply Paper 777, 46 p.

56. McLaughlin, T.G., 1954, Geology and ground-water resources of Baca County, Colorado: U.S. Geological Survey Water-Supply Paper 1256, 229 p.

57. Meko, D.M., 1992, Dendroclimatic evidence from the Great Plains of the United States, *in* Bradley, R.S., and Jones, P.D., eds., Climate since A.D. 1500: London, Routledge, p. 312–330.

58. Muhs, D.R., 1985, Age and paleoclimatic significance of Holocene sand dunes in northeastern Colorado: Annals of the Association of American Geographers, v. 75, p. 566–582.

59. Muhs, D.R., and Holliday, V.T., 1995, Evidence of active dune sand on the Great Plains in the 19th century from accounts of early explorers: Quaternary Research, v. 43, p. 198–208.

60. Muhs, D.R., and Maat, P.B., 1993, The potential response of eolian sands to greenhouse warming and precipitation reduction on the Great Plains of the U.S.A.: Journal of Arid Environments, v. 25, p. 351–361.

61. Muhs, D.R., Stafford, T.W., Cowherd, S.D., Mahan, S.A., Kihl, R., Maat, P.B., Bush, C.A., and Nehring, J., 1996, Origin of the late Quaternary dune fields of northeastern Colorado: Geomorphology, v. 17, p. 129–149.

62. Muhs, D.R., Swinehart, J.B., Loope, D.B., Aleinikoff, J.N., and Been, J., 1999, 200,000 years of climate change recorded in eolian sediments of the High Plains of eastern Colorado and western Nebraska: Geological Society of America, Field Guide 1, p. 71–91.

63. Prescott, J.R., and Robertson, G.B., 1997, Sediment dating by luminescence: A review: Radiation Measurements, v. 27, p. 893–922.

64. Reheis, M.C., 1980, Loess sources and loessal soil changes on a downwind transect, Boulder–Lafayette area, Colorado: The Mountain Geologist, v. 17, no. 1, p. 7–12.

65. Rosenberg, N.J., 1980, Drought in the Great Plains—Research on impacts and strategies: Littleton, Colorado, Water Resources Publications, 225 p.

66. Sampson, J.J., and Baber, T.G., 1974, Soil survey of Adams County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 72 p.

67. Scott, G.R., 1962, Geology of the Littleton quadrangle, Jefferson, Douglas, and Arapahoe Counties, Colorado: U.S. Geological Survey Bulletin 1121–L, 53 p.

68. Scott, G.R., 1968, Geologic and structure contour map of the La Junta quadrangle, Colorado and Kansas: U.S. Geological Survey Miscellaneous Investigations Series Map I–560, scale 1:250,000.

69. Scott, G.R., 1969, Geologic map of the southwest and southeast Pueblo quadrangles, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–597, scale 1:24,000.

70. Scott, G.R., 1978, Map showing geology, structure, and oil and gas fields in the Sterling 1° × 2° quadrangle, Colorado, Nebraska, and Kansas: U.S. Geological Survey Miscellaneous Investigations Series Map I–1092, scale 1:250,000.

71. Scott, G.R., 1982, Paleovalley and geologic map of northeastern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1378, scale 1:250,000.

72. Scott, G.R., 1985, Map showing gravel-bearing surficial deposits and basaltic rocks near Trinidad, Las Animas County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–1738, scale 1:50,000.

73. Scott, G.R., Taylor, R.B., Epis, R.C., and Wobus, R.A., 1978, Geologic map of the Pueblo 1° × 2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1022, scale 1:250,000.

74. Sharps, J.A., 1980, Geologic map of the Limon 1° × 2° quadrangle, Colorado and Kansas: U.S. Geological Survey Miscellaneous Investigations Series Map I–1250, scale 1:250,000.

75. Shroba, R.R., 1980, Geologic map and physical properties of the surficial and bedrock units of the Englewood quadrangle, Denver, Arapahoe, and Adams Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1524, scale 1:24,000.

76. Sieg, C.H., Meko, D., DeGaetano, A.T., and Wanmei, N.I, 1996, Dendroclimatic potential in the northern Great Plains, *in* Dean, J.S., Meko, D.M., and Swetnam, T.W., eds., Tree rings, environment and humanity: Radiocarbon, p. 295–302.

77. Smith, R.O., Schneider, P.A., Jr., and Petri, L.R., 1964, Ground-water resources of the South Platte River basin in western Adams and southwestern Weld Counties, Colorado: U.S. Geological Survey Water-Supply Paper 1658, 132 p.

78. Soister, P.E., 1965a, Geologic map of the Fort Lupton quadrangle, Weld and Adams Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–397, scale 1:24,000.

79. Soister, P.E., 1965b, Geologic map of the Hudson quadrangle, Weld and Adams Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–398, scale 1:24,000.

80. Soister, P.E., 1965c, Geologic map of the Platteville quadrangle, Weld County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–399, scale 1:24,000.

81. Soister, P.E., 1968a, Geologic map of the Hanover NW quadrangle, El Paso County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–725, scale 1:24,000.

82. Soister, P.E., 1968b, Geologic map of the Corral Bluffs quadrangle, El Paso County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–783, scale 1:24,000.

83. Soister, P.E., 1972, Geologic map of the Peoria quadrangle, Arapahoe and Adams Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–875, scale 1:24,000.

84. Stahle, D.W., and Cleaveland, M.K., 1988, Texas drought history reconstructed and analyzed from 1698–1980: Journal of Climate, v. 1, p. 59–74.

85. Stahle, D.W., Cleaveland, M.K., and Hehr, J.G., 1985, A 450-year drought reconstruction for Arkansas, United States: Nature, v. 316, p. 530–532.

86. Stockton, C.W., and Meko, D.M., 1983, Drought recurrence in the Great Plains as reconstructed from long-term tree-ring records: Journal of Climate and Applied Meteorology, v. 22, p. 17–29.

87. Stuiver, M., and nine others, 1998, INTCAL98 radiocarbon age calibration, 24,000–0 cal BP: Radiocarbon, v. 40, p. 1041–1083.

88. Thorson, J.P., Carroll, C.J., and Morgan, M.L., 2001, Geologic map of the Pikeview quadrangle, El Paso County, Colorado: Colorado Geological Survey Open-File Report 01–03, scale 1:24,000.

89. Toepelman, W.C., 1924, Underground water resources of parts of Crowley and Otero Counties: Colorado Geological Survey Bulletin 27, Pt. II, 72 p.

90. Trimble, D.E., and Machette, M.N., 1979a, Geologic map of the greater Denver area, Front Range urban corridor, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–856–H, scale 1:100,000.

91. Trimble, D.E., and Machette, M.N., 1979b, Geologic map of the Colorado Springs–Castle Rock area, Front Range urban corridor, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–857–F, scale 1:100,000.

92. Tweto, Ogden, 1975, Laramide (Late Cretaceous–early Tertiary) orogeny in the Southern Rocky Mountains, *in* Curtis, B.F., ed., Cenozoic history of the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 1–44.

93. Tweto, Ogden, 1979, Geologic map of Colorado: U.S. Geological Survey, scale 1:500,000.

94. Varnes, D.J., and Scott, G.R., 1967, General and engineering geology of the United States Air Force Academy site, Colorado: U.S. Geological Survey Professional Paper 551, 93 p.

95. Voegeli, P.T., and Hershey, L.A., 1965, Geology and ground-water resources of Prowers County, Colorado: U.S. Geological Survey Water-Supply Paper 1772, 97 p.

96. Weist, W.G., Jr., 1964, Geology and ground-water resources of Yuma County, Colorado: U.S. Geological Survey Water-Supply Paper 1539–J, 53 p.

97. Weist, W.G., Jr., 1965, Geology and occurrence of ground water in Otero County and the southern part of Crowley County, Colorado, *with sections on* Hydrology of the Arkansas River valley in the project area, by W.G. Weist, Jr., and E.D. Jenkins; Hydrologic properties of the water-bearing materials, by E.D. Jenkins; *and* Quality of the ground water, by C.A. Horr: U.S. Geological Survey Water-Supply Paper 1799, 90 p.

98. Wintle, A.G., 1993, Recent developments in optical dating of sediments: Radiation Protection Dosimetry, v. 47, p. 627–635.

99. Woodhouse, C.A., and Overpeck, J.T., 1998, 2000 years of drought variability in the central United States: Bulletin of the American Meteorological Society, v. 79, p. 2693–2714.

100. Woodyard, S.O., Preator, R.E., Moreland, R.E., and McCullough, M.B., 1973, Soil survey of Baca County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 57 p.

101. Zier, C.J., and Anderson, J.L., 1989, Chapter 7, Excavation, *in* Zier, C.J., ed., Archaeological excavation of Recon John Shelter (5PE648) on the Fort Carson Military Reservation, Pueblo County, Colorado: Volume prepared for the U.S. National Park Service, Rocky Mountain Region, and U.S. Army Office of the Environment, Energy, and Natural Resources, Fort Carson, Colorado, p. 58–82.

Sources of Map Data

1. Moreland, D.C., 1980, Soil survey of Larimer County area, Colorado: U.S. Department of Agriculture, Soil Conservation Service and Forest Service, in cooperation with the Colorado Agricultural Experiment Station, 174 p.

2. Crabb, J.A., 1982, Soil survey of Weld County, Colorado, Northern Part: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agriculture Experiment Station, 145 p.

3. Amen, A.E., Anderson, D.L., Hughes, T.J., and Weber, T.J., 1977, Soil survey of Logan County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with The Colorado Agricultural Experiment Station, 252 p.

4. Brubacher, J.I., and Moore, T.R., 1969, Soil survey of Sedgwick County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 61 p.

5. Brubacher, J.I., Amen, A.E., Fletcher, L.A., Geib, E.E., and Moore, T.R., 1971, Soil survey of Phillips County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 53 p.

6. Moreland, D.C., and Moreland, R.E., 1975, Soil survey of Boulder County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 86 p.

Index map showing sources of map data. Numbers correspond to numbered references in Sources of Map Data.

7. Crabb, J.A., 1980, Soil survey of Weld County, Colorado, Southern Part: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agriculture Experiment Station, 135 p.

8. Spears, C.F., Amen, A.E., Fletcher, L.A., and Healey, L.R., 1968, Soil survey of Morgan County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 102 p.

9. Petersen, M.L., Crabb, J.A., and Larsen, R.J., 1986, Soil survey of Washington County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 187 p.

10. Larsen, R.J., 1981, Soil survey of Yuma County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with Yuma Soil Conservation District, Yuma County Soil Conservation District, and Colorado Agricultural Experiment Station, 136 p.

11. Shroba, R.R., 1980, Geologic map and physical properties of the surficial and bedrock units of the Englewood quadrangle, Denver, Arapahoe, and Adams Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1524, scale 1:24,000.

12. Price, A.B., and Amen, A.E., 1984, Soil survey of Golden area, Colorado, parts of Denver, Douglas, Jefferson, and Park Counties: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with Jefferson County and the Colorado Agricultural Experiment Station, 405 p.

13. Scott, G.R., 1962, Geology of the Littleton quadrangle, Jefferson, Douglas, and Arapahoe Counties, Colorado: U.S. Geological Survey Bulletin 1121–L, 53 p., plate 1, scale 1:24,000.

14. Maberry, J.O., and Lindvall, R.M., 1972, Geologic map of the Parker quadrangle, Arapahoe and Douglas Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–770–A, scale 1:24,000.

15. Sampson, J.J., and Baber, T.G., 1974, Soil survey of Adams County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 72 p.

16. Larsen, L.S., and Brown, J.B., 1971, Soil survey of Arapahoe County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 78 p.

17. Bryant, Bruce, McGrew, L.W., and Wobus, R.A., 1981, Geologic map of the Denver 1° x 2° quadrangle, north-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1163, scale 1:250,000.

18. Larsen, L.S., Baber, T.G., Wesswick, E.L., McCoy, D.E., and Harman, J.B., 1966, Soil survey of Elbert County, Colorado, Eastern Part: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 79 p.

19. Sharps, J.A., 1980, Geologic map of the Limon 1° x 2° quadrangle, Colorado and Kansas: U.S. Geological Survey Miscellaneous Investigations Series Map I–1250, scale 1:250,000.

20. Madole, R.F., U.S. Geological Survey, unpublished data.

21. Madole, R.F., 2003, Geologic map of the Falcon NW quadrangle, El Paso County, Colorado: Colorado Geological Survey Open-File Report 03–8, scale 1:24,000.

22. Madole, R.F., and Thorson, J.P., 2003, Geologic map of the Elsmere quadrangle, El Paso County, Colorado: Colorado Geological Survey Open-File Report 02–2, scale 1:24,000.

23. Larsen, L.S., 1981, Soil survey of El Paso County area, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 212 p.

24. Scott, G.R., Taylor, R.B., Epis, R.C., and Wobus, R.A., 1978, Geologic map of the Pueblo 1° x 2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1022, scale 1:250,000.

25. Sharps, J.A., 1976, Geologic map of the Lamar quadrangle, Colorado and Kansas: U.S. Geological Survey Miscellaneous Investigations Series Map I–944, scale 1:250,000.

26. Coffin, D.L., 1967, Geology and ground-water resources of the Big Sandy Creek valley, Lincoln, Cheyenne, and Kiowa Counties, Colorado: U.S. Geological Survey Water-Supply Paper 1843, 49 p., plate 1, scale 1:125,000.

27. Geib, E.E., 1991, Soil survey of Cheyenne County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 184 p.

28. Larsen, R.J., Wiggins, T.J., Holden, D.L., McCulloch, M.B., and Preator, R.E., 1979, Soil survey of Pueblo area, Colorado, parts of Pueblo and Custer Counties: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Experiment Station, 92 p.

29. Larsen, R.J., Martin, D.R., and Mayhugh, R.E., 1968, Soil survey of Crowley County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 70 p.

30. Anderson, D.L., Lesh, J.G., and Wickman, D.W., 1981, Soil survey of Kiowa County area, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 125 p.

31. Larsen, R.J., Martin, D.R., McCullough, M.B., 1972, Soil survey of Otero County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 83 p.

32. Preator, R.E., Moreland, R.E., Woodyard, S.O., and McCullough, M.B., 1971, Soil survey of Bent County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 72 p.

33. Pannell, J.P., Larsen, R.J., McCullough, M.B., Moreland, R.E., and Woodyard, S.O., 1966, Soil survey of Prowers County, Colorado: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with the Colorado Agricultural Experiment Station, 147 p.

34. STATSGO (State Soil Geographic Data Base). The U.S. Natural Resources Conservation Service defined and compiled STATSGO units at a scale of 1:250,000. Most of the units include several soil series.

35. McLaughlin, T.G., 1954, Geology and ground-water resources of Baca County, Colorado: U.S. Geological Survey Water-Supply Paper 1256, 232 p., plate 1, scale 1: 125,000.

Indian paintbrush *(Castilleja sp.)*. *Drawing by Carol Quesenberry, USGS*.

Glossary

Some terms in this glossary have multiple meanings or are defined differently by different scientific disciplines. The definitions listed here are for this publication, and are not necessarily all-inclusive. Several definitions have been adapted from the Glossary of Geology (Gary and others, 1972; Bates and Jackson, 1995).

A

A horizon A soil layer at the ground surface, or underlying an O horizon (organic litter), that is characterized by humified organic matter mixed with the mineral fraction of soil.

AB horizon A transitional horizon between A and B soil horizons. It has properties of both horizons, but those of the A horizon are dominant.

AC horizon A transitional horizon between A and C soil horizons. It has properties of both horizons, but those of the A horizon are dominant.

Alluvium Sediment deposited by streams or by unconfined runoff, such as sheet flow.

Arkose A feldspar-rich sedimentary rock. It commonly is pink or reddish and consists chiefly of angular to subangular coarse sand-size grains derived from the disintegration of granite or granitic rocks, including high-grade metamorphic rocks.

B

B horizon A soil layer that underlies an O, A, or E horizon that is dominated by obliteration of all or much of the original rock structure, including stratification in unconsolidated sediment, and development of various properties that distinguish several kinds of B horizons (Soil Survey Division Staff, 1993). Only those kinds of B horizons referred to in the pamphlet are defined in this glossary. For definitions of other kinds of B horizons see Soil Survey Division Staff (1993) and Birkeland (1999).

BA horizon A transitional horizon between A and B soil horizons. It has properties of both horizons, but those of the B horizon are dominant.

BC horizon A transitional horizon between B and C soil horizons. It has properties of both horizons, but those of the B horizon are dominant.

Bkb horizon A buried soil B horizon containing a visible accumulation of alkaline earth carbonates, primarily calcium carbonate. The lower case **k** indicates the presence of the accumulated carbonate, and the **b** indicates that the horizon is part of a soil that is buried by younger sediment.

Blowout dune A circular or bowl-shaped dune that is primarily a feature of deflation. Its form is apparently controlled more by partial stabilization by vegetation and (or) moisture, than by wind strength or direction (after McKee, 1979).

Bt horizon A soil layer characterized by the accumulation of silicate clay that either formed in place or was translocated downward within or into the horizon. A Bt horizon has more clay than the deposit in which it formed (parent material).

C

C horizon A soil layer in various stages of weathering, excluding bedrock, that lacks properties of A and B horizons (after Birkeland, 1999).

^{14}C yr B.P. An abbreviation for radiocarbon years before present. The base (zero) year for the present is A.D. 1950, or, in other words, before present is defined as before A.D. 1950 (see definition of conventional ^{14}C age).

C_3 plants Plants that incorporate carbon dioxide into a 3-carbon sugar in the initial step of photosynthesis. Their $\delta^{13}C$ values range from –20 to –35 ‰, but most are between –24 and –28 ‰. The majority of plant species, including most trees and shrubs and cool season grasses, are C_3 plants.

C_4 plants Plants that incorporate carbon dioxide into a 4-carbon sugar in the initial step of photosynthesis. The C_4 pathway is a water conservation strategy used by buffalo and grama grass, major constituents of the short-grass prairies of eastern Colorado. C_4 plants discriminate less against $^{13}CO_2$ than C_3 plants and thus have more positive $\delta^{13}C$ values, –9 to –17 ‰ with a mean between –12 and –13‰.

Cal yr B.P. An abbreviation for calendar years before present. Calendar years are determined by calibrating (with tree-ring chronologies, for example) a radiocarbon age to correct for the fluctuations in the production of atmospheric radiocarbon that occur over time. As with ^{14}C yr B.P., before present is defined as before A.D. 1950.

Clastic Pertains to sediment or rock composed primarily of fragments derived from pre-existing rocks or minerals and transported some distance from their place of origin.

Clay A particle size that in the Wentworth scale (used by geologists) is smaller than 1/256 millimeter or 4 microns and in the USDA (U.S. Department of Agriculture) scale (used by soil scientists) is smaller than 2 microns. This term also is used for a complex group of layered silicate minerals formed chiefly by the alteration of primary silicate minerals. Clay minerals are characterized by small particle size (colloidal) and the capacity to adsorb significant amounts of water and ions on their surfaces.

Claystone Rock that like shale is composed chiefly of clay- and silt-size particles, but lacks the fine lamination or fissility of shale.

Clovis A culture identified by the association of several distinct tool types, including well-made, fluted spear points, used in many parts of North America between about 12,000 and 10,600 ^{14}C yr B.P. (age range from Dennis Stanford, oral communication, 2005).

Coarse sand A geologic term (Wentworth scale) for sand particles having a diameter in the range of 0.5–1.0 millimeter (500–1,000 microns).

Complex dune Two or more dunes of different types that overlap or are superimposed on one another (after McKee, 1979).

Compound dune Two or more dunes of the same type that overlap or are superimposed on one another (after McKee, 1979).

Conglomerate A sedimentary rock consisting of subangular to rounded clasts in a matrix of mostly sand and silt; the lithified equivalent of gravel.

Contact Boundary between two different types or ages of rocks or surficial deposits.

Conventional ^{14}C age A term that implies (1) the use of the 5,568-yr half-life of ^{14}C, (2) assumed constancy of atmospheric ^{14}C in the past, (3) the use of oxalic acid as a standard, (4) the $\delta^{13}C$ value was determined and used to correct for isotopic fractionation, and (5) A.D. 1950 is the base (zero) year (after Stuiver and Polach, 1977). The term is not a synonym for radiometric ^{14}C age in contrast to an AMS (accelerator mass spectrometer) ^{14}C age.

Crystalline rock A rock consisting entirely of intergrown crystals or fragments of crystals. Term is most commonly used in referring to bodies of igneous and metamorphic rocks.

D

Deflation Pertains to the sorting, lifting, or removal of particles by wind.

$\delta^{13}C$ value The ratio between the $^{13}C/^{12}C$ of the radiocarbon sample and the $^{13}C/^{12}C$ of the PDB standard (a fossil belemnite from the PeeDee Formation in South Carolina) expressed as per mil (‰). This value indicates the degree to which the isotopic composition of the sample varies from the PDB standard. It is used to adjust ^{14}C ages to correct for isotopic fractionation. This correction may be especially significant in areas where both C_3 and C_4 plants are common (see definitions of C_3 and C_4 plants).

Drought A relative term that is defined in different ways by meteorologists, hydrologists, agronomists, and others. Common to most definitions of drought is the notion that conditions are drier than average over a specific area for longer than is normal or expected (see Beaudoin, 2002, for a useful discussion of the characterization of drought).

Dune field Informal term for localities where dunes are extensive, but cover small areas compared to sand seas whose volumes are large and measured in cubic kilometers (after Lancaster, 1995).

E

Eolian Pertains to the wind and materials moved, shaped, or deposited by wind.

F

Feldspar The most abundant group of minerals in the earth's crust. All members are closely related in form and physical properties, but fall into two subgroups, orthoclase and plagioclase.

Fine sand A geologic term (Wentworth scale) for sand particles having a diameter in the range of 0.125–0.25 millimeter (125–250 microns).

Flood plain Flat area adjacent to a stream channel that was constructed by the stream in the present climate and that is flooded frequently (after Dunne and Leopold, 1978).

Fluvial Pertains to stream processes, deposits, and landforms.

Folsom A culture that overlapped and followed the Clovis culture but was less widespread. It existed between about 10,900 and 10,400 ^{14}C yr B.P. (Dennis Stanford, oral communication, 2005) and is identified by the association of several tool types, including distinctive, fluted spear points.

G

Geomorphology The scientific study of landscapes and the processes that shape them (Bloom, 1998).

Gravel A deposit that consists chiefly of abundant subangular to rounded clasts larger than 2 millimeters, but also containing variable amounts of matrix (material smaller than 2 millimeters).

H

Humus Soil organic-matter, typically dark colored, that is resistant to biological and chemical attack and is so decomposed that the source materials cannot be identified.

I

Infrared stimulated luminescence (IRSL) A subdivision of OSL dating that uses photons of infrared wavelengths (1.4 eV excitation) to stimulate luminescence from potassium feldspars (after Aitken, 1998). See definition of luminescence dating.

Interfluve The area between streams; a ridge or upland between valleys.

K

ka An abbreviation for kilo-annum (1,000 years).

L

Laramide age Pertains to a time of mountain building in the Rocky Mountain region that began 70–65 million years ago and ended by about 45 million years ago (latest Cretaceous and early Tertiary time).

Leeside The side away from the wind, or downwind; also called leeward.

Lithify To change to stone, as in consolidating loose sediment into solid rock.

Loamy sand A texture term for soil that is 70–85 percent sand and the remaining15–30 percent is mostly silt plus a small percentage of clay.

Loess A surficial deposit of windblown origin that consists chiefly of silt (dust) that where unweathered is typically pale brown, homogeneous, and nonstratified.

Luminescence dating A general term for methods that determine the time elapsed since buried mineral grains were last exposed to sunlight or intense heat. The methods utilize luminescence from the release of electrons trapped in defects in quartz or feldspar. The electrons were trapped after being displaced by radioactivity in the surrounding sediment. Luminescence is stimulated by heat (TL) or photon bombardment (OSL). These dating methods require that the electron traps be emptied by exposure to light or heat prior to burial.

M

Ma An abbreviation for Mega-annum (1,000,000 years).

Massive As applied to stratified rocks and sediment, massive denotes thick, homogeneous layers in which stratification or other internal structures, such as minor joints or laminations, are not present or are obscure.

Medium sand A geologic term (Wentworth scale) for sand particles having a diameter in the range of 0.25–0.5 millimeter (250–500 microns).

Megadrought A drought of extraordinary severity (dryness and duration). The term does not apply to droughts of a few years or less, but rather to droughts comparable to or longer than that of the 1930s when precipitation was significantly below average for most of a decade.

Microclimate Pertains to generally minor differences in climate experienced over small parts of the landscape, such as a south-facing slope versus a north-facing slope, or a ridge crest compared to a valley bottom.

N

Numerical age The age of a material or feature calculated and expressed in units of time, usually years

O

Optical date or age A numerical date or age obtained by photon-stimulated (often called optical-stimulated) luminescence. See also the definition of luminescence dating.

Optically stimulated luminescence (OSL) An umbrella term for luminescence dating that uses photons of any wavelength to stimulate luminescence (after Aitkin, 1998). The term implies a signal can be related directly to the trapped-charge population via stimulation with light. See also the definition of luminescence dating.

P

Paleowind Prehistoric wind.

Parabolic dune A sand dune that approximates a parabola in plan view. The convex front of the parabola faces downwind and the arms trail upwind toward the open end of the parabola.

Parent material The material from and in which soil forms.

Parts per mil (‰) Parts per thousand.

Pebble A rock fragment that is at least somewhat rounded having a diameter between 2 and 64 millimeters (0.17 and 2.5 inches).

Pedogenesis Soil genesis.

Pedogenic Pertaining to soil formation.

Plains Woodland A culture influenced by developments in the eastern woodlands such as the manufacture of distinctive pottery. The culture is recognized in eastern Colorado including the Front Range starting about A.D. 100 and persisting there until about A.D. 1000 (K.D. Black, written communication, 2005).

Plano A big-game hunting culture that existed on the plains of eastern Colorado between about 10,000 and 7,000 ^{14}C yr B.P. (Cassells, 1997). It appeared as the Folsom culture was ending. Like Folsom people, Plano people utilized long, finely flaked projectile points, but without the fluting characteristic of Folsom points.

Protohistoric The time during the earliest part of recorded history. In eastern Colorado, it may be defined as beginning with the arrival of the horse about A.D. 1700 and the appearance of European trade goods among Native American artifacts in archeological excavations (J.B. Benedict, written communication, 2005).

Q

Quartz Crystalline silica (SiO_2); next to feldspar, it is the most common rock-forming mineral.

R

Radiometric age An age that is determined from nuclear decay and is expressed in years. Age estimates in years are derived from equations that relate the ratio of decay products to the parent products in the sample.

Relative dating The chronologic placement of a feature or event in a relative sense rather than by a date or age expressed in years. Superposition and crosscutting relations are examples.

Residuum Unconsolidated to weakly consolidated material essentially formed in place by disintegration and decomposition of underlying bedrock.

S

Saltation Sediment transport by bounding or skipping in a downwind or downstream direction. Transport is driven by impact and rebound in fluid flow that is insufficient to keep the bouncing particles in suspension.

Sandy loam A soil texture term for a soil that is 50–70 percent sand (after Birkeland, 1999), less than 20 percent clay, and less than 50 percent silt.

Sedimentary rock A rock formed of sediment, organic matter, or material precipitated from solution that was deposited or accumulated on the earth's surface.

Shale A thinly bedded sedimentary rock formed from mud (mainly silt- and clay-size particles).

Sheetwash alluvium Sediment deposited by unconfined runoff or sheet flow, also called overland flow.

Silt Geologic term (Wentworth scale) for particles having a diameter in the range of 1/256 to 1/16 millimeter (4–62 microns), which is smaller than very fine sand and larger than clay.

Simple dune Single or individual dunes of any of the basic types that are not in contact with other dunes (see definitions for compound and complex dunes).

Soil Engineers and soil scientists define soil in a variety of ways. In this publication, soil refers to a natural body consisting of layers (horizons) of mineral and (or) organic constituents of variable thicknesses, which differ from their parent materials in morphological, physical, chemical, and mineralogical properties (after Birkeland, 1999).

Soil horizon A layer of soil approximately parallel to the ground or soil surface having properties produced by soil-forming processes, and some of the properties are not like those of the layers just above or beneath it (after Soil Survey Division Staff, 1993). Horizons may be distinguished from adjacent layers (horizons) by properties such as color, texture, structure, consistence, and the presence or absence of carbonates.

Soil profile A vertical section of soil that includes all of its horizons and the parent material. Parent material is not soil, but is part of the soil profile.

Soil series A group of soils having horizons that, except for the texture of the A or surface horizon, are similar in all profile characteristics and in arrangement in the soil profile.

Soil texture Refers to the relative proportions of sand, silt, and clay in a mass of soil or a soil horizon.

Sorting Processes by which particles of similar size, shape, or specific gravity are separated from dissimilar particles. Better sorting indicates a greater similarity among particles. Sorting is a measure of the range in particle sizes present and provides information about conditions of sediment transport and deposition.

Stratigraphy The definition, description, and interpretation of stratified rocks and sediment in terms of a variety of attributes including their properties, origin, age, and spatial distribution.

Superposition In a vertical succession of strata, the stratum on top is younger than the stratum upon which it lies.

Surficial deposit Unconsolidated to weakly consolidated transported deposits lying on bedrock at or near the earth's surface. Residuum is regarded as a surficial material rather than a deposit because the term deposit conveys a sense of transport.

Surficial geology Geology of surficial materials, including those that formed in place as well as those that were transported and deposited.

T

Terrace deposit A surficial deposit, usually alluvium but may include eolian sediment, underlying a terrace. The terrace itself is a surface or two-dimensional landform that is higher than the flood plain.

Thermoluminescence (TL) A luminescence dating method in which heat is used to stimulate luminescence (see also the definition of luminescence dating).

Two sigma (2σ) Sigma (σ) is used in statistics to denote the standard deviation of the measured population. In this publication, the two-sigma (two standard deviations) limits of several conventional ^{14}C ages are listed in tables and discussed in the text. There is a 95 percent probability that a given ^{14}C age is between the two-sigma limits listed for it.

U

Unconformity A gap or interruption in stratigraphic succession.

Upper Republican A culture of the "Plains Village Tradition" in Nebraska, Kansas, southeastern Wyoming, and northeastern Colorado, between A.D. 1000 and 1400. Characterized by part-time bison hunting and, in eastern territories, corn farming and earthlodge villages. They are considered ancestral to the historic Pawnee tribe (K.D. Black, written communication, 2005).

V

Very coarse sand A geologic term (Wentworth scale) for sand particles having a diameter in the range of 1–2 millimeters.

Very fine sand Geologic term (Wentworth scale) for sand particles having a diameter in the range of 0.125–0.0625 millimeter (125–62.5 microns).

W

Weathering A general term for several processes operating at or near the earth's surface that cause the physical disintegration and (or) chemical decomposition of rock and surficial materials.

Windward Term for the side facing the wind or in the direction from which the wind is blowing.

Glossary References

Aitken, M.J., 1998, An introduction to optical dating—The dating of Quaternary sediments by the use of photon-stimulated luminescence: Oxford, Oxford University Press, 267 p.

Bates, R.L., and Jackson, J.A., 1995, Glossary of geology, 3rd ed.: Alexandria, Va., American Geological Institute, 805 p.

Birkeland, P.W., 1999, Soils and geomorphology 3rd ed.: New York, Oxford University Press, 430 p.

Bloom, A.L., 1998, Geomorphology: A systematic analysis of late Cenozoic landforms, 3rd ed.: Upper Saddle River, New Jersey, Prentice–Hall, Inc., 482 p.

Beaudoin, A.B., 2002, On the identification and characterization of drought and aridity in postglacial paleoenvironmental records from the northern Great Plains, *in* Wolfe, S.E. and Running, G.L. IV, eds., Drylands: Holocene climatic, geomorphic and cultural change on the Canadian prairies: Géographie physique et Quaternaire, v. 56, p. 229–246.

Dunne, T., and Leopold, L.B., 1978, Water in environmental planning: San Francisco, W.H. Freeman and Company, 818 p.

Gary, Margaret, McAfee, Robert., Jr., and Wolf, C.L., eds., 1972, Glossary of geology, 1st ed.: Washington, D.C., American Geological Institute, 857 p.

Lancaster, N., 1995, Geomorphology of desert dunes: New York, NY, Routledge, 290 p.

McKee, E. D., 1979, Introduction to a study of global sand seas, *in* McKee, E.D., ed., A study of global sand seas: U.S. Geological Survey Professional Paper 1052, p. 1–19.

Soil Survey Division Staff, 1993, Soil survey manual: U.S. Department of Agriculture Handbook No. 18, 437 p.

Stuiver, M., and Polach, H.A., 1977, Reporting of ^{14}C data: Radiocarbon, v. 19, p. 355–363.