On the origin and age of the Great Sand Dunes, Colorado

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Abstract

Over the past 100 yr, several hypotheses have been proposed for the origin and age of the Great Sand Dunes. These hypotheses differ widely in the descriptions of dune morphometry, the immediate source of eolian sand, and when sand transport occurred. The primary purpose of this paper is to evaluate these hypotheses and, where warranted, to present new ideas about the origin and age of the Great Sand Dunes. To evaluate the previous hypotheses, we had to develop more detailed information about the surficial geology of the northern San Luis Valley. Thus, we mapped the surficial geology of an area extending several tens of kilometers north, south, and west of the Great Sand Dunes and examined subsurface stratigraphy in more than 200 wells and borings. In addition, we used relative-dating criteria and several radiocarbon and OSL ages to establish the chronology of surficial deposits, and we determined the U–Pb ages of detrital zircons to obtain information about the sources of the sand in the Great Sand Dunes. The first principal finding of this study is that the lower part of the closed basin north of the Rio Grande, referred to here as the sump, is the immediate source of the sand in the Great Sand Dunes, rather than the late Pleistocene flood plain of the Rio Grande (the most widely accepted hypothesis). A second principal finding is that the Great Sand Dunes are older than late Pleistocene. They postdate the draining of Lake Alamosa, which began ∼440 ka, and predate the time when streams draining the west flank of the Sangre de Cristo Mountains were deflected by incipient dunes that formed near the mountain front. Geomorphic and stratigraphic evidence indicate that this deflection occurred prior to the end of the next to last glaciation (Bull Lake), i.e., prior to ∼130 ka.
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1. Introduction

Hypotheses about the age and origin of the Great Sand Dunes have appeared intermittently in various publications since Hayden (1873) first described them, but detailed information about the distribution of eolian sand and other surficial deposits in the area has been slow to develop. Nearly a century passed between publication of the first report about the Great Sand Dunes and publication of the first geologic map of the area (Johnson, 1969). However, except for showing the distribution of alluvial-fan deposits and some eolian sand, even this map provided little information about the surficial geology of the San Luis Valley because of its small scale (1:250,000) and inclusion of various surficial deposits in a single unit that also included Tertiary bedrock (Santa Fe Formation).

To evaluate existing hypotheses about the age and origin of the Great Sand Dunes we needed much more information than was currently available about the distribution, character, genesis, and ages of surficial deposits on the floor of the northern San Luis Valley (Fig. 1).

Thus, the starting point for our study was to map the surficial geology of an area extending several tens of kilometers north, south, and west of the Great Sand Dunes, and to obtain numerical ages (OSL and ^{14}C) and relative-age data (such as the degree of soil development and content of secondary calcium carbonate) for these deposits. In addition, we examined subsurface stratigraphy in logs of 178 wells (most 20 to 45 m deep) drilled by the Bureau of Reclamation (unpub. data,

1977–1984) and 34 wells (15 to 45 m deep) and 20 borings (~ 3 to 5 m deep) drilled by the U.S. Geological Survey (Powell, 1958).

A complex array of alluvial, eolian, paludal, and lacustrine deposits are present on the San Luis Valley floor. As the spatial and temporal relations of these deposits were determined, new ideas about the age and origin of the Great Sand Dunes evolved. In the following sections, we discuss (1) previous hypotheses about the origin and age of the Great Sand Dunes, (2) the geologic setting of the dunes, (3) the height, area, thickness, and volume of the dunes and the dune types present, (4) sand provenance and the means by which sand was transported to the Great Sand Dunes, (5) probable causes and timing of eolian sand transport, and (6) the age of the Great Sand Dunes.

2. Previous hypotheses about the origin and age of the Great Sand Dunes

Hayden (1873) was the first to comment on the origin and age of the Great Sand Dunes, although his contribution was a single sentence (p. 176) in which he indicated that the Great Sand Dunes are composed of "loose materials" of the Miocene Santa Fe Formation. Endlich (1877) reached a different conclusion. He wrote (p. 143): "These dunes seem to be of comparatively recent date, geologically speaking, and belong to the Post-Glacial age." Because of its mineralogy, Endlich recognized that at least part of the eolian sand was derived from volcanic rocks in the San Juan Mountains "fully fifty miles distant," and that it had been transported to the east margin of the San Luis Valley by westerly winds. Siebenthal (1910) made
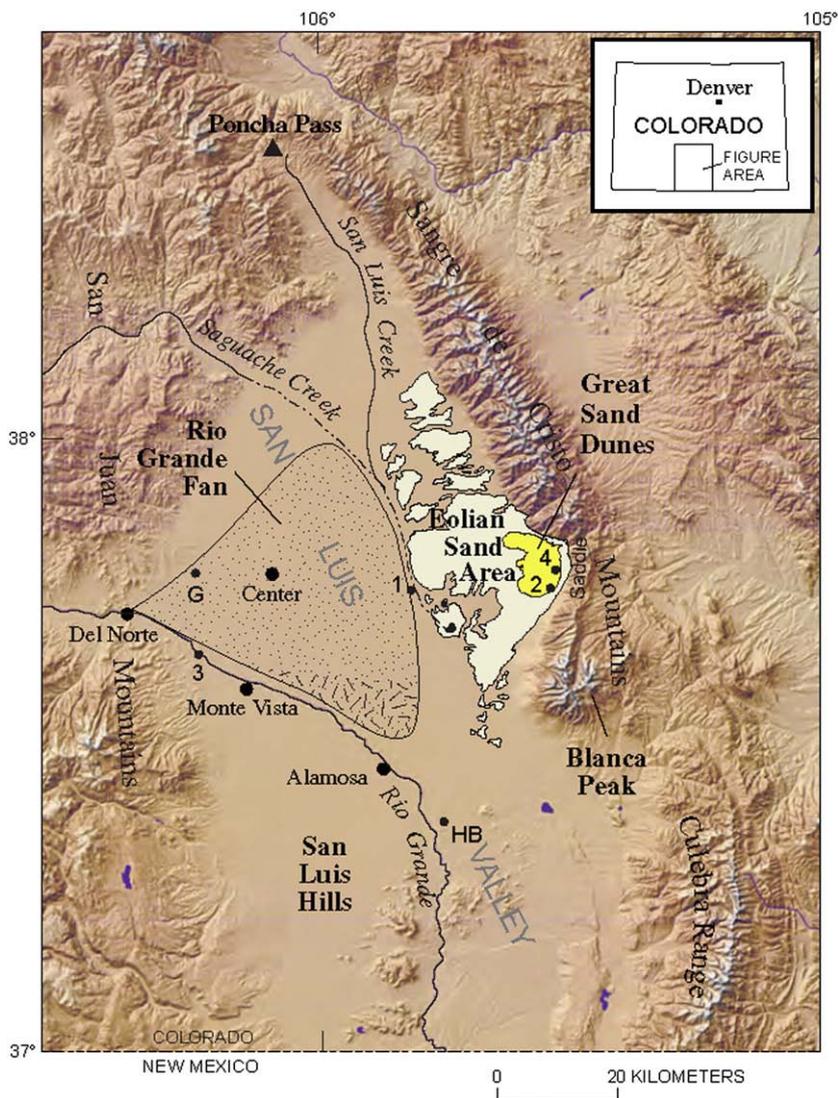

Fig. 1. Map showing the San Luis Valley and geographic place names mentioned in the text. HB is the location of Hansen Bluff and G is the location of Fig. 11. Stipple pattern indicates the extent of the Rio Grande fan. Dashed pattern denotes area where the fan was eroded in places and dissected by the Rio Grande after it assumed a course along the southern margin of the fan. The Great Sand Dunes are located in an embayment in the west flank of the Sangre de Cristo Mountains, adjacent to a saddle on the range crest that is ~ 14 km wide and 780 to 930 m lower than the range crest on either side and 1400 m lower than the highest peaks to the north (Crestone Peak) and south (Blanca Peak). Map base is from the U.S. Geological Survey color shaded-relief map of Colorado.
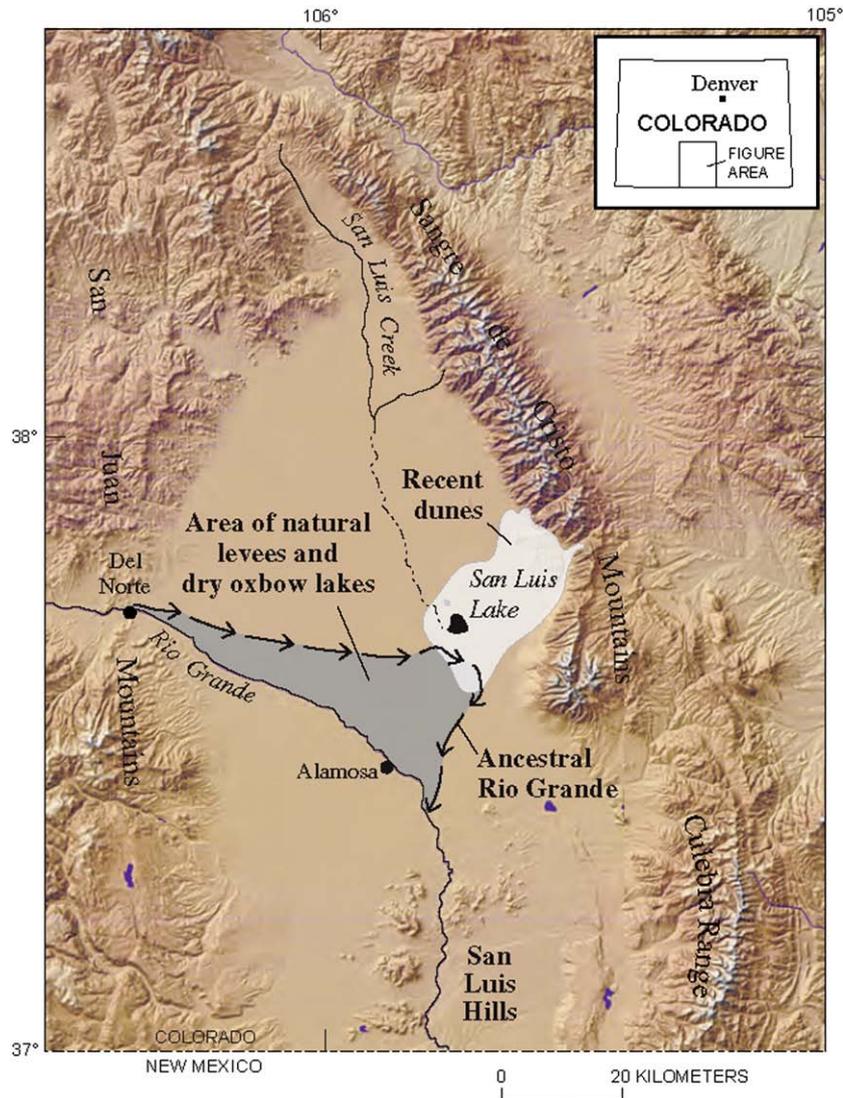
Fig. 2. Map from Johnson (1967, Fig. 1) showing the inferred course of an ancestral Rio Grande (arrows) and the location of landforms and surficial deposits that were the basis of Johnson's hypothesis for the origin of the Great Sand Dunes (here labeled Recent dunes).

the first comprehensive geologic study of the San Luis Valley, but did not make a geologic map of the area. Nevertheless, he named and described the Alamosa Formation, which is at or near the surface over much of the valley, and noted that Recent (a term since replaced by Holocene) deposits—such as dune sand, alluvial-fan deposits, stream-channel and flood-plain alluvium, and alkali-lake deposits—overlie the Alamosa Formation in some places. Siebenthal believed that the Alamosa Formation is lacustrine and post-Miocene but pre-glacial in age; thus, he inferred it to be late Pliocene or early Pleistocene (1910, p. 46). He also believed that the Great Sand Dunes were older than the Alamosa Formation, agreeing with Hayden that the dunes are a remnant of the Miocene Santa Fe Formation. Wegemann (1939) described the Great Sand Dunes in a short paper in which he acknowledges that the essential facts are from Siebenthal (1910). However, he differs from Siebenthal in asserting that at least part of the sand in the Great Sand Dunes was deflated from the Alamosa Formation when the lake in which it was deposited drained. This interpretation makes the

Great Sand Dunes at least as old as the youngest part of the Alamosa Formation. Swancara (1955) adopted Wegemann's interpretation, but provided more detail about the location and nature of the lava dam that impounded the lake in which the Alamosa Formation accumulated. Burford (1960, 1961) accepted the views of Wegemann (1939) and Swancara (1955) about the origin and age of the Great Sand Dunes. Merk (1960, 1962), on the other hand, believed that the origin and age of the Great Sand Dunes was open to question given the conflicting opinions of Hayden, Endlich, and Siebenthal.

Johnson (1967) introduced an entirely new interpretation of the origin and age of the Great Sand Dunes. He hypothesized that the dunes formed at the end of the Pleistocene from sand that was derived from flood-plain deposits of the Rio Grande. Johnson's interpretation has essentially become the canonical interpretation (e.g., Huntley, 1979; Fryberger, 1990; Landreth, 1997; Trimble, 2001; Janke, 2002; Marîn et al., 2005; Forman et al., 2006). According to Johnson (1967), during late Pleistocene time the Rio Grande flowed directly eastward across the

San Luis Valley from where it exited the San Juan Mountains at Del Norte to the vicinity of San Luis Lake (Fig. 2). There, the river made a 90° bend and flowed directly south through the San Luis Hills. He concluded that since the late Pleistocene, the Rio Grande gradually moved southwestward away from this sharp bend until it now occupies a gently curved channel between Del Norte and the north end of the San Luis Hills. Johnson believed that the area between the ancestral and present-day channels of the Rio Grande consists of shallow crescent-shaped swales that are abandoned oxbow lakes and low serpentine-shaped mounds of loose sand and silt that are ancient natural levees of the Rio Grande. He saw this loose sand and silt as the source of abundant eolian sand that subsequently was transported northeastward by prevailing southwesterly winds to form the Great Sand Dunes.

Madole and Romig (2002) reviewed the work of Johnson (1967). They noted that the crescent-shaped swales described in the area between the inferred channel of the ancient Rio Grande and its present-day channel are actually playas rather than oxbow lakes, and the serpentine-shaped mounds of loose sand are mostly eolian sand, rather than ancient natural levees; furthermore, Johnson's area of "natural levees and dry oxbow lakes" (Fig. 2) extends far beyond (northeast of) anything that conceivably resembles a levee or oxbow lake. They concluded that the inferred easterly course of the ancient Rio Grande (Fig. 2) was based on a misinterpretation of sand-ridge genesis. Also, eolian sand (not mapped by Johnson, 1967, 1969) extends too far north of the Great Sand Dunes (Fig. 1) for the Rio Grande to have been the sand source, and the orientation of parabolic dunes north of the Great Sand Dunes, which Johnson did not discuss or show in Fig. 2, cannot be reconciled with a Rio Grande source. In addition, leeside dune belts are absent along the downwind side of the Rio Grande even though this stream flows at nearly right angles to the prevailing wind much of the way across the San Luis Valley.

Accordingly, Madole and Romig (2002) proposed that the sand in the Great Sand Dunes was derived from dry lakebeds on the floor of the closed basin north of the Rio Grande. They suggested that the Great Sand Dunes are the product of multiple episodes of sand transport that were controlled primarily by climatically driven fluctuations of water table, which occurred intermittently over a time span of unknown duration, but that may have included much of the Pleistocene. During times of more effective moisture, stream inflow from the surrounding mountains increased. As a result, more sediment was transported to the basin floor, water table rose, and shallow lakes formed in some places. During megadroughts, water table in the basin fell, exposing sandy lake-floor sediment to wind erosion. The present paper modifies and expands upon this interpretation.

3. Geologic setting of the Great Sand Dunes

The Great Sand Dunes are near the eastern margin of the northern San Luis Valley in south-central Colorado. The San Luis Valley is the largest intermontane basin in the Southern Rocky Mountains; it extends north–south for ∼220 km from Poncha Pass (Fig. 1) to Taos in northern New Mexico (Fig. 3),
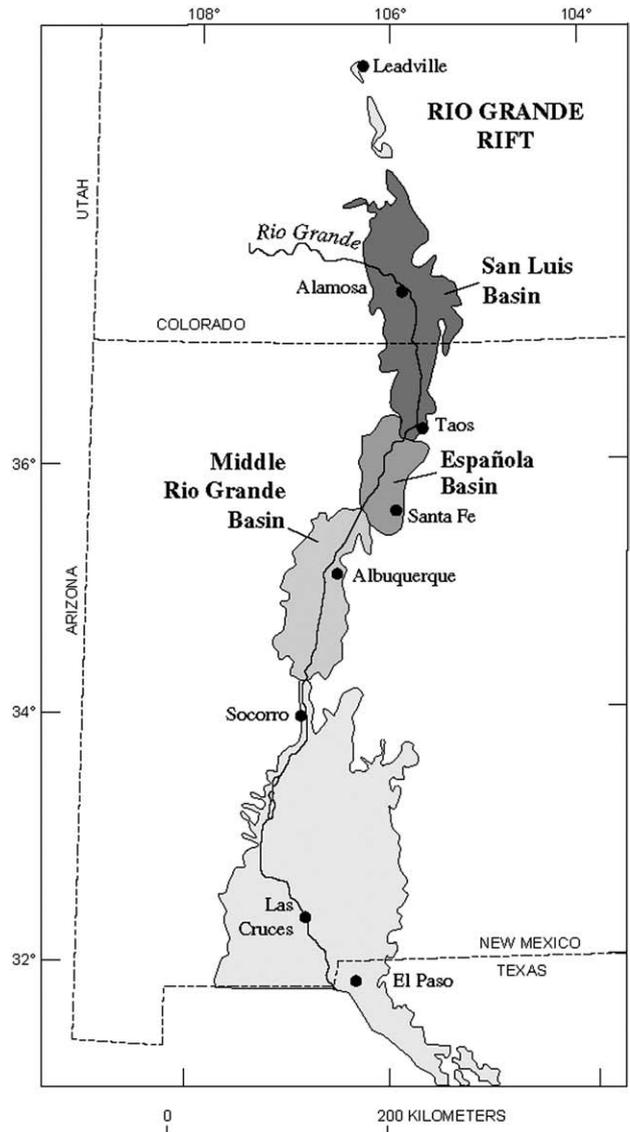

Fig. 3. Map of the Rio Grande rift in Colorado, New Mexico, and Texas showing the principal basins in the northern part of the rift (figure courtesy of V.J.S. Grauch, U.S. Geological Survey).

and its widest east–west dimension is ∼75 km. The valley is closed off on the north by the convergence of the Sangre de Cristo Mountains and San Juan Volcanic field and by an east–west trending, fault-bounded uplift that separates the upper valley of the Arkansas River from the San Luis Valley (Van Alstine, 1968). In Colorado, the San Luis Valley is flanked by the Sangre de Cristo Mountains and Culebra Range on the east and the San Juan Mountains on the west.

Initially, the San Luis Valley was one of several discrete, closed basins on the floor of the Rio Grande rift (Fig. 3), a zone of crustal stretching that extends from central Colorado (near Leadville) to northern Mexico, a distance of more than 1100 km (Keller and Cather, 1994). Eventually, several closed basins within the Rio Grande rift were connected by through going drainage. Exactly when drainage within the rift was connected to the Rio Grande between El Paso and the Gulf of Mexico (and
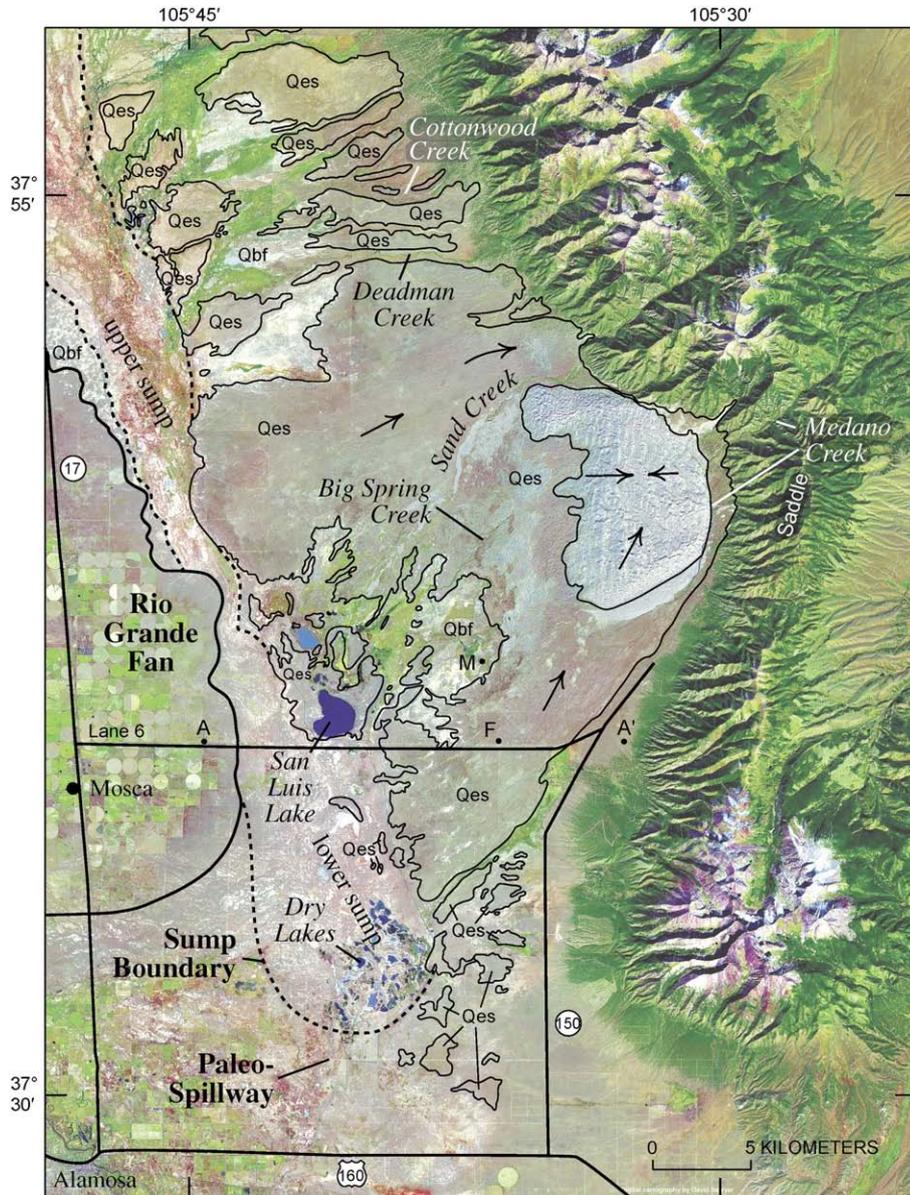
Fig. 4. Landsat image of the southern two-thirds of the eolian sand area shown in Fig. 1. Deadman Creek and other streams farther north, which presently are ephemeral, have cut relatively broad valleys across eolian sand, and underflow and seasonal surface runoff in them sustain extensive marshes (mapped as Qbf) in their lower reaches. Arrows denote directions of dominant sand-transporting winds. M is the location of Fig. 13 and F is the location of the Stewart's Cattle Guard archeological site (5AL101). Map units: Qes, eolian sand; Qbf, undivided alluvial, paludal, and lacustrine basin-floor deposits. Small, unlabeled areas within Qbf are deposits of Qes. A and A′ mark the ends of the cross section shown in Fig. 6. The image is part of Landsat 7 ETM+ acquired October 14, 1999 (Sawyer et al., 2004).

not just the Hueco bolson at El Paso) is the subject of ongoing research (J.W. Hawley, written commun., 2007). The Rio Grande probably drained from the Espanola basin in northern New Mexico to the Gulf of Mexico by 700 ka. The San Luis Valley was the last of the closed basins to be integrated into the Rio Grande watershed; integration was established or renewed sometime after Lake Alamosa began to drain ∼440 ka (Machette, 2004; Machette and Marchetti, 2006).

Like other closed basins in the Rio Grande rift, the San Luis Valley is a half-graben. The dominant displacement here was down on the east; in other basins the dominant displacement was down on the west. Sediment aggraded in the San Luis Valley as rifting progressed and gave rise to a relatively flat

surface that conceals the presence of a complex, highly faulted subsurface structure (Kluth and Schaftenaar, 1994; Brister and Gries, 1994). Lipman and Mehnert (1975) placed the onset of rifting in the San Luis Valley at about 26 Ma, and Wallace (2004) concluded that rifting in the Culebra reentrant, the eastward recess in the rift margin south of Blanca Peak (Fig. 1), began ∼25 Ma. However, the pronounced topographic relief that exists today between the San Luis Valley floor and adjacent mountains (∼2100 m) probably did not develop until well after 15 Ma (Chapin and Cather, 1994).

The kinds and ages of the rocks in the mountains flanking the San Luis Valley are markedly different, which is of great importance for determining where the sand in the Great Sand
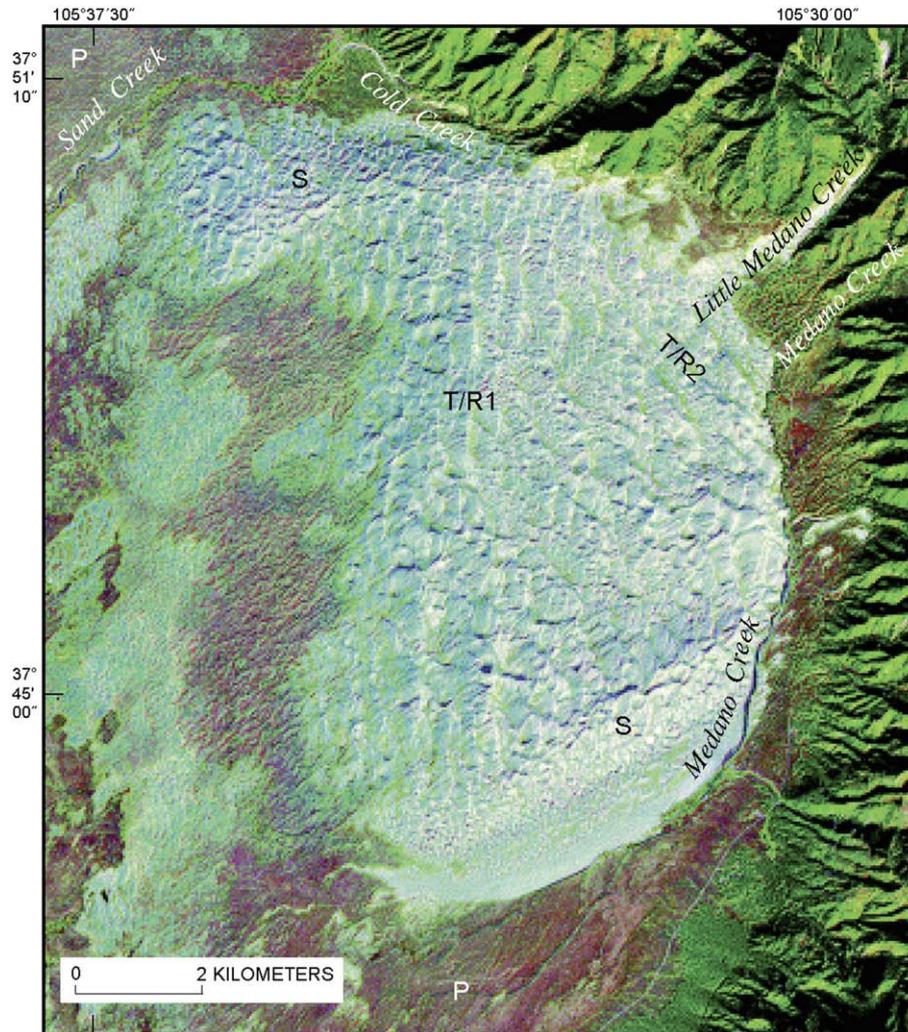
Fig. 5. Landsat image shows the complexity of the Great Sand Dunes. Star dunes (S) are prominent on the northern and southern edges of the Great Sand Dunes, and two sets of transverse or barchanoid/reversing dunes are evident, one trending north–south on the west (T/R1) and a second set (T/R2) farther east trending northwest–southeast. Parabolic dunes (P) at the southern edge of the image trend ∼N 37°E, and parabolic dunes out of sight to the north and west (but indicated on Fig. 4) trend ∼N 65°E.

Dunes came from. The San Juan Mountains on the west consist almost entirely of uppermost Eocene to middle Miocene volcanic rocks ranging in age from ∼35 to ∼18 Ma (Lipman, 2007). In contrast, the core rocks of the Sangre de Cristo Mountains, which are exposed in the vicinity of the Great Sand Dunes, consist mostly of various gneisses and quartz monzonite of Paleoproterozoic (2500–1600 Ma) and Mesoproterozoic age (1600–1000 Ma) (Johnson et al., 1989).

Quaternary deposits underlie most of the San Luis Valley floor. By far, the Alamosa Formation, named by Siebenthal (1910), is the thickest most widespread surficial deposit on the floor of the San Luis Valley. This formation consists chiefly of relatively thin alternating beds of gravel and finer sediment that is either predominantly sand, sandy silt, or sandy clay. The Alamosa Formation is overlain in many places by younger Quaternary sediment (dune sand, alluvial-fan deposits, stream-channel and flood-plain alluvium, and lake deposits) that Siebenthal (1910) considered Recent (now called Holocene). Our mapping indicates that most of the eolian sand area (Fig. 1)

overlaps piedmont slope and fan alluvium that McCalpin (1982) correlates with the last two glaciations (Pinedale and Bull Lake), and that we consider to postdate the Alamosa Formation.

The Great Sand Dunes lie within an embayment near the west flank of the Sangre de Cristo Mountains where the trend of the range changes from southeasterly to south–southwesterly (Fig. 1). The main body of eolian sheet sand and low dunes flanking the Great Sand Dunes extends from the Dry Lakes on the south to Deadman Creek on the north (Fig. 4). This eolian sand is essentially continuous, except for an area between San Luis Lake and the Great Sand Dunes where it is largely absent. We attribute this absence to deflation and to fluvial erosion at times when the discharges of Sand Creek, Big Spring Creek, and Little Spring Creek were greater than at present. Deadman Creek, and other streams farther north, which drain the high Crestone Peaks (elevation ∼4080 to 4360 m) section of the Sangre de Cristo Mountains, have segmented the eolian sand area by cutting relatively broad, flat-floored valleys westward to San Luis Creek (Figs. 1 and 4), the local base level for these

piedmont streams. However, under the present climate, streams draining the west flank of the Sangre de Cristo Mountains are lost to infiltration within a few kilometers of the mountain front, except in unusually wet years. These streams recharge and sustain extensive wetlands (cienagas) near the distal edge of the piedmont slope.

4. Height, area, thickness, volume, and dune types

4.1. Height, area, and thickness

Visitors to the Great Sand Dunes routinely ask about the height, area, and volume of the dunes. However, beyond satisfying the curiosity of visitors, the morphometric attributes of the Great Sand Dunes are important in understanding the processes that formed them and in estimating their age. In particular, the quantity of sand presently in the Great Sand Dunes places demands on source regions and sand-transport systems, which eventually can be quantified and modeled in the context of a numerically dated eolian history.

Published estimates of the height and area of the Great Sand Dunes vary widely. Estimates of the maximum height of the Great Sand Dunes relative to adjacent terrain range from ~ 183 m to 244 m (Burford, 1960; Wiegand, 1977; Huntley, 1979; Rupert and Plummer, 2004), and estimates of their area range from, ~ 78 km² to 130 km² (Wegemann, 1939; Burford, 1961; Wiegand, 1977; Andrews, 1981; Rupert and Plummer, 2004). The variation in height is primarily the result of improved measurements over time, whereas the variation in area is largely a function of how the boundaries of the Great Sand Dunes are defined. In addition, ongoing wind erosion and deposition more or less continuously modify the morphometry of the Great Sand Dunes. For example, Merk (1960) noted that during a 32-hour period, one storm moved the crest of a transverse dune 4.3 m to the southwest, and periodic surveys indicate that between 2000 and 2005 the height of the highest dune decreased from 229 m to 226 m as it migrated ~ 18 m north–northwest (Andrew Valdez, National Park Service, written commun., 2005). Presently, the height of the highest dune is nearly 230 m (Rupert and Plummer, 2004).

For our study, we define the Great Sand Dunes as those dunes having the following characteristics: they are >10 m high, contiguous, presently active, have identifiable slip faces, and contain bedding that dips >20°. Dunes at the edge of the active sand mass that barely meet these criteria are included in the area of the Great Sand Dunes if they are contiguous with them (Figs. 4 and 5), but outlying areas of well-defined active dunes that may be higher than 10 m are not considered to be part of the Great Sand Dunes. They are, however, part of a larger eolian sand area that Fryberger et al. (1979) referred to as the sand sheet. Eolian sheet sand and low dunes extend along the east side of the San Luis Valley over a north–south distance of ~ 65 km (Figs. 1 and 4). In all, eolian sand blankets ~625 km² of this area (Fig. 1); the Great Sand Dunes cover ~ 72 km² (11.5%) and low-relief dunes and sheet sand cover the remaining 553 km².

Only two previous studies commented on the thickness of the Great Sand Dunes. Huntley (1979) thought that the sand is as much as 300 m thick based on the log of Amoco test well 1–32 drilled ~ 10 km southwest of the Great Sand Dunes, whereas Andrews (1981) estimated that the eolian sand is 100 to 180 m thick. We believe that eolian sand thickness probably is comparable to the height of the Great Sand Dunes above the surrounding terrain, which is at odds with the estimate of Huntley (1979). His estimated thickness of 300 m would place the base of the eolian sand at a level 70 to 75 m below the ground surface in areas flanking the highest dunes (225–230 m). In contrast, we believe that the bottom of the Great Sand Dunes is near the levels of Sand Creek and Medano Creek because numerous well logs (Bureau of Reclamation, unpub. data, 1977–1984; Powell, 1958) indicate that alluvium, consisting mostly of beds of sand, pebble gravel, and clayey sediment, is present at shallow depths in many places near the Great Sand Dunes (e.g., see Fig. 6). In addition, cutbanks along streams adjacent to the Great Sand Dunes (e.g., Sand Creek, Fig. 7) and along streams incised into the piedmont slope north of the Great Sand Dunes (e.g., Cottonwood Creek, Deadman Creek, and the unnamed valley between these two creeks, Fig. 4) expose thick deposits of alluvium, the upper surface of which is 10–12 m higher than stream level. Furthermore, a
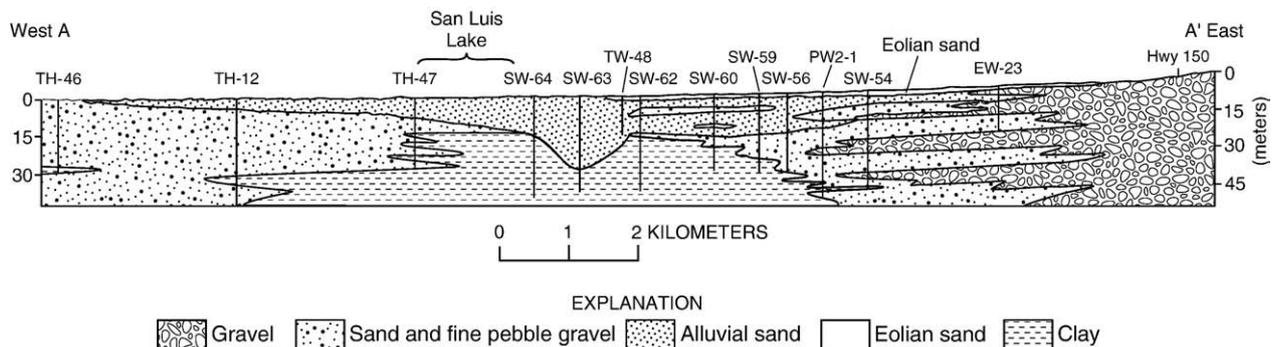

Fig. 6. Cross-section A–A′ along Lane 6 (see Fig. 4 for location) shows Quaternary stratigraphy from west of the sump to near the mountain front. Gravelly alluvium containing clasts as large as 6.5 cm was transported as far as 10 km from the mountain front during times when stream power of mountain streams was greater than today. Pebble-size clasts of volcanic rock from the west are widespread in the western part of the section, but are a minor constituent compared to sand. The clayey sediment in the central part of the cross section probably is lacustrine. Subsurface data from wells labeled TH are from Powell (1958); all other data (SW, TW, EW, PW) are from wells drilled by the Bureau of Reclamation.
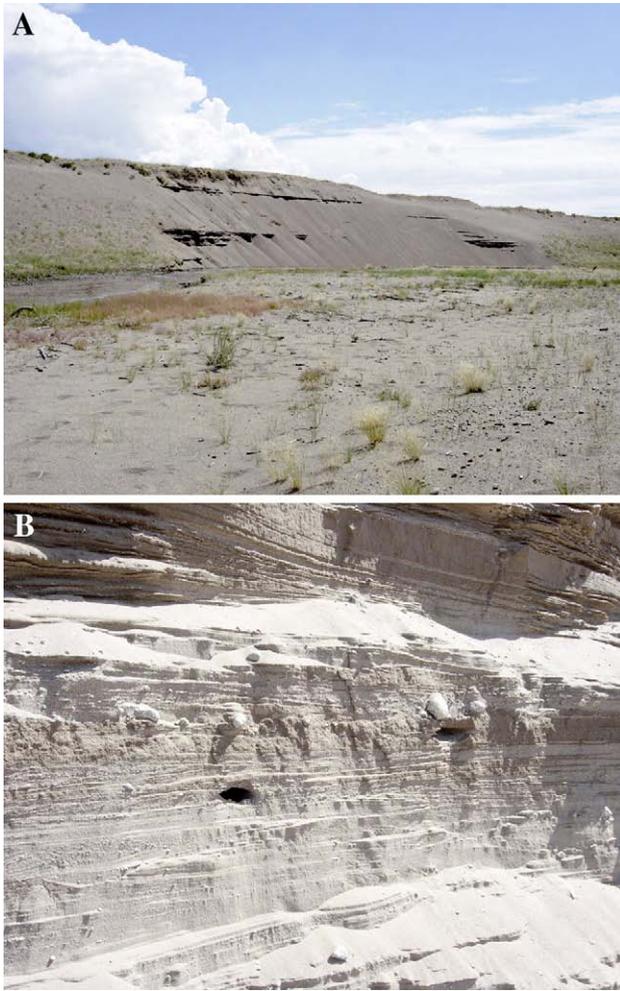
Fig. 7. (A) View southwest of terrace along Sand Creek just downstream from the end of the cottonwood forest in that valley. The terrace is ~11 m higher than the stream channel, and is adjacent to the north edge of the Great Sand Dunes. (B) Photograph of alluvium underlying the terrace shown in (A). This sediment is typical of fluvial strata in the area. The larger cobble, right center, is ~8 cm in maximum dimension.

Folsom archeological site that was occupied ~10,800 ^{14}C yr BP (Jodry, 1987, 1992; Jodry and Stanford, 1992) is within 1–3 m of the present ground surface at locality F (Fig. 4). Also, at Head Lake (see Fig. 14 for location) Shafer (1989) obtained a radiocarbon age of 10,490±290 ^{14}C yr BP (Beta-30562) for bulk sediment collected 35–45 cm below the lake floor and an age of 11,060±160 ^{14}C yr BP (A-05143) for peaty sediment 45–55 cm below the lake floor. The thick deposits of alluvial sand, gravel, and wetland sediment that are at or near the surface over a broad area in the vicinity of the Great Sand Dunes are difficult to reconcile with a basal contact for the Great Sand Dunes that is several tens of meters below the present surface according to the interpretation of Huntley (1979). To do so would require the existence of either an anomalous topographic depression in which eolian sand accumulated or the simultaneous aggradation of eolian sand in juxtaposition with aggrading alluvium.

4.2. Volume

The volume of sand in the Great Sand Dunes is difficult to estimate because of a lack of information about the lower boundary and the limits of accuracy of the topographic maps that depict their upper surface. Assuming that the topographic maps are exact and that the lower boundary of the Great Sand Dunes is a horizontal plane extending eastward from the west edge of the dunes, digital elevation models indicate that the volume of sand in the Great Sand Dunes is ~13 billion m^3. The lower boundary, however, is not likely to be horizontal. Instead, it probably resembles the present-day piedmont slopes north and south of the Great Sand Dunes, which are (1) approximately planar, (2) inclined gently westward from about 1.5° near the mountain front to 0.25° or less near the basin floor, (3) slightly concave upward at the mountain front where slope steepens from about 1.5° to 2.5°, and (4) cut by shallow valleys. Assuming similar characteristics for the lower boundary of the Great Sand Dunes, and assuming that the topographic maps are

Fig. 8. View north of the southern edge of the Great Sand Dunes shows small sharply defined reversing dunes that have low, steep slip faces on the west (left) mantling the crests of much larger transverse dunes that have slip faces on the east (right).

exact, the volume of sand is ∼ 10 billion m³. The representative thickness of the Great Sand Dunes (10 to 13 billion m³/72 km²) is therefore ∼ 139 to 181 m.

The topographic maps used in these calculations were made more than 40 yr ago. The contour-line elevations are accurate to within ± 6 m. Even if the inaccuracies in the contour-line elevations are all in the same direction (unlikely) and equal to the maximum (even more unlikely), the resulting error in the volume estimate would be no more than ± 4.3% (6/139), i.e. ± 430 million m³. We thus estimate that the volume of sand in the Great Sand Dunes is between ∼ 10 and 13 billion m³ ± 430 million m³, with 10 billion m³ being the more likely value. We estimate that the remaining 553 km² of the eolian sand area (Fig. 1) contain between ∼ 2 and 5 billon m³ of sand, assuming a typical thickness of 3 to 9 m for this area. The total volume of sand in the 625-km² eolian area is therefore on the order of 12 to 18 billion m³.

4.3. Dune forms and wind regime

A complex wind regime exists in the vicinity of the Great Sand Dunes. At present, southerly to westerly winds dominate where monitored near Alamosa (Western Regional Climate Center website: http://www.wrcc.dri.edu; also Fig. 1 of Fryberger et al., 1979), but easterly winds, although subordinate to southwesterly winds, play a role in shaping the Great Sand Dunes. This complex wind regime has produced a variety of dune types that include star, transverse (or barchanoid), reversing, parabolic, barchan, and blowout dunes (Andrews, 1981).

Star dunes, a type characterized by three or more ridges radiating from a central point, are the highest dunes in the area. They are the product of winds that blow from several different directions, which cause them to grow upward rather than to migrate forward as do transverse dunes (Breed and Grow,

1979). Star dunes are present along the north and southeast edges of the Great Sand Dunes (S, Fig. 5).

The dominant forms in the west-central part of the Great Sand Dunes trend generally north–south (T/R1, Fig. 5), and have been identified as transverse dunes in several studies (Merk, 1960, 1962; Johnson, 1967; Hutchison, 1968; Wiegand, 1977; McKee and Bigarella, 1979; Andrews, 1981; McCalpin, 1982; Fryberger, 1990; Schenk, 1990). McKee and Bigarella (1979, p. 104) described these dunes as barchanoid or transverse types in which two groups of steeply dipping foresets, facing in nearly opposite directions, were developed. Schenk (1990, p. 3–4) also referred to the T/R1 dunes as "large barchanoid and transverse dunes maintained by prevailing southwest winds" the crests of which "are periodically reversed by strong winds from the east". Merk (1960, 1962) described these complex transverse dunes as consisting of large primary (also called transverse) dunes that have slip faces on the east, formed by winds blowing from the west, and smaller sharply defined secondary dunes that have slip faces on the west (Fig. 8) that were shaped by winds blowing from east to west through the saddle on the crest of the Sangre de Cristo Mountains. The secondary dunes are 3 to 6 m high, but their steep slip faces are generally only ∼ 0.6 to 1.2 m high (Merk, 1960, 1962). From time to time, the secondary dunes are "erased" by strong southwesterly and westerly winds.

McKee (1966) defined the term reversing dune to apply to dunes that contain foreset beds that dip in opposite directions. He noted that reversing dunes tend to develop to unusual heights but migrate only a limited distance because seasonal shifts in direction of the dominant wind cause them to move alternately in nearly opposite directions. The term reversing dune has been applied to the dunes that Merk (1960, 1962) described as primary and secondary (McKee and Bigarella, 1979; Fryberger, 1990; Schenk, 1990), even though little is
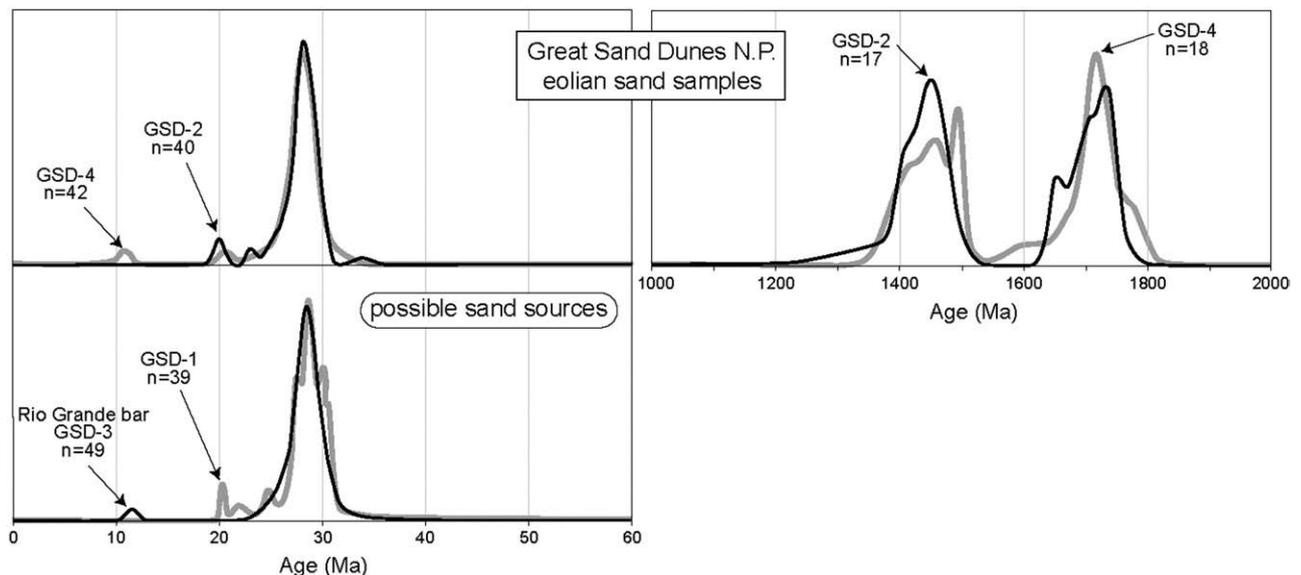

Fig. 9. Relative probability plots of U–Pb age data of detrital zircons collected at localities GSD 1–4 (locations 1–4, Fig. 1). Note—one grain of Proterozoic age from locality 3 (GSD-3) was not plotted.

known about paleowind directions in the area because exposures of Great Sand Dunes strata are shallow, small, and relatively few in number. Use of the term reversing dune implies that the impressive height of the Great Sand Dunes is the result of upward growth due to wind reversals.

A second, less conspicuous, set of transverse dunes (T/R2, Fig. 5) trend northwest–southeast obliquely across the north–south trending transverse dunes in the east-central part of the Great Sand Dunes. These dunes have not been discussed much in previous studies perhaps because their pattern is difficult to perceive on large-scale aerial photography or on imagery that does not capture the enhancement provided by vegetation. These northwest–southeast trending dunes have steep slip faces on the northeast, indicative of sand transport from southwest to northeast, a direction that also is reflected in the trend of parabolic dunes south of the Great Sand Dunes.

Other basic dune types, such as blowout, parabolic (P, Fig. 5), and a few barchan dunes, are present in areas flanking the Great Sand Dunes. South of the Great Sand Dunes, the trend of the arms and axes of parabolic dunes indicates that they probably were derived from the vicinity of the Dry Lakes by southwesterly winds blowing on average N 37° E toward the Great Sand Dunes. A smaller area of parabolic dunes just north of the Great Sand Dunes (Figs. 4 and 5) reflects a different dominant wind direction. The trends of these dunes show that sand-transporting winds there, although still southwesterly, had a greater westerly component, blowing toward the Sangre de Cristo Mountains at ~N 65° E. This wind direction is essentially normal to the northwest–southeast trend of the Sangre de Cristo Mountains north of the Great Sand Dunes (Figs. 1 and 4). Consequently, in the northern part of the area, wind drifted sand high onto alluvial fans and adjacent mountain slopes. Some parabolic dunes just north of the Great Sand Dunes curve slightly south near their east end, which suggests that the embayment in the mountain front and the broad, low saddle on the crest of the Sangre de Cristo Mountains influences wind flow and sand movement. This saddle is ~14 km wide and 780 to 930 m lower than the range crest on either side, and it is nearly 1400 m lower than the highest peaks to the north (Crestone Peak) and south (Blanca Peak). South of the Great Sand Dunes, sand drift was nearly parallel rather than perpendicular to the north–northeast–south–southwest trending mountain front (Fig. 4).

5. Source of sand in the Great Sand Dunes

Sand provenance has attracted more research than any other aspect of the Great Sand Dunes. Endlich (1875, 1877), who was the first to discuss sand provenance, concluded that the mineralogy of the Great Sand Dunes indicates that much of the sand was derived from volcanic rocks in the San Juan Mountains. Burford (1960), although concerned primarily with the bedrock geology of the Medano Peak area, came to the same conclusion. The presence of sanidine and volcanic glass in the light-mineral fraction of the dune sand and the large percentage of hypersthene and minor basaltic hornblende in the nonmagnetic heavy-mineral fraction of the dune sand indicated to

him that most of the sand in the Great Sand Dunes originated in the San Juan Mountains. Not only did he find hypersthene in the Great Sand Dunes, but he also found it in sandy sediment on the flanks and summit of the Medano Pass area, even though the bedrock in the Sangre de Cristo Mountains adjacent to the Great Sand Dunes does not contain hypersthene (Burford, 1960, p. 117).

Hutchison (1968) studied the provenance of the Great Sand Dunes by identifying the minerals in 91 samples collected in four key areas: the Great Sand Dunes, streams draining the San Juan Mountains, streams draining the Sangre de Cristo Mountains, and localities on the San Luis Valley floor. In addition, he examined the mineralogy of the bedrock in the montane drainage basins that were the sources of the stream sediment that he sampled. Hutchinson was able to identify several minerals that were exclusively from either the San Juan Mountains or the Sangre de Cristo Mountains. Thus, he concluded (p. 92) that (1) "the sands of the Great Sand Dunes consist mainly of minerals derived from the central and southwestern parts of the San Juan Mountains, and (2) "the sands of the Great Sand Dunes have minor amounts of minerals derived from the Sangre de Cristo Mountains".

Wiegand (1977) also quantified the mineralogy of the sand in and near the Great Sand Dunes. He collected sand at 83 widely spaced localities on the Great Sand Dunes, 13 localities on the sheet sand just upwind from the Great Sand Dunes, and 4 localities along the boundary between the Great Sand Dunes and Medano Creek. He found that, on average, the sand is about 28% quartz, 52% volcanic rock fragments, and 20% other minerals. Quartz and some of the other minerals could have come from either the San Juan or Sangre de Cristo Mountains, but the percentage of volcanic rock fragments present suggested to Wiegand that more than half of the material in the Great Sand Dunes came from the San Juan Mountains.

We obtained additional information about the sources of sand in the Great Sand Dunes by determining the U–Pb ages of detrital zircons in sand collected at four localities. Two samples were collected from the Great Sand Dunes (localities 2 and 4, Fig. 1). Locality 4 is on the top of one of the highest dunes near the east edge of the Great Sand Dunes. A third sample was collected from a sand bar in the Rio Grande southeast of Del Norte (locality 3, Fig. 1) and a fourth was collected from just upwind (west) of the eolian sand sheet west of the Great Sand Dunes (locality 1, Fig. 1).

Zircons from localities 2 and 4 have similar age distributions (GSD-2 and GSD-4, Fig. 9). The 57 grains analyzed from locality 2 represent two populations that differ both in morphology and age: 17 grains are rounded and of Proterozoic age and 40 grains are euhedral, prismatic, and of Tertiary age (20–34 Ma; mostly between 26 and 30 Ma). The Proterozoic grains fall into two age groups; one group ranges from ~1.34 to 1.47 Ga and the other group ranges from 1.65 to 1.74 Ga. Zircons from locality 4 also can be divided into two groups: 18 grains are rounded and Proterozoic and 42 grains are euhedral, prismatic and Tertiary (11–32 Ma; mostly 26–30 Ma). Again, Proterozoic grains fall into two age groups; one group ranges from ~1.39 to 1.50 Ga and the other

group ranges from 1.61 to 1.78 Ga. Thus, both samples from the Great Sand Dunes contain ~30% Proterozoic zircons and 70% Tertiary zircons.

In contrast, zircons from localities 1 and 3 are almost entirely euhedral, prismatic, and of Tertiary age. Of the 40 zircons in the sample collected between 0.3 and 1.0 m below the ground surface just upwind of the Great Sand Dunes (locality 1), 39 are Tertiary (20–34 Ma; mostly 28–31 Ma) and one grain is Proterozoic. Of the 49 zircons from the sand bar on the Rio Grande southeast of Del Norte (locality 3), 48 are Tertiary (12–33 Ma; mostly 26–30 Ma) and one grain has an age of 1.46 Ga (GSD-3, Fig. 9).

On the basis of U–Pb age distributions, ~70% of the zircons in the sand collected on the Great Sand Dunes were derived from Tertiary rocks of the San Juan volcanic field to the west of the dunes and ~30% of the zircons were derived from Proterozoic (~1.4 and 1.7 Ga) crystalline basement rocks of the Sangre de Cristo Mountains to the east of the Great Sand Dunes.

The research described above suggests that although some of the sand in the Great Sand Dunes and adjacent sand sheet and low dunes was derived from rocks in the Sangre de Cristo Mountains, the vast majority was derived from rocks in the San Juan Mountains 70 km and more to the west. This conclusion raises the following question: by what mechanisms was this enormous quantity of sand (upwards of 10 billion m^3) transported eastward from the San Juan Mountains to the San Luis Valley floor and from there to the Great Sand Dunes and adjacent eolian sand area (Fig. 1)?

6. Sand transport across the San Luis Valley

We hypothesize that transport of sand-size fragments of volcanic rock from the San Juan Mountains eastward across the
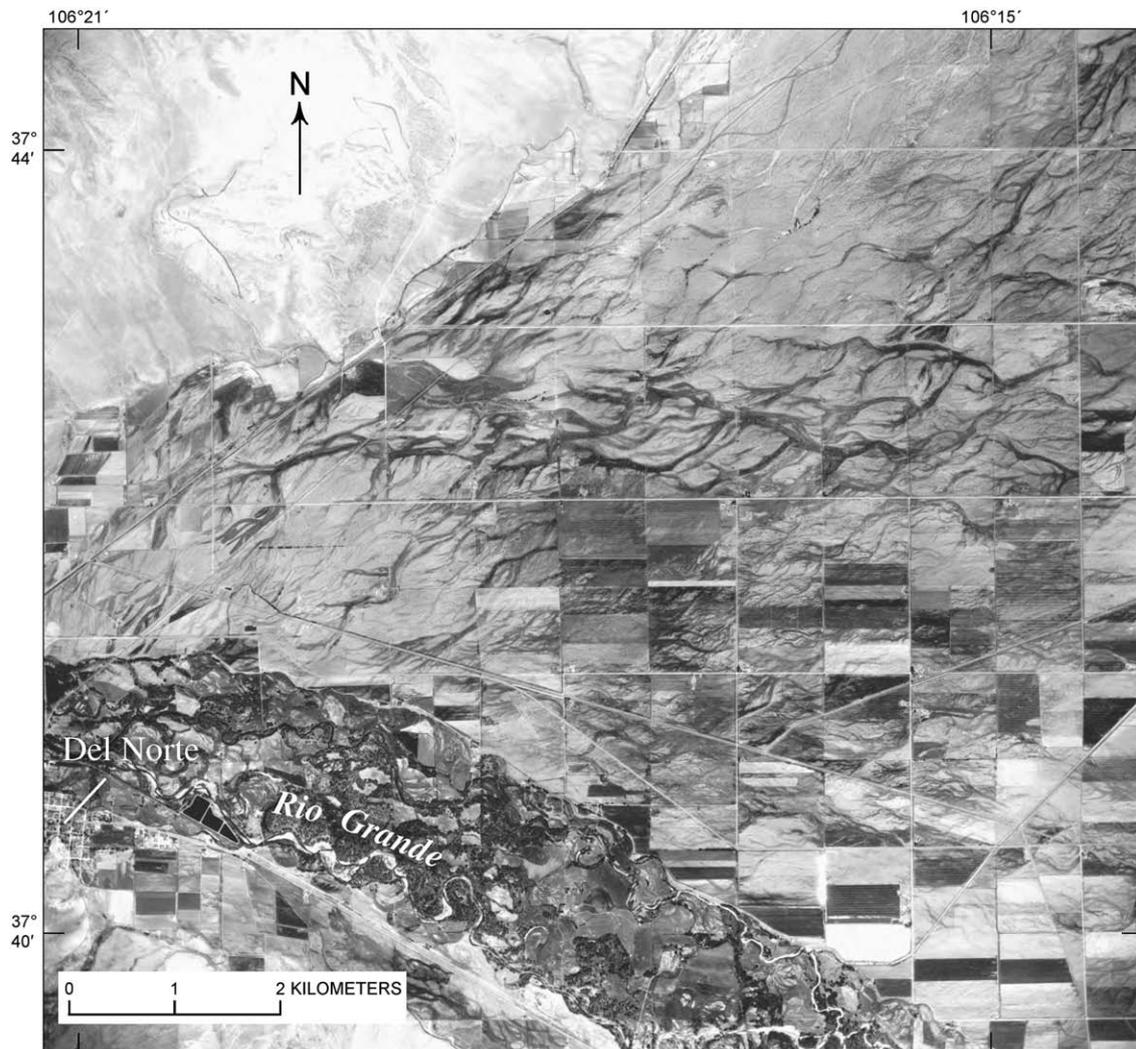

Fig. 10. Vertical airphoto of the proximal part of the Rio Grande fan shows northeast-and east-trending relict braided-stream channels. The sharp topographic expression of the channels and the degree of soil development in the alluvium indicate that the surface sediment here is of latest Pleistocene age. During the last glaciation (Pinedale), the Rio Grande flowed northeast from Del Norte rather than southwest as it does today. Soil development on the fan surface is generally weak, but where gravel is less abundant and finer, Bt horizons are present and have moderately well-developed structure and thin discontinuous to nearly continuous clay films (Pannell et al., 1980). Locality G (Figs. 1 and 11) is 3.4 km north of the northern edge of the airphoto. Army Map Service aerial photograph taken August 1960.

Fig. 11. Cobble gravel and interbedded sand (at least 9 m thick) exposed in a quarry ~12 km northeast of Del Norte (locality G, Fig. 1). The quarry is near the northern margin of the Rio Grande fan and the gravel here is not as coarse as it is farther south and southwest. No streams, other than the Rio Grande, can account for this deposit. The nearest stream entering the San Luis Valley in this area is ~6 km north of the quarry, and it is small and disappears near the edge of the valley.

San Luis Valley for tens of kilometers began with meltwater runoff from Pleistocene glaciers and snowfields. The San Juan Mountains were the most important source of sediment deposited in the San Luis Valley because most stream flow into the valley comes from these mountains. The water budget of the San Luis basin for the period 1950–1980 shows that ~89% of the inflow from adjacent highlands comes from the San Juan Mountains and ~11% comes from the Sangre de Cristo Mountains (Hearne and Dewey, 1988). The source of inflow in the past was likely similar to that of the present.

The Rio Grande drains the largest watershed flanking the San Luis Valley, and thus, it probably was the single most important source of fluvial sediment deposited in the valley. During latest Pleistocene time, the principal glacier in the Rio Grande drainage basin was one of the largest in the Southern Rocky Mountains (Atwood and Mather, 1932) although it was second in length to the Animas River glacier, which drained southward from the San Juan ice field to Durango. However, the Rio Grande drainage basin spans twice the area of the Animas River drainage basin, and it contained large glaciers in several tributaries to the Rio Grande. The main Rio Grande glacier was about 60 km long and covered nearly 1000 km² (Atwood and Mather, 1932). It terminated at an elevation of ~2710 m near

Hogback Mountain (Benson et al., 2005), which is ~70 km west of and 300 m higher than Del Norte, at the west edge of the San Luis Valley (Fig. 1).

Melting glaciers and snowfields produce large volumes of water that carry tremendous volumes of sediment (Ritter et al., 2002, p. 354). The character and distribution of gravel terrace deposits in many valleys of the Southern Rocky Mountains indicate that they are principally the product of glaciation (Madole, 1991a,b). In some intermontane basins, gravel terrace deposits can be traced directly to terminal moraines (Madole, 1991c,d). Because of increased runoff from melting glaciers and snowfields, the Rio Grande had greater stream power (stream power is proportional to discharge and slope; Bagnold, 1973, 1977) during glaciations than between glaciations. Thus, the Rio Grande transported greater quantities of sediment and coarser sediment to the San Luis Valley during glaciations.

When the Rio Grande of glacial times exited the mountains, it spread onto the floor of the San Luis Valley forming a large alluvial fan (a plain sandur) known locally as the Rio Grande fan (Figs. 1 and 4). Initially, the fan covered at least 1150 km², but more than 100 km² have been removed by erosion, primarily in the southeastern part of the fan. The Rio Grande fan has a very low gradient, ranging from ~3.5 m/km near the fan apex to 1 m/km or less at the distal edge of the fan. The proximal part of the fan, between Del Norte and Center, consists chiefly of coarse gravel (cobbles, pebbles, and a small percentage of boulders). Relicts of a broad, braided stream system are still clearly visible on the fan surface 10 km northeast of Del Norte (Fig. 10). Gravel has been mined at several localities in this area (Fig. 11), and many acres are devoted to storing cobbles that have been removed from tilled fields. The gravel becomes progressively finer eastward. Beyond Center (Fig. 1), pebble gravel gives way to an area, 15–20 km wide, that is underlain mostly by sand and lesser amounts of pebble gravel. The Rio Grande fan extended so far east that it deflected the southward flowing San Luis Creek to the southeast (Figs. 1 and 4). However, by the time the braided streams reached the distal edge of the Rio Grande fan, discharge was so dissipated that stream power was insufficient to carve a well-defined valley out of the closed basin, even during glacial times when peak flows were greatest.

Extensive deposits of eolian sand do not extend along the entire eastern edge of the San Luis Valley (Fig. 1). Instead, these deposits are restricted to an area that corresponds approximately to the shape and length of a topographically low area that Powell (1958) and Emery et al. (1971) called "the sump", which we redefine slightly to include a lower and upper sump (Fig. 4); furthermore, eolian sand deposits are thickest and most extensive on the eastern side of the sump. On the basis of these spatial relations, we propose that the sump area was the immediate source of eolian sand in the Great Sand Dunes area.

The sump area is the lowest part of the closed basin north of the Rio Grande. It is a shallow, nearly flat-floored depression 3–5 m deep and 4–15 km wide that lies mostly between the distal edge of the Rio Grande fan on the west and the distal edge of the piedmont slope of the Sangre de Cristo Mountains on the east (Fig. 4). It slopes gently (0.3 m/km) southward between San

Fig. 12. Alluvium deposited by Big Spring Creek underlies a terrace that is ~1 m higher than stream level. Interbedded sand and organic-rich mud indicate that aggradation occurred here during a time of rising water table. Organic-rich mud accumulates in slack water areas such as that beneath the aquatic vegetation at the bottom of the photograph. The 2-sigma calendar year range of the radiocarbon age is 2980–2760 cal yr BP.

area to the Rio Grande. Today, there is no outflow of surface water from the sump, nor is there an integrated drainage system within it. Also, at present, all streams disappear long before reaching the sump; on the east, they generally disappear within 0.5–3 km from the mountain front, except in unusually wet years. However, relict channels indicate that at times in the past runoff in these streams was much greater and they flowed to and through the upper part of the sump. During those times, the sump was a sediment depocenter.

We thus propose that meltwater runoff from Pleistocene glaciers and snowfields transported sand-sized fragments of volcanic rock from the San Juan Mountains eastward across the San Luis Valley and deposited this material in the area now known as the sump. Meltwater runoff from the Sangre de Cristo Mountains also brought sand-sized material to the sump area but in much lesser amounts than that from the San Juan Mountains. When conditions became favorable for eolian transport, sand was moved from the sump area to the eolian sand area shown in Fig. 1. The orientation of parabolic and transverse dunes, which are present only northeast and east of the sump, indicates that sand-transporting winds were (and still are; Fig. 1 of Fryberger et al., 1979) chiefly southwesterly and westerly. The sump, therefore, was the immediate source of the sand in the Great Sand Dunes, but the original sources of the sand were the San Juan Mountains and Sangre de Cristo Mountains, the former greatly dominating the latter.

7. Causes and timing of sand deflation

7.1. Requisites for forming dunes and sand sheets

Dune formation requires more than just sand and strong winds. Under ideal conditions, gentle winds (4.5–5 m s^{-1} or

Luis Lake and the Dry Lakes (~11 km). The Dry Lakes, which presently contain water supplied from deep wells, occupy the lowest part of the sump. The topographic and hydrologic divide between the Dry Lakes and the Rio Grande (paleospillway, Fig. 4) is the southern boundary of the sump. Topographic closure at the south end of the sump presently is only 1.5–2.0 m high near the entrance to a shallow channel, which in prehistoric time carried overflow from the south edge of the Dry Lakes

Fig. 13. View of a grass-covered swale just west of the sand sheet (locality M, Fig. 4) that was a marsh, if not a shallow lake, when water table was between 1 and 2 m higher than at present. Organic-rich mud from above the contact between eolian sand and marsh/lake sediment has an estimated age of 2990±35 ^{14}C yr BP (WW6159-LT; U.S. Geological Survey Lab., Reston, VA).
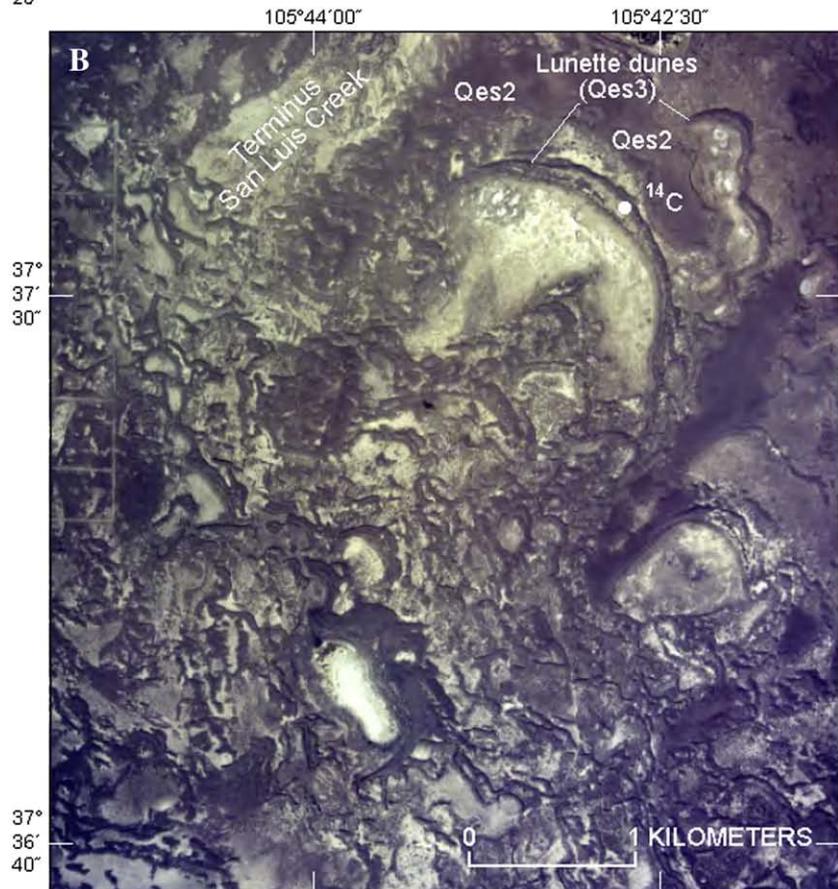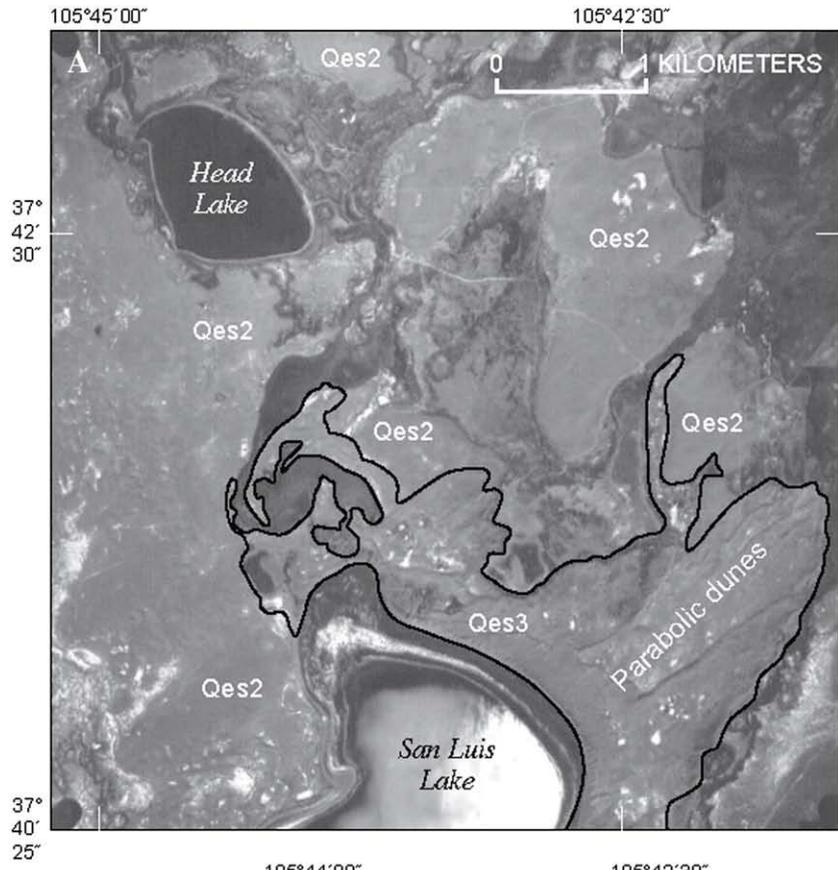
16–18 km/h) can set sand grains into motion (Ritter et al., 2002). In contrast, strong winds may be unable to erode sand, unless the sand is free to move (i.e., is loose, dry, and has a relatively smooth surface devoid of nonerodible materials, such as vegetation and rocks). For example, present-day wind velocities in the Great Plains exceed what is required to erode loose, dry, bare sand 30–60% of the time (Muhs and Maat, 1993), yet wind transport of sand is minimal, primarily because of vegetation. Even sparse vegetation can inhibit wind transport of sand. Also, surface wetting from rain and snowmelt suppresses wind erosion, as do factors such as surface roughness, the presence of a wide range of particle sizes, and the binding effects of minor amounts of clay, precipitated salts, and frozen ground (Nickling and Ecclestone, 1981; Ash and Wasson, 1983; Nickling, 1984; Wolfe and Nickling, 1993; Lancaster, 1995; Wiggs et al., 1995, 2004).

Requisites for forming dunes and sand sheets include: (1) a sand supply, (2) frequent strong winds, (3) conditions that allow dry, loose, bare (unvegetated) sand to move when wind blows, and (4) conditions that stop wind-transported sand from moving onward and thus cause it to accumulate. The first requisite is easily met in the Great Sand Dunes area because sand is abundant in the distal part of the Rio Grande fan and adjacent sump. Well logs and cores show that sand is abundant in the upper 30 m of section underlying most of this area (Fig. 6). The second requisite also is met inasmuch as strong winds sweep east and northeast across the valley on many days of the year (Western Regional Climate Center website, http://www.wrcc.dri.edu). Active blowouts and dunes in many places attest to the fact that present-day winds are capable of transporting sand. Several parabolic and barchan dunes in areas flanking the Great Sand Dunes have migrated hundreds of meters, some as much as 30 m/yr during the 20th century (Marîn et al., 2005). The fourth requisite is satisfied because the Sangre de Cristo Mountains are a major topographic barrier to wind flow and sand transport; furthermore, winds frequently blow westward through the saddle on the crest of the Sangre de Cristo Mountains (Figs. 1 and 4). Thus, it is the third requisite for forming dunes and sand sheets—the absence of vegetation and binding or cementing agents on or in the sand—that is most critical.

We propose that two processes operating at different times and of different magnitudes provided conditions that eliminated or minimized vegetation and maintained a supply of loose, dry sand. We believe that most eolian sand transport occurred during glacial times primarily because of the availability of massive amounts of sand. However, the presence of at least three different ages of Holocene eolian sand in the Great Sand Dunes

area (Madole, 2001, 2005; Madole and Mahan, 2007) indicate that transport and deposition of eolian sand also occurred episodically during nonglacial times, although in smaller amounts compared to glacial times. We suggest that episodic transport of eolian sand during the Holocene was controlled mostly by fluctuations in water-table level, which is near the surface in the sump and adjacent parts of the Rio Grande fan and lower piedmont slope (Siebenthal, 1910; Powell, 1958; Emery et al., 1971; Rupert and Plummer, 2004).

7.2. Glacial floods in the Pleistocene

Seasonal meltwater runoff during glaciation caused flooding and sedimentation over a broad area as the Rio Grande fan (outwash plain) prograded eastward. As described by Bloom (1998, p. 387) "active outwash plains are excellent source areas for dune sand and loess, because they carry massive sediment loads, but nearly dry up at night or during the winter, when melting is slower. Eolian deflation may then remove sand and silt from the dry river bed, but the sediments are renewed with each runoff event."

7.3. Water-table fluctuations in the Holocene

Evidence for changes in water-table level during the Holocene is present in (1) stream terrace deposits, (2) sediment on playa floors and in dried-up marshes, and (3) the geomorphology and stratigraphy of lunette dunes.

Stratified sandy terrace alluvium containing thin streaks of radiocarbon dateable organic-rich clayey silt, whose modern counterparts form in slack water areas along Big Spring Creek (Fig. 4), indicate that this stream was 1 to 1.5 m higher than at present ~2000 yr ago (1820 ± 60 ^{14}C yr BP; Beta-199427; 1920 ± 60 ^{14}C yr BP, Beta-158353) and that at least 1 m of sediment aggraded on the valley floor between 2760 ± 60 ^{14}C yr BP (Beta-160264) and 1820 ± 60 ^{14}C yr BP (Fig. 12). Similar evidence that the water table was 1 to 1.5 m higher than at present ~3000 yr ago (2990 ± 35 ^{14}C yr BP; laboratory no. WW6159-LT) comes from organic-rich silty lamina underlying grass-covered swales (Fig. 13) that were formerly marshes west of the Great Sand Dunes.

Dunes that were deflated from the basin of San Luis Lake (Fig. 14) indicate that water table also fell to levels more than 1–2 m lower than the present water table at times within the last 1000 yr. San Luis Lake occupies a basin that was formed by wind erosion. Sand eroded from that basin comprises a system of parabolic dunes that migrated as far as 2.3 km northeast from San Luis Lake (Fig. 14A). Crosscutting relations among three

Fig. 14. Geomorphic and stratigraphic relations shown in vertical aerial photographs of lake basins and leeside dunes indicate that water table was at least 2 m lower than present during late Holocene time, and fish fossils in the playa shown in (B) and fish bones in archeological sites in the Dry Lakes area indicate that lakes as much as 3.65 m deep existed here in late Holocene time (Jones, 1977). (A) The deflation basin, now occupied by San Luis Lake, was an important source of eolian sand when water table was low and the basin was dry. Parabolic dunes (unit Qes3) migrated as far as 2.3 km northeast from this sand source. Radiocarbon and OSL ages indicate that these dunes formed during the past 1000 yr (De Lanois, 1993; Madole, 2005). Older eolian sand (Qes2), chiefly of middle Holocene age, is present downwind (northeast) of the late Holocene dunes. (B) Aerial view of playas and lunette dunes ~4 km south of San Luis Lake. Charcoal in playa-floor sediment ~1 m below the base of a 7-m-high lunette dune at the locality labeled ^{14}C indicates that the dune is younger than 1050 ± 70 ^{14}C yr BP (Beta-199426). A similar but larger lunette dune (Qes2) formed here during middle Holocene time.
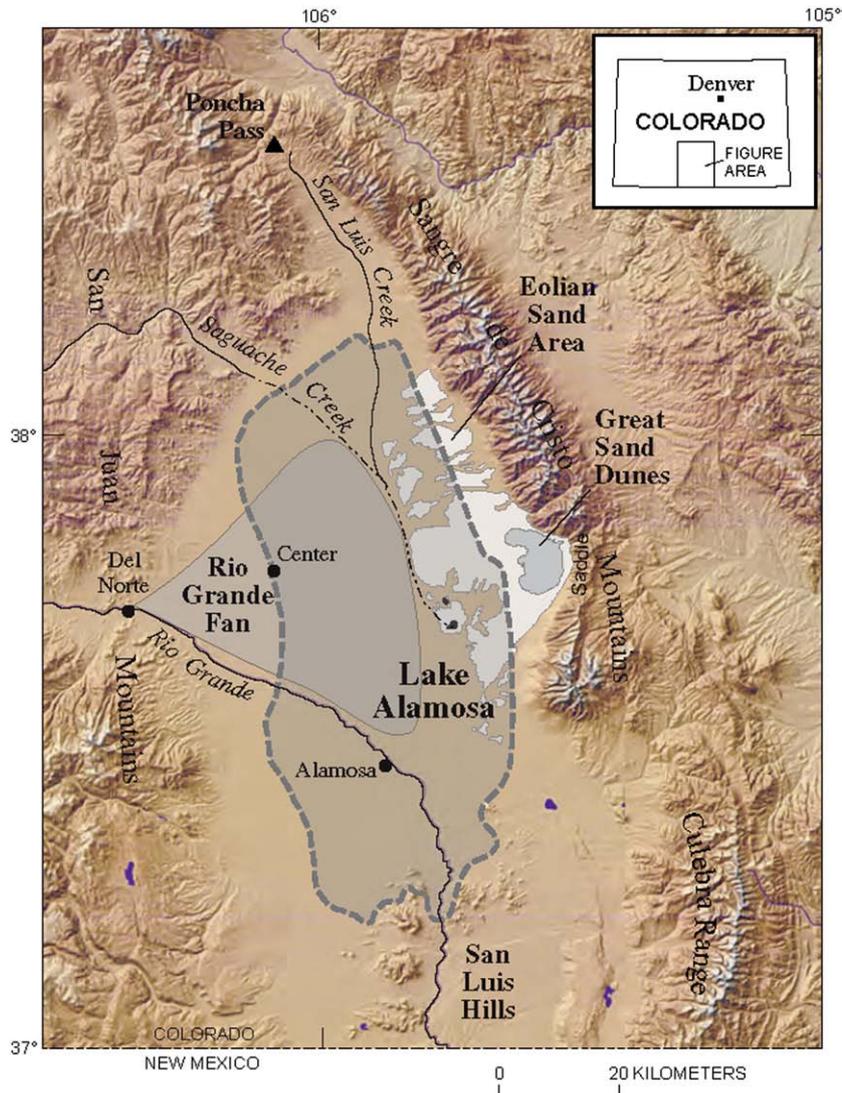
Fig. 15. Map showing the inferred extent of Lake Alamosa based on the altitude of its highest shoreline (2325 to 2330 m; Machette, 2004). Shoreline location is less certain in the northern and western parts of the area because much of the topography there—such as the Rio Grande fan, surficial deposits on the piedmont slope of the Sangre de Cristo Mountains, and eolian sand—postdate Lake Alamosa.

sets of dunes suggest that the dunes are products of separate episodes of wind erosion and deposition, but more importantly, the dunes could not have formed unless water table was lower than the basin floor. De Lanois (1993) reported radiocarbon ages of 928 ± 45 ^{14}C yr BP and 920 ± 60 ^{14}C yr BP for sediment containing organic matter at depths of ~ 70 cm and 90 cm, respectively, beneath the floor of San Luis Lake. The 2σ calendar-year age range for these radiocarbon ages is ~ 950–700 cal yr BP. In addition, charcoal from ~ 1 m below the contact between playa sediment and the base of a prominent lunette dune (7 m high) 4 km south of San Luis Lake (Fig. 14B) provided a radiocarbon age of 1050 ± 70 ^{14}C yr BP (Beta-199426), which has a 2σ age range of 1080–790 cal yr BP.

Relatively small increases in water-table level in the San Luis sump have the potential to produce sizeable lakes because the sump floor is so flat over long distances. When water table was higher than it is at present, areas that are now either dry playas or grass-covered swales (Fig. 13) were lakes and marshes.

Extensive lakes and marshes in and near the sump would have suppressed sand transport and killed terrestrial vegetation in the flooded areas. When the water table fell below the level of the sump floor, lakes, ponds, and perennial streams disappeared and playas emerged (Fig. 14B): the dry lake floors and streambeds, together with other vegetation-free parts of the sump and adjacent areas, then became sources of windblown sand. If playas and stream channels remain dry for a long time, deflation in them eventually slows or ceases because of revegetation, hardening of playa surfaces, or exhaustion of deflatable sand. The level to which the water table falls limits the quantity of sand that can be deflated at any one time. Sand cannot be deflated to levels lower than the wetter part of the capillary fringe just above the water table because wet sand resists deflation. In addition, a bed of cohesive sediment (clay or clayey silty sand), a lag gravel, or cementation by iron and manganese oxides may impose a limit on deflation that is even less than the depth to water table.

Fig. 16. Photograph of a gravel pit on an alluvial fan adjacent to the northern part of the eolian sand area (Fig. 1) shows deposits of two ages. Gravel deposits of different ages are superposed on alluvial fans along the mountain front, and where exposed, the weathering profiles in buried deposits are preserved better than those developed on the oldest gravel terrace deposits, which are not buried by younger deposits as they are on alluvial fans. The depth and intensity of oxidation in the two gravel deposits shown here differ markedly. The zone of oxidation in the upper (gray) gravel is thin (generally <30 cm), indistinct, and typical of deposits of Pinedale (latest Pleistocene) age, whereas, the zone of oxidation in the lower (reddish-brown) gravel is 1 to 2 m thick, distinct, and consistent with deposits of middle Pleistocene age. The oxidation of gravel in the oldest terrace deposit along Sand Creek (11-m-high terrace upstream from the end of the cottonwood forest) is similar to that in the lower gravel shown here.

Fluctuations in water-table level of 2 to 3 m have the potential to produce lakes that would cover most of the area or the entire area from the Dry Lakes to the north end of San Luis Lake (Fig. 4), a distance of ~18 km. Also, a 3-m rise in water table might maintain a shallow lake in the northern part of the area independent of the one in the south because of the high rate of recharge in the north, which comes from several drainage basins on both the east and west sides of the San Luis Valley in that area.

During times of more effective moisture, not only did water table rise and shallow lakes form on the basin floor, but sand supply also was replenished by inflow from the surrounding mountains. When water table fell this sand became available for eolian transport. Thus, lakebeds on the basin floor episodically contributed new sand to a growing dune system. The lower sump (Fig. 4) has probably flooded more frequently than areas farther north because smaller fluctuations in water-table level can cause this area to flood; consequently, the lower sump probably is the primary source of the sand in the Great Sand Dunes.

8. Age of the Great Sand Dunes

The Great Sand Dunes have been assigned various ages ranging from Miocene (Hayden, 1873; Siebenthal, 1910) to post-glacial (inferred to mean Holocene) (Endlich, 1877), post-Pinedale (i.e., the last glaciation) (McCalpin, 1982), and 12,000 to 2000 yr old (Chatman et al., 1997). Some publications cover all bases by listing a broad age range such as Pliocene to Holocene (e.g., cover photo, *Geology*, September 1986). Publications that reference Johnson (1967) generally list the age of the Great Sand Dunes as late Pleistocene. However, some publications (Trimble, 2001; Janke, 2002) inferred that Johnson's late Pleistocene age assignment meant ~12,000 yr ago.

We use geomorphic and stratigraphic data to estimate the age of the Great Sand Dunes. We conclude that they postdate the drainage of Lake Alamosa and predate the time when streams (Cold Creek, Little Medano Creek, and Medano Creek) were deflected by eolian sand that had accumulated near the foot of the Sangre de Cristo Mountains.

8.1. Lake Alamosa

Lake Alamosa occupied a large part of the San Luis Valley north of the San Luis Hills episodically from ~3.5 Ma to ~440 ka (Machette, 2004; Machette and Marchetti, 2006). The highest shoreline of Lake Alamosa was at an altitude of 2325 to 2330 m (Machette, 2004), at which time the lake extended ~100 km north of its lava dam in the San Luis Hills (Fig. 15). According to a preliminary cosmogenic surface-exposure age, the level of Lake Alamosa rose, and overtopped a low point in the San Luis Hills ~440,000 ^{3}He yr ago (Machette and Marchetti, 2006). Incision of a gorge through the San Luis Hills and the lowering of Lake Alamosa began with this overtopping.

Although Lake Alamosa would have inhibited wind transport of sediment across the San Luis Valley while it existed, the eastern shoreline of the lake might have been a source of eolian

sand. However, the relatively minor amount of eolian sand downwind (east) of the San Luis Valley both in the Culebra embayment south of Blanca Peak and in the area north of the Great Sand Dunes (Fig. 15) indicates that little sand was deflated from the eastern shore of the lake. Also, the floor of Lake Alamosa does not appear to have been a significant sand source after the lake drained: in particular, strata capable of producing billions of cubic meters of eolian sand probably are not present beneath this part of the valley. Well-log data (Bureau of Reclamation, unpub., 1977–1984; Powell, 1958) indicate that thick sand beds are uncommon in the area. For example, just north of the Great Sand Dunes, which is in the upper part of the Lake Alamosa basin, Powell (1958) described alternating thin beds of mud, sand, clay, and gravel in which the dominant grain size changed 164 times between the surface and a depth of 305 m, and south of the Great Sand Dunes, Rogers et al. (1985, 1992) described a similar stratigraphy at Hansen Bluff (HB, Fig. 1) in the lower part of the Lake Alamosa basin. If the floor of Lake Alamosa were ever a source of eolian sand, it would have ceased being one when deflation reached beds of cohesive sediment or created a coarse lag deposit from beds of pebbly sand in either the southern or northern part of the former lake basin.

Subsurface data in the northern part of the Lake Alamosa basin indicate that the Great Sand Dunes postdate Lake Alamosa. Well logs and cross sections (Fig. 6 of this paper, and cross sections C–C′, D–D′, and E–E′, Plate 11, Powell, 1958) show that a north–south trending, sand-filled channel, as much as 31 m deep, is incised into thick clayey sediment (presumably lacustrine; see Fig. 6) west and southwest of the Great Sand Dunes. This sand-filled channel is evident in well logs that are spaced out over a north–south distance of ∼9 km (Fig. 6 and wells T-42, T-43, and T-48 of Powell, 1958, Plate 11). Regardless of the genesis of the clayey strata shown in Fig. 6, the sand-filled channel could not form while Lake Alamosa still occupied the area, and as discussed in Section 4.1, we believe that the bottom of the Great Sand Dunes is near the levels of Sand Creek and Medano Creek, which are stratigraphically higher than the base of the sand-filled channel. Thus, we conclude that the Great Sand Dunes are younger than Lake Alamosa, which began to drain ∼440 ka (Machette and Marchetti, 2006) and persisted for an unknown length of time thereafter. The absence of coarse flood deposits downstream from the San Luis Hills suggests that Lake Alamosa did not drain catastrophically. Conceivably, a shallow water table may have maintained wetlands in the lake basin for a long time after Lake Alamosa drained.

8.2. Deflection of Medano, Little Medano, Cold, and Sand Creeks

Prior to the formation of the Great Sand Dunes, streams draining the west flank of the Sangre de Cristo Mountains in the vicinity of the mountain front embayment (Cold Creek, Little Medano Creek, and Medano Creek) would have flowed more or less directly westward, as do other streams farther north (Fig. 4). Today, Little Medano Creek bends nearly 90° to the south at the

east edge of the Great Sand Dunes, whereas Cold Creek is deflected northwestward at an angle of ∼45° (Fig. 5). We attribute these deflections to the growth of incipient dunes in the embayed part of the mountain front. After they were deflected, these streams formed channels that followed the flanks of the Great Sand Dunes. Thus, the age of the oldest alluvium along the deflected reaches of these creeks establishes a minimum date for the antiquity of the Great Sand Dunes. The age estimated for the oldest terrace deposit is based on (1) its position in the landscape relative to other landforms and (2) the degree to which its surface sediment is weathered, which is primarily a matter of depth of oxidation.

The oldest alluvium along the deflected reaches of Cold, Little Medano, and Medano Creeks became a terrace deposit when these creeks deepened their valley floors to levels 10 to 12 m lower than upper surface of the oldest alluvium. Two other lower (younger) terraces are well defined in these valleys and in other valleys farther north (e.g., Cottonwood Creek, Deadman Creek, and the unnamed stream between these two creeks), but are relevant to this study only in that they document the progress of valley deepening after the 10- to 12-m-high terrace was formed.

Near the mountain front, the oldest alluvium along the deflected streams is gravelly but becomes progressively sandier westward, and is nearly all sand within a few kilometers of the mountain front (Fig. 7). Where the alluvium consists of gravel that resisted erosional stripping, it is deeply oxidized and many clasts in it are highly weathered, characteristics that are not found in surficial deposits of latest Pleistocene age (∼35 to 12 ka) in this area.

The depth and intensity of oxidation in unconsolidated surficial deposits increase with time, but the process is slow on a geological time scale (Birkeland, 1999). Thus, large differences in the depth and intensity of oxidation between different deposits suggest that the deposits differ greatly in age. The weathering of the high-terrace gravel is much greater than that observed in similar gravel mantling alluvial fans along the west edge of the Sangre de Cristo Mountains (Fig. 16), some of which is traced to Pinedale moraines that terminate at the fan apices (McCalpin, 1982). The Pinedale glacier in the upper Rio Grande receded from its terminal moraine between ∼21,500 and 16,600 [10]Be yr ago (Benson et al., 2005). The glaciers that terminated at fan apices along the west flank of the Sangre de Cristo Mountains probably would have begun to recede at about the same time as the Rio Grande glacier. Thus, the B horizon (the distinctly oxidized horizon) of soil developed on Pinedale moraines along the west flank of the Sangre de Cristo Mountains is the product of soil formation that began after ∼21,500 [10]Be yr ago. The B horizon on these moraines is thin to absent (0 to 10 cm thick), and the B horizons of soils developed in Pinedale fan alluvium range from 0 to ∼36 cm thick (McCalpin, 1982). Also, the principal soils developed in alluvium of Pinedale age in the proximal part of the Rio Grande fan (Dunul and Norte soil series, classified as Typic Torriorthent and Typic Ustorthent, respectively; Pannell et al., 1980) consist of simple A/C horizon sequences; i.e., they lack B horizons or material that is distinctly oxidized.

In contrast to the thin zone of oxidation or lack of oxidation on moraines and alluvial fans on the east side of the San Luis Valley (McCalpin, 1982) and on the Rio Grande fan (Pannell et al., 1980), the zone of oxidation in the oldest alluvium of the deflected streams is typically 1 to 2 m thick (Fig. 16). The degree to which this alluvium is weathered is consistent with a middle Pleistocene age (defined as the time between 778 and 126 ka; International Commission on Stratigraphy, 2005). Thus, we conclude that the oldest alluvium is at least as old as the next to last glaciation (called Bull Lake), which in this region ended ~130 ka (Shroba et al., 1983; Fullerton et al., 2003); i.e., the Great Sand Dunes began to form prior to 130 ka.

9. Conclusions

The distribution of eolian sand along the east edge of the San Luis Valley indicates that the closed basin north of the Rio Grande, referred to here as the sump, was the immediate source of eolian sand in the Great Sand Dunes. Eolian sand is restricted to an area that corresponds approximately to the length of the sump, and the sand is thickest and most extensive on the downwind side of the sump.

The sump was a depocenter for alluvium, chiefly of fluvial origin, derived from the Sangre de Cristo Mountains on the east and the San Juan Mountains on the west, but most sediment came from the San Juan Mountains by way of the Rio Grande fan and Saguache Creek. The Rio Grande fan is a large (~1150 km^2), low gradient (~3.5 m/km to <1 m/km) plain sandur (outwash plain). Large amounts of sand underlie the distal edges of the Rio Grande fan, the piedmont slope west of the Sangre de Cristo Mountains, and the sump, which lies between the fan and piedmont slope.

Although sand is abundant in the sump area, eolian transport of it from this area occurred only when sand was "available" (free to move). We believe that flooding at different times and of different magnitudes was the primary control on sand "availability." Large-scale flooding occurred during glaciations and smaller scale flooding occurred at other times because of fluctuations of water-table level. Eolian sand began to accumulate in the Great Sand Dunes area during middle Pleistocene time, and it has continued to be deposited episodically to the present.

The height and morphology of the Great Sand Dunes is due to the location and geometry of the source area, the "availability" of sand for wind transport, a complex wind regime, and the focusing of wind by the mountain-front embayment and saddle.

The conclusions summarized here constitute a set of hypotheses that suggest numerous avenues for future research and testing. First, numerical ages, although challenging to obtain, are needed to test the dates estimated here for the origin of the Great Sand Dunes and for the timing of climate changes that occurred during their development. Second, the estimated quantity of sand presently in the Great Sand Dunes places demands on (1) source regions in the San Juan and Sangre de Cristo Mountains, (2) fluvial transport from these source regions to the sump, and (3) eolian transport from the sump to the Great Sand Dunes. These demands should be quantified and

modeled in the context of a numerically dated eolian history to assess relations between dune development and local (and possibly global) climate change over the past 440,000 yr, the time since Lake Alamosa began to drain.

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