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Late Quaternary loess in northeastern Colorado: Part II—Pb isotopic evidence for the variability of loess sources

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ABSTRACT

A new application of the Pb isotopic tracer technique has been used to determine the relative importance of different silt sources for late Wisconsin loess in the central Great Plains of eastern Colorado. Samples of the Peoria Loess collected throughout the study area contain K-feldspar derived from two isotopically and genetically distinct sources: (1) glaciogenic material from Early and Middle Proterozoic crystalline rocks of the Colorado province, and (2) volcaniclastic material from the Tertiary White River Group exposed on the northern Great Plains. Pb isotopic compositions of K-feldspar in loess from two dated vertical sections (at Beecher Island and Last Chance, Colorado) vary systematically, implying climatic control of source availability. We propose a model whereby relatively cold conditions promoted the advance of Front Range valley glaciers discharging relatively little glaciogenic silt, but strong winds caused eolian erosion of White River Group silt due to a decrease in vegetation cover. During warmer periods, valley glaciers receded and discharged abundant glaciogenic silt, while surfaces underlain by the White River Group were stabilized by vegetation. Isotopic data from eastern Colorado loess sections record two warm-cold-warm cycles during late Wisconsin time between about 21 000 and 11 000 radiocarbon yr B.P., similar to results from other studies in the United States and Greenland.

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INTRODUCTION

Recent studies of Quaternary climate change have emphasized the importance of thick, possibly continuous, loess sequences in China and Tajikistan that contain detailed terrestrial records of Quaternary glacial-interglacial cycles, comparable to the foraminiferal oxygen isotope record in deep-sea sediments (Kukla et al., 1988; Hovan et al., 1989; Ding et al., 1994; Forster and Heller, 1994; Xiao et al., 1995; Shackleton et al., 1995). In the Great Plains region of Nebraska, Kansas, and eastern Colorado, late Quaternary loess is the most extensive surficial sediment. At many localities, the thickest loess stratigraphic unit is of late Wisconsin age (i.e., latest Quaternary), deposited between ca. 20 and 10 ka, based on numerous radiocarbon and thermoluminescence ages (Johnson, 1993; May and Holen, 1993; Martin, 1993; Maat and Johnson, 1996; Pye et al., 1995). These ages agree reasonably well with radiocarbon and thermoluminescence ages of the Peoria Loess in the central lowland region (i.e., east of the Missouri River in Iowa, Illinois, Missouri, Wisconsin, and elsewhere) (Ruhe, 1983; Forman et al., 1992; Grimley et al., 1998). Six new accelerator mass spectrometry ^{14}C ages from two localities in eastern Colorado indicate that the thickest (to 10 m) loess deposits were laid down between ca. 20.0 and 11.8 ka (Muhs et al., 1999, companion paper in this volume). This age range is close to the estimated time of maximum extent of late Wisconsin (Pinedale) glaciers in the Front Range of Colorado and final Pinedale deglaciation (Madole, 1986) and confirms earlier correlations of loess in Colorado with the Peoria Loess to the east (Scott, 1978; Sharps, 1980).

Loess east of the Missouri River is interpreted as being glaciogenic in origin (Flint, 1971). During the last glacial maximum ca. 20–15 ka (the late Wisconsin, or Pinedale glaciation), continental ice entered the headwaters of the Missouri, Mississippi, Illinois, and Ohio Rivers. Fine-grained particles from silt-rich outwash from this ice were transported by northwesterly and westerly winds and deposited as loess over much of Iowa, Missouri, Illinois, and Wisconsin, and to a lesser extent over South Dakota, Minnesota, Indiana, Ohio, Arkansas, Kentucky, Tennessee, Mississippi, and Louisiana. Loess distribution, thickness, and particle size have distinctive downwind trends that support this model (Ruhe, 1983). The source of thick loess in the western Great Plains is less apparent. Valley glaciers, which occurred on both sides of the continental divide in the Front Range of Colorado, were far smaller than the Laurentide ice sheet (Madole et al., 1998) and would have generated much less silt-sized outwash sediment.

In this paper we document evidence for the source of loess in eastern Colorado, using Pb isotopic compositions of detrital K-feldspar as tracers. From these data it is possible to infer paleowind directions. In addition, the change in sources is used to devise a model of climate change over a period of about 10 k.y. in late Pleistocene time.

POSSIBLE SOURCES OF LOESS IN COLORADO

The lack of an obvious glaciogenic link for the Peoria Loess of the Great Plains has generated debate about the origin of this sediment for at least 50 yr. Although no recent investigators have doubted the eolian origin of loess of the Great Plains, there is considerable divergence of opinion about the source of the sediment. Some workers have favored a glacial outwash origin, suggesting that rivers having their headwaters in

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GSA Bulletin; December 1999; v. 111; no. 12; p. 1876–1883; 7 figures.

the Rocky Mountains of Colorado were major sources (Bryan, 1945; Frye and Leonard, 1951; Swineford and Frye, 1951; Pye et al., 1995). Other workers downplayed (but did not exclude) the importance of glacial outwash as a source and emphasized alternative sources such as nonglaciogenic alluvium, old till sheets, Tertiary bedrock such as volcaniclastic siltstone of the White River Group (major outcrops occur in southern Wyoming and northern Colorado, Fig. 1), and eolian sand seas, such as the Nebraska Sand Hills (Condra and Reed, 1950; Lugn, 1968). Flint (1971) challenged the single-source, glacial outwash hypothesis, suggesting that Pinedale valley glaciers in the Front Range were too small to produce the large volume of loess in the Great Plains. Based on new mapping, Welch and Hale (1987) concluded that loess in Kansas probably had multiple sources, including glacial outwash, dune sand, and the Tertiary Ogallala Group.

In eastern Colorado, the possible sources for the Peoria Loess are glaciogenic silt transported by the South Platte River, and/or the White River Group. The South Platte River drains the region of Pinedale valley glaciers in the Front Range and is west, north, and northwest of the main bodies of loess in eastern Colorado (Fig. 1). Sediment in the South Platte River (Aleinikoff et al., 1994) is derived primarily from Early and Middle Proterozoic (1.4 and 1.7 Ga) crystalline rocks of the Colorado province (Tweto, 1987; Aleinikoff et al., 1993). However, sediments of the White River Group (upper Eocene to lower Oligocene) are also appealing as possible sources for the calcareous, silt-rich loess of eastern Colorado because they are physically and chemically weathered, contain 65%–85% silt and 20%–30% $CaCO_3$ (Denson and Bergendahl, 1961), have a sparse vegetation cover, and have a broad surface distribution north to northwest of most of the loess deposits in eastern Colorado (Fig. 1). We do not consider the Miocene Ogallala Formation a likely source because it contains minimal silt-sized material (Sato and Denson, 1967). Extensive sand dunes in northeastern Colorado are also unlikely sources because they are composed dominantly of sand-sized material and are the same age as, or younger than, the loess (Muhs et al., 1996).

Geochemical methods, together with mineralogical studies, can sometimes identify eolian sediment sources (e.g., Biscaye et al., 1997; Eden et al., 1994; Gallet et al., 1996, 1998; Liu et al., 1993; Muhs et al., 1990, 1996). Gallet et al. (1996, 1998) and Biscaye et al. (1997) also used isotopic data to discriminate sources of eolian sediment. However, geochemical and mineralogical analyses do not result in unequivocal evidence for the source of the Peoria Loess in eastern Colorado (Muhs et al., 1999). Radiogenic isotopic studies were initiated to resolve the ambiguity of the geochemical data. This region is particularly attractive to test the application of isotopic analysis for the determination of loess source because the two proposed provenances differ in age by about 1700 m.y. Thus, the K-feldspar Pb isotopic compositions and zircon U-Pb ages of the two sources are distinct.

ANALYTICAL METHODS

The Pb isotopic "fingerprinting" approach has been used in applications as wide ranging as identifying sources of glacial till in Manitoba and Newfoundland (Bell and Murton, 1995) and differentiation of tectonostratigraphic terranes in Alaska (Aleinikoff et al., 1987). We sampled: (1) Peoria Loess, (2) White River Group sediments, and (3) alluvium of two ages from the South Platte River (modern sediments, and silt deposited during the late Wisconsin on South Platte River terraces) (Fig. 1). Samples of both late Wisconsin and modern alluvium were collected to verify our presumption that material transported in the late Wisconsin is similar to modern sediments in the South Platte River.

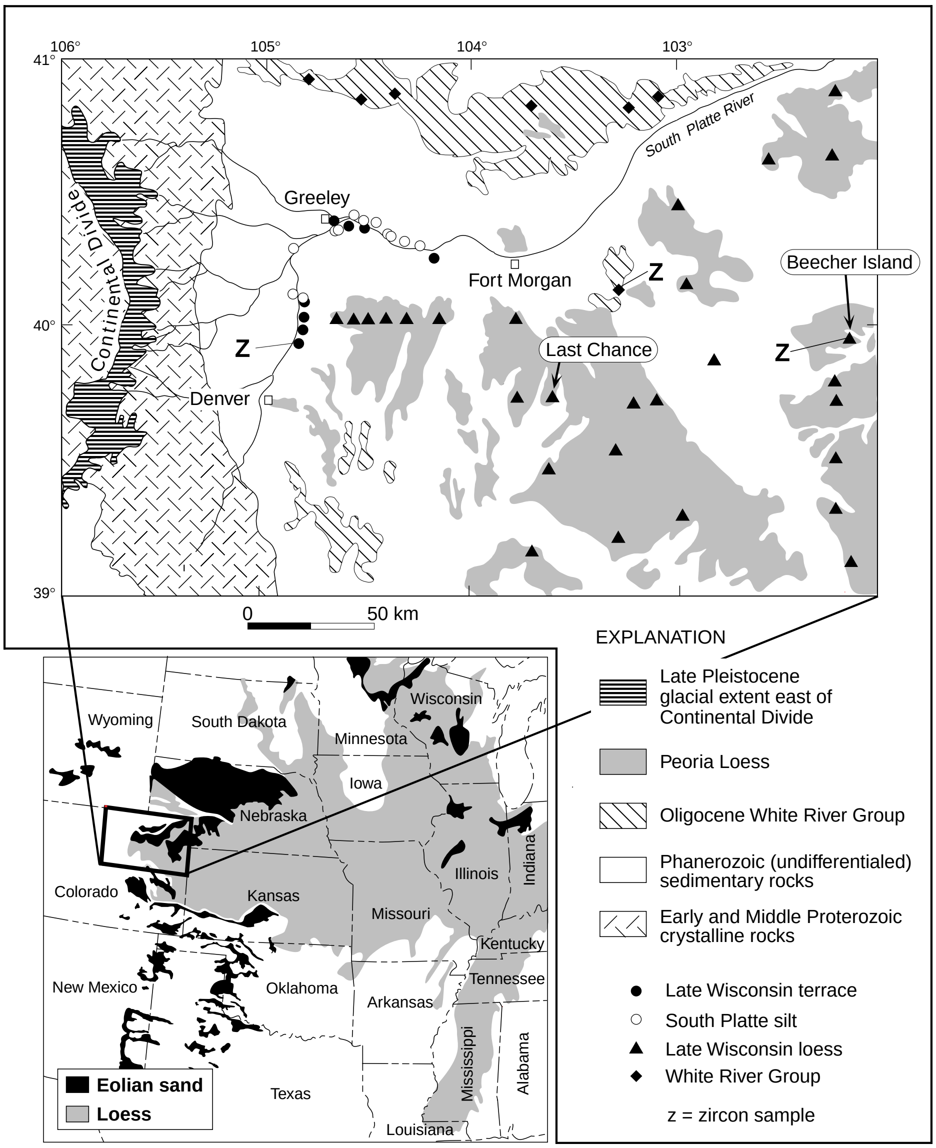

Figure 1. Generalized geologic map of northeastern Colorado, showing sample locations. Compiled, with modifications, from Scott (1978), Sharps (1980), Crabb (1980), Bryant et al. (1981), and Madole et al. (1998). Small-scale inset shows regional distribution of Holocene eolian sand and latest Pleistocene loess in the midcontinent (compiled from Flint, 1971; Muhs and Holiday, 1995).

Terrace samples consist of sediments that were transported by the South Platte River during late Wisconsin time and may be correlative with the Peoria Loess. Care was taken to sample South Platte River alluvium only upstream of loess deposits in order to avoid problems of fluvially reworked loess. We collected unaltered loess below the zone of pedogenesis but within 2 m of the surface throughout the study area (Fig. 1). We also sampled at 0.5 m intervals from two dated vertical sections of the Peoria Loess.

K-feldspars were isolated by flotation in sodium polytungstate and purified by magnetic separation to remove grains that contain opaque inclusions. K-feldspars from modern alluvium and late Wisconsin terrace deposits were sieved so that only grains finer than 200 mesh (<0.074 mm) were analyzed. Pb isotopic compositions of K-feldspar fractions (weighing 5–15 mg) were analyzed on a VG 54E mass spectrometer with a single Faraday cup.

Very fine grained zircons were extracted from samples of loess and prospective sources using a Wilfley table (running slower than when processing material from coarse-grained rocks), magnetic separator, and methylene iodide. Most grains have typical detrital characteristics such as frosted, pitted, and rounded surfaces, and a high degree of sphericity (Fig. 2). The U-Pb ages were determined on individual zircons using the SHRIMP II ion microprobe at the Australian National University following standard procedures outlined by Compston et al. (1984) and Williams and Claesson (1987). Most zircons analyzed have diameters only slightly larger than the 20 µm diameter of the primary oxygen-ion beam spot.

The Pb isotopic compositions of K-feldspar from the Peoria Loess are compared with that from fractions of K-feldspar from the White River Group, modern channel and overbank deposits of the South Platte River, and silt from late Wisconsin terraces along the South Platte River using standard common Pb plots ($^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$; ISOPLOT program of Ludwig, 1991) (Fig. 3, A and B). Ion microprobe ages of zircons from the Peoria Loess, the White River Group, and the late Wisconsin South Platte River terrace are compared using a relative probability plot (essentially a nearly binless, weighted histogram) (Fig. 4). For zircons older than 1.0 Ga, the $^{207}Pb/^{206}Pb$ age is plotted. Younger grains are plotted using the $^{206}Pb/^{238}U$ age because Late Proterozoic and Phanerozoic $^{207}Pb/^{206}Pb$ ages have very large uncertainties due to the minimal growth of radiogenic ^{207}Pb in the past 1000 m.y. Uncertainties (2 σ) for $^{207}Pb/^{206}Pb$ ages are 1%–19%, and most are in the range of 2%–5%. Uncertainties for $^{206}Pb/^{238}U$ ages, with two exceptions, are 5%–9%.

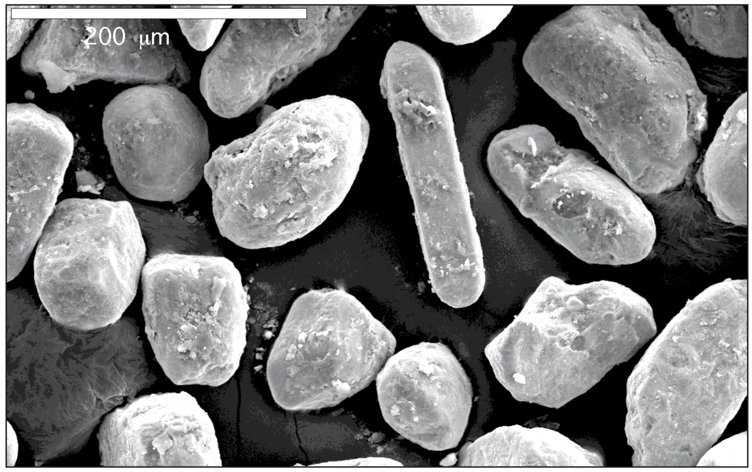

Figure 2. Scanning electron microscope digital image of zircon from loess sample Li-210, collected at a depth of about 5 m at the Beecher Island locality. Elongate prismatic zircon has morphology characteristic of 34 Ma volcanic zircon from the White River Group. More rounded grains are typical of the Proterozoic population found in both the loess and White River Group.

RESULTS

The Pb isotopic compositions of fine-grained K-feldspar from the South Platte River channel and overbank deposits, late Wisconsin terrace deposits, siltstone of the White River Group, and the Peoria Loess are readily distinguishable (Table DR1[1], Fig. 3). South Platte River silt has $^{206}Pb/^{204}Pb$ ranging from about 17.0 to 17.8, whereas silt from late Wisconsin terraces of the South Platte River has $^{206}Pb/^{204}Pb$ ranging from about 17.4 to 18.6. The less radiogenic part of the field of Pb isotopic ratios of silt from late Wisconsin terraces overlaps with data from fine-grained South Platte alluvium. However, about half of the terrace samples have significantly higher ratios than the alluvium, approaching ratios measured on K-feldspars from the White River Group (Fig. 3A). We conclude that the South Platte River was carrying a higher proportion of K-feldspar from the White River Group in late Wisconsin time than at present, and the paleoclimatic implications for this change in composition of suspended sediment are discussed in the following. K-feldspars from volcaniclastic siltstone of the White River Group have Pb isotopic ratios that are typical of Tertiary volcanic material (Fig. 3A) and are much more radiogenic than those of the South Platte River and of some of our samples from late Wisconsin terrace sediment. K-feldspars from the Peoria Loess have Pb isotopic compositions that span the entire range of ratios measured in both possible sources (Fig. 3B), indicating that the loess was derived from both glaciogenic silt in the South Platte River (eroded from Front Range crystalline rocks) and from silt of the Tertiary White River Group.

The U-Pb ages of detrital zircons in one sample each from the Peoria Loess and late Wisconsin terrace silt of the South Platte River and from three samples of White River Group silt were determined to provide independent evidence for the source of the loess (Table 2 [see footnote 1], Fig. 4). Our sampling strategy for zircon analysis was to collect loess from a well-dated locality within a relatively thick exposure of the Peoria Loess. Loess sample CO-210 was collected at the Beecher Island locality in eastern Colorado (Fig. 1), about 1 m below a buried soil dated as 11–12 ka (Muhs et al., 1999). Zircon extracted from a sample of South Platte River late Wisconsin terrace silt was collected at a quarry exposure about 15 km north of Denver, Colorado (Fig. 1). Zircon from three samples of the White River Group (collected southeast of Fort Morgan, Colorado, in Badlands National Park, South Dakota, and southwest of Scottsbluff, Nebraska) were analyzed because of the large geographic exposure of this volcaniclastic sediment (data combined in Fig. 4).

The relative probability plot of zircon from the late Wisconsin terrace silt has three peaks of Proterozoic age (1.7, 1.4, and 1.1 Ga), corresponding closely with the ages of plutonic rocks in the Colorado province (Tweto, 1987), plus a small peak at about 450 Ma and one grain with an age of about 58 Ma (Fig. 4). In contrast, relative probability plots of the White River Group (composite plot) and the Peoria Loess have many peaks be-

[1]GSA Data Repository item 9994, supplemental Tables DR1 and DR2, is available on the Web at http://www.geosociety.org/pubs/drpint.htm. Requests may also be sent to Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301; e-mail: editing@geosociety.org.

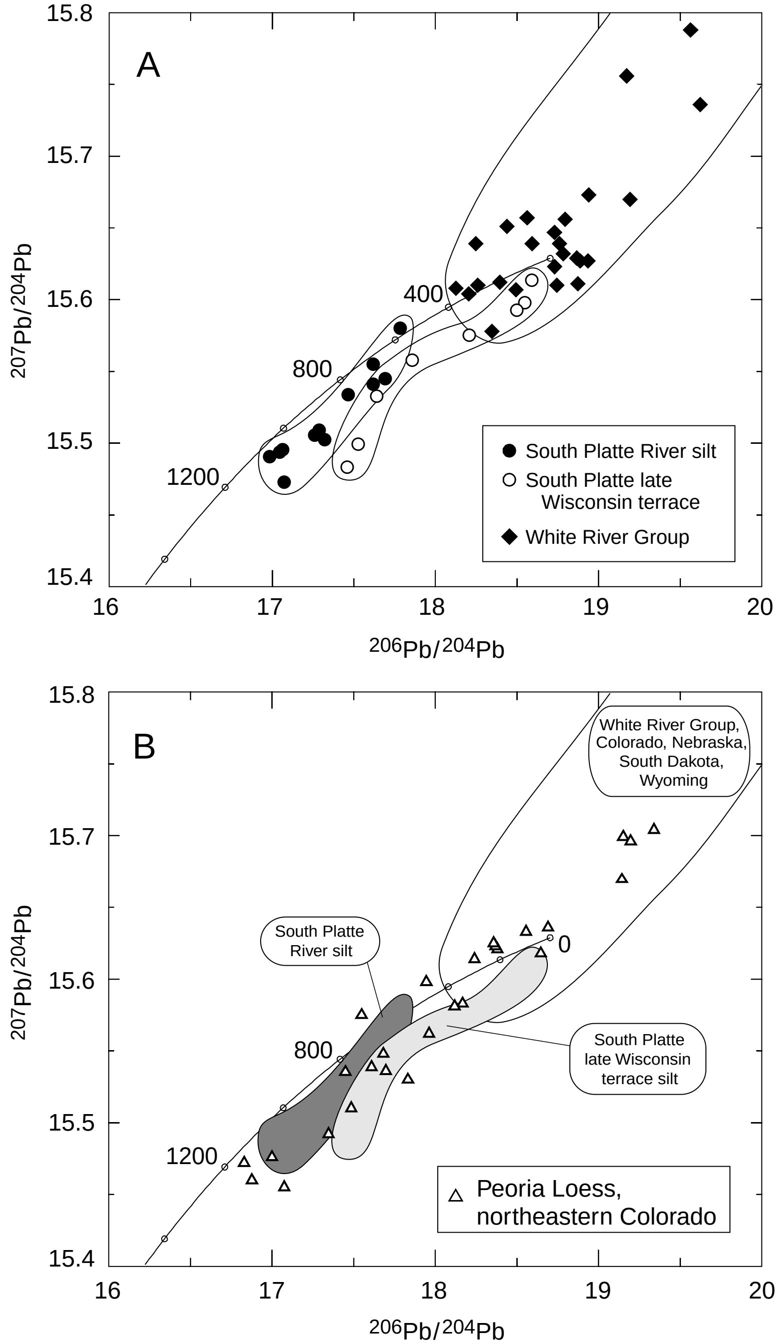

Figure 3. Pb isotopic compositions of K-feldspars from Peoria Loess and potential sources. (A) Data from possible sources. (B) Data from the Peoria Loess. Fields derived from A.

tween 1.0 and 2.8 Ga (including significant peaks at about 1.4 and 1.7 Ga, plus a subordinate population at about 1.0 Ga) and between 20 and 150 Ma. A population of elongate, euhedral, unabraded (i.e., igneous) zircons from the sample of White River Group from Colorado yields a composite age of 34 ± 1 Ma (weighted average of $^{206}Pb/^{238}U$ ages of 16 grains). This age agrees, within analytical uncertainty, with a zircon fission-track age of 32 ± 3 Ma (Zielinski and Naeser, 1977) and $^{40}Ar/^{39}Ar$ ages ranging from 30.05 ± 0.19 to 35.97 ± 0.45 Ma for the White River Group in Nebraska and Wyoming (Swisher and Prothero, 1990; Obradovich et al., 1995).

Two vertical sections were sampled in detail to assess the degree of source variability throughout late Wisconsin time. The Beecher Island section in the easternmost part of the study area (Fig. 1) is about 11 m thick (Fig. 5). Below the modern soil, a thin loess layer caps a buried soil that is dated as ca. 11.5 ka, separating the younger Beecher loess from the Peoria Loess. A second buried soil near the bottom of the section is ca. 20.5 ka, thus bracketing the period of Peoria Loess deposition to a maximum of about 9 k.y. To the west, the Last Chance section (Fig. 1) is less complete than the Beecher Island section because the 11.5 ka buried soil and younger loess are missing, but a buried soil dated as ca. 21.0 ka marks the bottom of the Peoria Loess (Fig. 5). Because of the lack of age control at the top of the Last Chance section, we are unable to determine the maximum total duration of loess deposition.

K-feldspars from the Peoria Loess in the two vertical sections have Pb isotopic compositions that span the entire range of ratios measured in both possible sources (Fig. 6), suggesting that the loess was derived from both glaciogenic silt in the South Platte River (primarily from Early to Middle Proterozoic crystalline rocks of the Colorado province) and silt from the White River Group. The isotopic ratios vary systematically within each section. In both sections, the oldest loess (just above the ca. 21.0 ka paleosol) has Pb isotopic compositions within the range of ratios measured in silt-size K-feldspars from the South Platte River. The ratios increase upsection (to values corresponding to ratios measured in K-feldspars from the White River Group) and decrease twice. The occurrence of this bimodal variation at both localities lends credence to the conclusion that this variation is nonrandom. However, we cannot correlate these sections because the Last Chance sequence does not have a bracketing age at the top of the section.

A comparison of grain morphologies supports the interpretation of multiple sources. K-feldspar grains from loess with relatively nonradiogenic Pb isotopic ratios (sample LI-226) (i.e., glaciogenic source) are rounded (Fig. 7A), indicating fluvial transport. In contrast, K-feldspar grains from loess with relatively radiogenic ratios (sample LI-221) have sharp edges and angular tips (Fig. 7B). These grains apparently have not undergone significant fluvial abrasion and do not have the features (such as rounding, pitting, and frosting) that are characteristic of fluvial detrital minerals. Although external morphology is not uniquely diagnostic of source, the differences in appearance of these two populations support the conclusion of source variability, transport mode, and/or distance of transportation.

PALEOCLIMATIC IMPLICATIONS

The identification of both South Platte River and White River Group sources of the Peoria Loess in eastern Colorado provides constraints for the direction of paleowinds during latest Pleistocene time. Because both sources occur to the north and northwest of the loess deposits, paleowind directions were from the north and/or northwest. However, this interpretation is contrary to the conclusions of certain atmospheric general circulation models (e.g., COHMAP Members, 1988) that have postulated the existence of anticyclonic winds (i.e., from the east or northeast) in interior North America in response to the Laurentide ice sheet. Thus, paleowind data from Colorado are consistent with other loess sequences indicating westerly or northwesterly winds during full glacial time (Muhs and Bettis, 1998).

To explain the variation in Pb isotopic composition of K-feldspar in loess in the two vertical sections in eastern Colorado, we suggest the following scenario, assuming that the rate of loess deposition was generally constant and that significant amounts of loess were not removed from the section by erosion. Under relatively cold conditions of a glacial period, valley glaciers of the Front Range advanced and glaciogenic silt derived from Proterozoic crystalline rocks of the Colorado province was entrained within the ice, with relatively little sediment released to streams. Concomitantly, the cold and arid glacial conditions may have reduced plant cover and thereby increased erosion of the White River Group. Although there may have been some eolian erosion directly from sediments of the White River Group, it is more likely that reduced vegetation cover would allow greater fluvial erosion and delivery to tributaries of the South Platte River. A large part of the area where sediments of the White River Group are found (Fig. 1) is highly dissected by small ephemeral streams, and we suspect that much eolian removal of White River Group–derived sediments took place after delivery to these channels. Reduced vegetation cover on sediments of the White River Group during late Wisconsin time would also explain why there is a greater proportion of White River Group–derived K-feldspars in late Wisconsin terrace sediments of the South Platte River. As conditions became warmer, vegetation was reestablished on surfaces of the White River Group, inhibiting erosion, while valley glaciers of the Front Range receded, generating more outwash in the process. Thus, we suggest that there was an antithetic relationship for the activation of sources of loess in eastern Colorado, both of which occurred in response to climatic variation. Highly radiogenic Pb isotopic ratios in K-feldspars in loess (derived from the Tertiary White River Group) indicate relatively cold conditions, whereas low Pb isotopic ratios in loess K-feldspars (glaciogenic derivation from the Proterozoic crystalline rocks, via the South Platte River) indicate relatively warm conditions.

The shifts in paleotemperatures inferred from Pb isotope data agree with conclusions from other proxy methods for evaluating past climatic conditions. Estimates of late Pleistocene glacier equilibrium lines in Colorado indicate summer temperature depressions of at least 8.5 °C (Leonard, 1989). On the basis of changing fossil beetle assemblages, mean July temperatures and January temperatures near Denver at 14.5 ka were 10–11 °C and 26–30 °C colder, respectively, than present temperatures (Elias, 1996). However, by 10 ka the beetle assemblages indicate warmer than present summers and winters. Carbon isotopic values in loess and paleosols at Beecher Island indicate a minimum summer temperature depression of 5–6 °C in full-glacial time, with warming at about 12 ka (Muhs et al., 1999). This postulated warming trend agrees with data from Front Range glacial deposits that indicate that final deglaciation occurred between about 15 and 12 ka (Madole, 1986). Our interpretation of the Pb isotope data from Beecher Island also suggests a warming trend during this interval.

Because our model for the cause of change in Pb isotopic ratios for the younger portion of our data set agrees with other independent evidence, we hypothesize that the method is also valid for the older portion of the section. The data suggest the occurrence of an earlier cycle of warming and cooling between peak late Wisconsin glaciation and final deglaciation. The mutual agreement of the Pb isotope ratio curves from Last Chance and Beecher Island provides additional confidence in this proxy method. The rapid cycle of climatic change (two warm-cold-warm cycles in a maximum of about 9000 yr) as suggested by the Pb isotope data from eastern Colorado loess sections

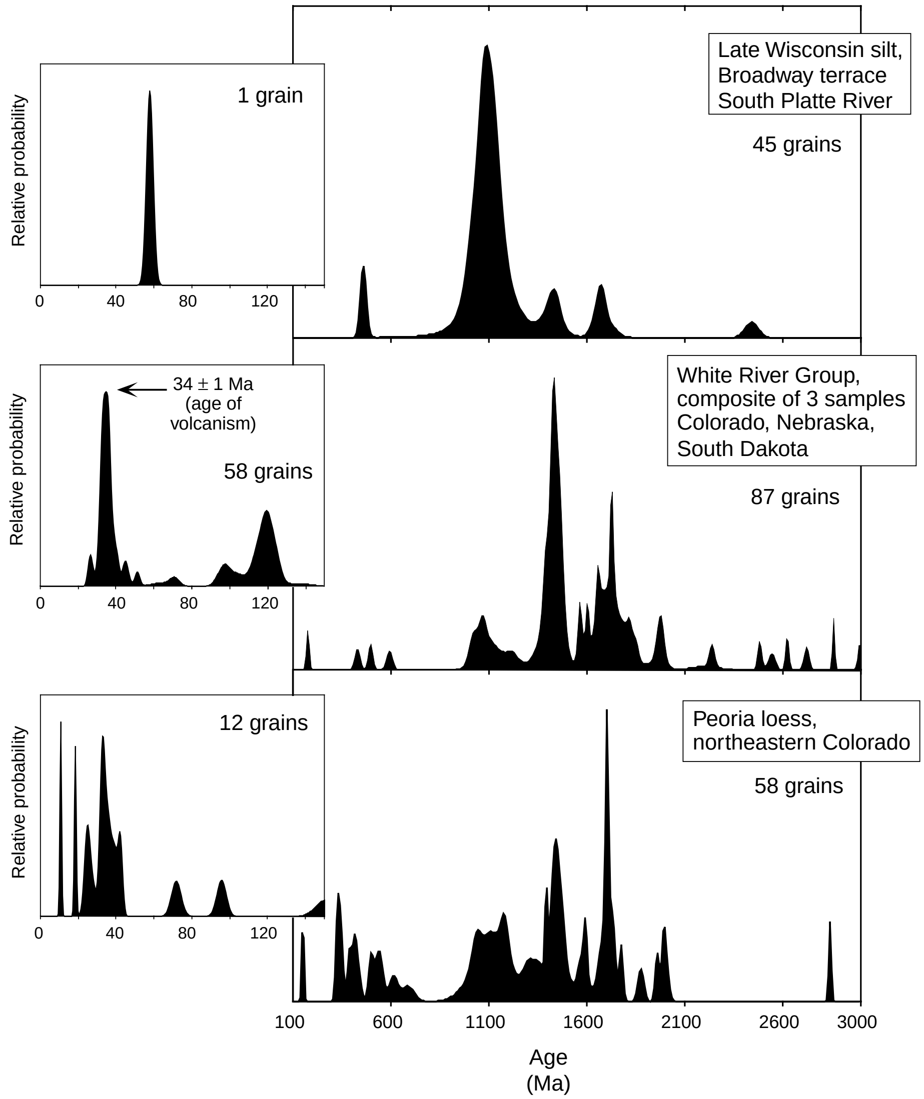

Figure 4. Relative probability plots of U-Pb ages of zircons from the Peoria Loess, South Platte River channel sediment, and siltstone of the White River Group.

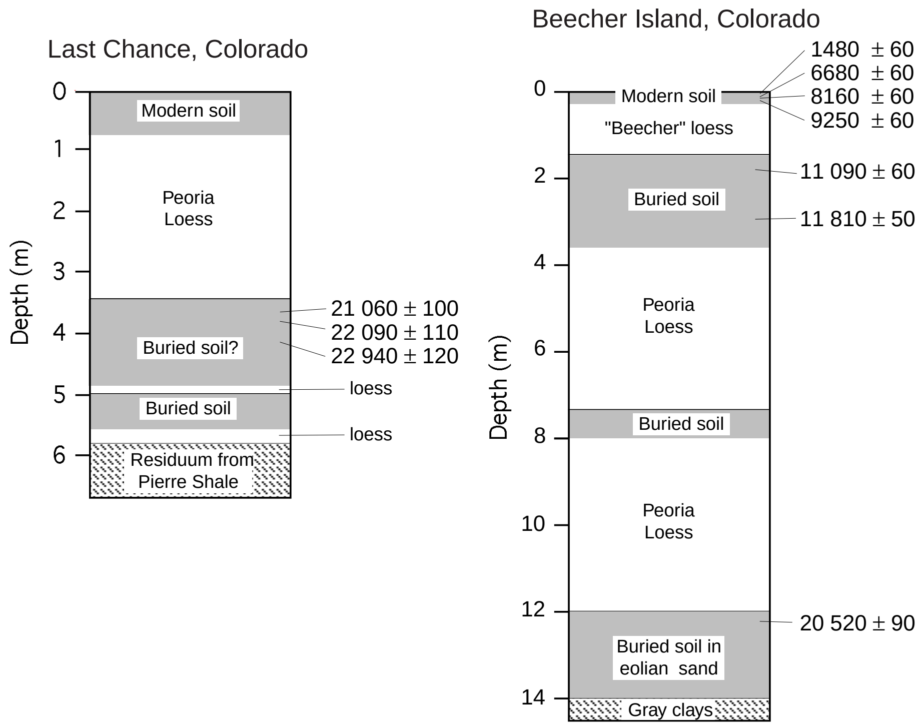

Figure 5. Stratigraphic sections of Peoria Loess from eastern Colorado. Samples were taken at 0.5 m intervals.

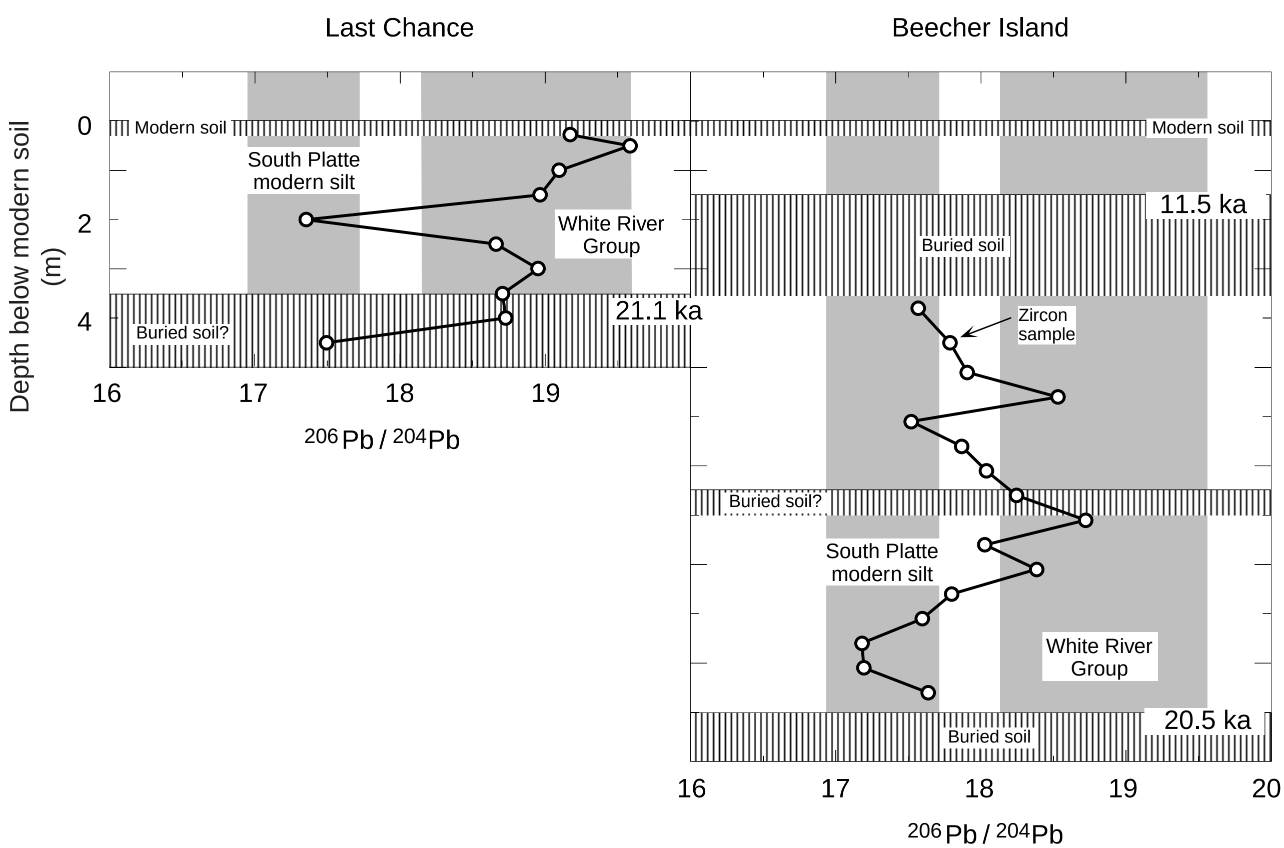

Figure 6. ^{206}Pb/^{204}Pb vs. depth of K-feldspar in loess from eastern Colorado.

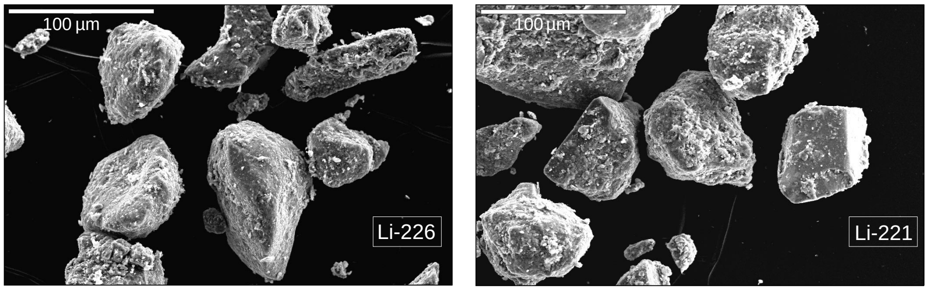

Figure 7. Scanning electron microscope digital images of K-feldspars in loess from the Beecher Island locality, Colorado. (A) K-feldspars with low $^{206}Pb/^{204}Pb$, derived from Proterozoic rocks of the Colorado province, presumably by glacial erosion and fluvial transport via the South Platte River. Note the high degree of abrasion and rounding. (B) K-feldspars with high $^{206}Pb/^{204}Pb$, indicative of derivation from a Tertiary source. Note sharp edges and flat crystal faces. Most of these grains are probably of volcanic origin and have only been moderately abraded by fluvial and eolian processes.

is similar to oxygen isotope and paleotemperature data from Greenland ice cores (Johnsen et al., 1992; Dansgaard et al., 1993). We conclude that the application of Pb isotopes to problems of climate change is a powerful tool if the appropriate conditions for varying, isotopically distinct loess sources exist.

CONCLUSIONS

1. The sources of loess in eastern Colorado are the South Platte River, which transported glaciogenic silt provided by late Wisconsin (Pinedale) glaciers in the Front Range, and sediments of the Tertiary White River Group.

2. Paleowind directions were predominantly from the north or northwest. There is no evidence for easterly or northeasterly paleowinds, contrary to the glacial anticyclone hypothesis derived by some atmospheric general circulation models.

3. The variation in dominant sediment source was probably due to climate changes within the last glacial period. Glaciogenic source sediments were dominant during relatively warm periods as glaciers retreated, whereas volcanogenic silt from the White River Group was dominant during relatively cold periods when vegetation cover was minimal.

4. According to our model, two warm-cold-warm cycles occurred in the central Great Plains during late Wisconsin time (from about 22 to 10 ka), in agreement with evidence from Greenland ice cores.

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TABLE 1. Pb ISOTOPIC COMPOSITIONS OF SILT-SIZE K-FELDSPAR

sample number	unit[1]	$^{206}Pb/^{204}Pb$ [2]	$^{207}Pb/^{204}Pb$ [2]	$^{208}Pb/^{204}Pb$ [2]	depth (m)[3]
Li 210*	loess [zircon sample]	18.373	15.621	38.224	
Li 37	loess	17.374	15.538	36.754	
Li 44	loess	17.561	15.541	37.088	
Li-45	loess	17.697	15.536	37.074	
Li-25	loess	17.075	15.455	36.657	
Li-4	loess	17.000	15.476	36.475	
Li-6	loess	17.681	15.548	37.247	
Li-21	loess	16.877	15.460	36.513	
St-16	loess	16.829	15.472	36.314	
St 29	loess	17.548	15.575	37.029	
Li-19	loess	17.945	15.598	37.326	
St-9	loess	18.369	15.623	37.831	
St-18	loess	18.167	15.583	37.732	
Li-10	loess	19.143	15.669	38.948	
Li-38	loess	18.118	15.581	37.648	
Li-36	loess	18.240	15.614	37.690	
Li-2	loess	19.151	15.699	38.820	
Li-32	loess	18.647	15.618	38.464	
ST-26	loess	18.357	15.625	37.928	
St-23	loess	19.197	15.696	39.025	
Li-16	loess	18.556	15.633	38.524	
GR-1	loess	17.486	15.51	37.571	
GR-2	loess	19.339	15.704	39.213	
GR-3	loess	17.347	15.492	37.121	
GR-4	loess	18.690	15.636	38.466	
GR-5	loess	17.833	15.53	37.195	
GR-7	loess	17.962	15.562	37.575	
possible sources					
CO-31	South Platte channel silt	17.047	15.494	36.674	
CO-34	South Platte channel silt	16.983	15.491	36.553	
CO-35	South Platte channel silt	17.781	15.580	37.685	
CO-74	South Platte channel silt	17.284	15.509	36.724	
CO-75	South Platte channel silt	17.065	15.495	36.765	
CO-76	South Platte channel silt	17.073	15.473	36.574	
CO-108	South Platte overbank silt	17.262	15.506	37.048	
CO-109	South Platte overbank silt	17.314	15.503	36.878	
CO-110	South Platte overbank silt	17.692	15.545	37.468	
CO-111	South Platte overbank silt	17.614	15.555	37.256	
CO-112	South Platte overbank silt	17.464	15.534	37.111	
CO-113	South Platte overbank silt	17.616	15.541	37.223	
CO-151	WRG [zircon sample]	18.205	15.604	39.093	
CO-91	WRG	18.784	15.632	38.825	
CO-94	WRG	18.593	15.639	38.615	

CO-99	WRG	18.729	15.647	38.711	
CO-102	WRG	18.939	15.673	39.153	
CO-126	WRG	18.731	15.623	38.926	
CO-133	WRG	18.439	15.651	38.585	
BADL-01	WRG	18.26	15.61	37.982	
BADL-02	WRG	18.759	15.639	18.811	
BADL-03	WRG	18.247	15.639	38.258	
BADL-04	WRG	18.493	15.607	38.373	
BADL-05	WRG [zircon sample]	18.865	15.629	38.618	
BADL-06	WRG	18.394	15.612	38.331	
BADL-07	WRG	18.914	15.622	38.751	
BADL-08	WRG	18.561	15.657	38.643	
SD-12	WRG	18.125	15.608	37.871	
WY-202	WRG	19.564	15.788	39.166	
WY-203	WRG	18.934	15.627	38.825	
WY-205	WRG	18.888	15.627	38.712	
WY-206	WRG	18.872	15.611	38.755	
WY-207	WRG	19.623	15.736	39.176	
WY-208	WRG	19.172	15.756	39.061	
WY-209	WRG	18.745	15.61	38.589	
WY-210	WRG [zircon sample]	18.346	15.578	38.08	
WY-211	WRG	18.795	15.656	38.581	
WY-212	WRG	19.193	15.67	38.882	
CO251	terrace silt	18.205	15.575	37.997	
CO252	terrace silt	18.549	15.598	38.181	
CO253	terrace silt	17.460	15.483	37.071	
CO254	terrace silt	17.523	15.500	37.16	
CO255	terrace silt	17.641	15.533	37.443	
CO256	terrace silt	17.858	15.558	37.732	
CO257	terrace silt	18.588	15.614	37.286	
CO258	terrace silt [zircon sample]	18.500	15.593	38.873	

Vertical Stratigraphic Sections

Beecher Island, CO(39°54′ N, 102°12′ W)

LI-213	17.568	15.559	37.161	3.95
LI-214	17.787	15.574	37.341	4.45
LI-215	17.906	15.573	37.413	5.10
LI-216	18.53	15.641	37.921	5.60
LI-217	17.52	15.55	37.029	6.10
LI-218	17.867	15.621	37.369	6.60
LI-219	18.039	15.615	37.551	7.10
LI-220	18.244	15.632	37.572	7.60
LI-221	18.721	15.698	38.091	8.10
LI-222	18.028	15.615	37.496	8.60
LI-223	18.384	15.626	37.962	9.10
LI-224	17.799	15.566	37.251	9.60
LI-225	17.596	15.544	37.056	10.10
LI-226	17.181	15.478	36.607	10.60
LI-227	17.193	15.513	36.686	11.10
LI-228	17.636	15.556	37.16	11.60

Last Chance, CO (39°44′ N, 103°35′ W)				
LI-12-2	19.17	15.681	39.239	0.28
LI-12-3	19.583	15.746	39.457	0.55
LI-12-4	19.095	15.681	38.644	1.05
LI-12-5	18.965	15.671	38.684	1.55
LI-12-6	17.354	15.512	36.761	2.05
LI-12-7	18.661	15.634	37.964	2.55
LI-12-8	18.951	15.663	38.471	3.05
LI-12-9	18.706	15.645	38.231	3.55
LI-12-10	18.727	15.694	38.307	4.05
LI-12-11	17.495	15.511	37.053	4.55

1 WRG = White River Group

2 Corrected for mass fractionation of 0.14%/a.m.u.

3 Samples not collected from vertical stratigraphic sections collected within about 2 m of the surface.

* equivalent to sample LI-214.

TABLE 2. SHRIMP U-Pb DATA FROM ZIRCON

grain[1]	Age[2] (Ma)	± (Ma)	grain[1]	Age[2] (Ma)	± (Ma)	grain[1]	Age[2] (Ma)	± (Ma)
loess 1.1	33	1	WRG1 1.1	33	1	terrace 1.1	464	15
loess 2.1	1164	32	WRG1 2.1	26	1	terrace 2.1	1130	22
loess 3.1	1302	27	WRG1 3.1	63	6	terrace 3.1	456	14
loess 4.1	539	22	WRG1 4.1	35	1	terrace 4.1	1070	20
loess 5.1	1721	17	WRG1 5.1	27	1	terrace 5.1	1104	33
loess 6.1	1098	36	WRG1 6.1	32	2	terrace 6.1	1090	26
loess 7.1	1210	34	WRG1 7.1	1426	27	terrace 7.1	1114	44
loess 8.1	1671	15	WRG1 8.1	31	2	terrace 8.1	1161	33
loess 9.1	1359	26	WRG1 9.1	1636	27	terrace 9.1	1061	38
loess 10.1	1215	116	WRG1 10.1	1387	47	terrace 10.1	1048	38
loess 11.1	1159	109	WRG1 11.1	33	2	terrace 11.1	1677	20
loess 12.1	1313	48	WRG1 12.1	1384	54	terrace 12.1	1223	200
loess 13.1	72	3	WRG1 13.1	1426	82	terrace 13.1	1085	44
loess 14.1	540	18	WRG1 14.1	34	1	terrace 14.1	1075	36
loess 15.1	1033	81	WRG1 15.1	33	1	terrace 15.1	1071	536
loess 16.1	1588	47	WRG1 16.1	1462	22	terrace 16.1	1082	35
loess 17.1	614	21	WRG1 17.1	1450	18	terrace 17.1	1046	49
loess 18.1	151	5	WRG1 18.1	34	1	terrace 18.1	1092	24
loess 19.1	1961	11	WRG1 19.1	1412	28	terrace 19.1	1098	56
loess 20.1	36	1	WRG1 20.1	1425	12	terrace 20.1	1708	42
loess 21.1	2843	6	WRG1 21.1	33	1	terrace 21.1	1135	31
loess 22.1	1448	17	WRG1 22.1	36	1	terrace 22.1	1413	40
loess 23.1	1479	15	WRG1 23.1	1422	24	terrace 23.1	1116	40
loess 24.1	1063	56	WRG1 24.1	1429	14	terrace 24.1	1106	45
loess 25.1	1167	31	WRG1 25.1	35	2	terrace 25.1	1133	66
loess 26.1	1705	7	WRG1 26.1	36	1	terrace 26.1	1122	68
loess 27.1	1993	10	WRG1 27.1	1431	12	terrace 27.1	1010	153
loess 28.1	345	12	WRG1 28.1	1474	21	terrace 28.1	1209	98
loess 29.1	1456	28	WRG1 29.1	1431	13	terrace 29.1	1148	137
loess 30.1	1678	51	WRG1 30.1	1457	25	terrace 30.1	1432	51
loess 31.1	1010	65	WRG1 31.1	2202	78	terrace 31.1	1087	57
loess 32.1	1877	16	WRG1 32.1	36	1	terrace 32.1	1003	54
loess 33.1	1436	18	WRG1 33.1	1657	8	terrace 33.1	1139	69
loess 34.1	1427	21	WRG1 34.1	1422	13	terrace 34.1	1437	26
loess 35.1	1439	27	WRG1 35.1	1729	12	terrace 35.1	1080	144
loess 36.1	2007	14	WRG1 36.1	32	1	terrace 36.1	1015	28
loess 37.1	39	2	WRG1 37.1	1819	12	terrace 37.1	1131	61
loess 38.1	1051	40	WRG1 38.1	1428	13	terrace 38.1	1007	78
loess 39.1	32	1	WRG1 39.1	1443	14	terrace 39.1	1130	80
loess 40.1	431	16	WRG1 40.1	1415	35	terrace 40.1	1048	63
loess 42.1	1776	9	WRG1 41.1	1697	16	terrace 41.1	58	2
loess 43.1	687	33	WRG1 42.1	1439	21	terrace 42.1	2442	35
loess 44.1	1452	19	WRG1 43.1	1453	23	terrace 43.1	1204	109
loess 45.1	1393	6	WRG1 44.1	1722	19	terrace 44.1	1051	51
loess 46.1	339	12	WRG1 45.1	1725	5	terrace 45.1	1165	69
loess 47.1	26	2	WRG1 46.1	1718	14	terrace 46.1	1654	28
loess 48.1	1372	71	WRG1 47.1	1463	12			
loess 49.1	1736	12	WRG1 48.1	32	1			
loess 50.1	24	1	WRG1 49.1	1565	8			
loess 51.1	18	1	WRG1 50.1	34	1			

loess 52.1	1594	9	WRG2 1.1	1065	39	WRG3 1.1	1065	39
loess 53.1	414	11	WRG2 2.1	1117	26	WRG3 2.1	1117	26
loess 54.1	1704	6	WRG2 3.1	1651	18	WRG3 3.1	1651	18
loess 55.1	1122	77	WRG2 4.1	111	5	WRG3 4.1	109	5
loess 56.1	95	3	WRG2 5.1	120	4	WRG3 5.1	120	4
loess 57.1	1700	12	WRG2 6.1	119	2	WRG3 6.1	120	2
loess 58.1	326	8	WRG2 7.1	119	4	WRG3 7.1	118	4
loess 59.1	1038	21	WRG2 8.1	1432	48	WRG3 8.1	1432	48
loess 60.1	1571	17	WRG2 9.1	117	4	WRG3 9.1	114	4
loess 61.1	1702	11	WRG2 10.1	176	7	WRG3 10.1	176	7
loess 62.1	1713	23	WRG2 11.1	115	5	WRG3 11.1	111	4
loess 63.1	389	10	WRG2 12.1	137	7	WRG3 12.1	136	7
loess 64.1	1181	18	WRG2 13.1	496	11	WRG3 13.1	496	11
loess 65.1	498	12	WRG2 14.1	120	4	WRG3 14.1	119	4
loess 66.1	11	1	WRG2 15.1	1203	82	WRG3 15.1	1203	82
loess 67.1	1502	31	WRG2 16.1	1403	74	WRG3 16.1	1403	74
loess 68.1	42	1	WRG2 17.1	120	4	WRG3 17.1	119	4
loess 69.1	1113	29	WRG2 18.1	1033	35	WRG3 18.1	1033	35
loess 70.1	1431	24	WRG2 19.1	120	3	WRG3 19.1	120	3
			WRG2 20.1	116	4	WRG3 20.1	117	4
			WRG2 21.1	121	3	WRG3 21.1	120	3
			WRG2 22.1	123	4	WRG3 22.1	123	4
			WRG2 23.1	1839	50	WRG3 23.1	1826	50
			WRG2 24.1	1444	26	WRG3 24.1	1444	26
			WRG2 25.1	1140	117	WRG3 25.1	1140	117
			WRG2 26.1	125	3	WRG3 26.1	125	4
			WRG2 27.1	2996	11	WRG3 27.1	2996	11
			WRG2 28.1	114	3	WRG3 28.1	116	3
			WRG2 29.1	39	1	WRG3 29.1	39	1
			WRG2 30.1	1739	2	WRG3 30.1	1739	20
			WRG2 31.1	1642	42	WRG3 31.1	1568	41.
			WRG2 32.1	1791	22	WRG3 32.1	1791	22
			WRG2 33.1	118	4	WRG3 33.1	119	4
			WRG2 34.1	1470	16	WRG3 34.1	1470	16
			WRG2 35.1	120	4	WRG3 351	120	4
			WRG2 36.1	116	4	WRG3 36.1	116	4
			WRG2 37.1	1447	62	WRG3 37.1	1447	62
			WRG2 38.1	1952	49	WRG3 38.1	1942	50
			WRG2 39.1	101	4	WRG3 39.1	98	5
			WRG2 40.1	1695	24	WRG3 40.1	1695	24
			WRG2 41.1	1159	33	WRG3 41.1	1159	33
			WRG2 42.1	1679	39	WRG3 42.1	1637	39
			WRG2 43.1	123	3	WRG3 43.1	122	3
			WRG2 44.1	1442	52	WRG3 44.1	1442	52
			WRG2 45.1	1687	52	WRG3 45.1	1636	52

1 loess (Peoria Loess sample CO-210, equivalent to LI214 at Beecher Island, CO), WRG1 (White River Group sample CO-151, near Fort Morgan, CO), WRG2 (White River Group sample BADL-96-5 from Badlands National Park, SD), WRG3 (White River Group sample WY-210 near Scottsbluff, NE), terrace (South Platte River late Wisconsin terrace sample CO-258, near Denver, CO).

2 Ages >1.0 Ga are the $^{207}Pb/^{206}Pb$ age; ages <1.0 Ga are the $^{206}Pb/^{238}U$ age.

Note: complete table of isotopic data available from first author