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ABSTRACT

Loess is a widespread Quaternary deposit in Alaska and loess accretion occurs today in some regions, such as the Matanuska Valley. The source of loess in the Matanuska Valley has been debated for more than seven decades, with the Knik River and the Matanuska River, both to the east, being the leading candidates and the Susitna River, to the west, as a less favorable source. We report here new stratigraphic, mineralogic, and geochemical data that test the competing hypotheses of these river sources. Loess thickness data are consistent with previous studies that show that a source or sources lay to the east, which rules out the Susitna River as a source. Knik and Matanuska River silts can be distinguished using Sc–Th–La, La_N/Yb_N vs. Eu/Eu*, Cr/Sc, and As/Sb. Matanuska Valley loess falls clearly within the range of values for these ratios found in Matanuska River silt. Dust storms from the Matanuska River are most common in autumn, when river discharge is at a minimum and silt-rich point bars are exposed, wind speed from the north is beginning to increase after a low-velocity period in summer, snow depth is still minimal, and soil temperatures are still above freezing. Thus, seasonal changes in climate and hydrology emerge as critical factors in the timing of aeolian silt transport in southern Alaska. These findings could be applicable to understanding seasonal controls on Pleistocene loess accretion in Europe, New Zealand, South America, and elsewhere in North America.

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1. Introduction

Loess is extensive over Asia, New Zealand, Europe, South America, North America, and over smaller areas of the Middle East and Africa (see maps in Muhs, 2013a,b). Loess can be one of the most reliable means by which to reconstruct past atmospheric circulation patterns, because the sediment is entrained and transported directly by the wind. Transport paths of aeolian silt, and therefore past wind directions, can be inferred when the source sediments are already known (a rare occurrence) or estimated indirectly when distance-decay functions (downwind trends in loess properties) point to a particular source (see examples in Muhs, 2013a,b). In the midcontinent of North America (Fig. 1a), loess is extensive and glaciogenic sources of loess have long been identified as the major outwash-bearing rivers issuing from Pleistocene ice sheets that once covered the region. Diminishing loess thickness, particle size, and carbonate content can identify sources of loess, as these trends are observed in a downwind direction (Smith, 1942; Ruhe, 1983; Muhs and Bettis, 2000). In Asia, similar trends are recognized on the Loess Plateau of China and document arid regions to the north or northwest as loess sources (Porter et al., 2001; Ding et al., 2005).

Problems can arise with distance-decay functions, however, when multiple candidate sediment sources lie upwind of a loess body. In such situations, use of mineralogical, isotopic, or geochemical signatures can be utilized to distinguish between competing loess and dust sources. For example, Chiapello et al. (1997) differentiated Sahel dust and Saharan dust in Africa on the basis of major element chemistry and clay mineralogy. Chen et al. (2007) used Sr and Nd isotopes to identify the most likely arid basins that are sources of loess in China. Aleinikoff et al. (2008) used Pb isotopes in K-feldspars and U-Pb ages of detrital zircons to distinguish loess sources in the Great Plains region of North America. Muhs and Budahn (2006) distinguished different fluvial sources of loess for central Alaska using a suite of relatively immobile trace elements, including the rare earth elements.

Study of modern or recent glaciogenic dust and loess deposits is important because such sediments are the closest analogs for many of the glaciogenic Pleistocene loess bodies around the world (Arnalds, 2010; Bullard, 2012; Prospero et al., 2012). Loess is extensive over much of Alaska (Fig. 1b) and much of it

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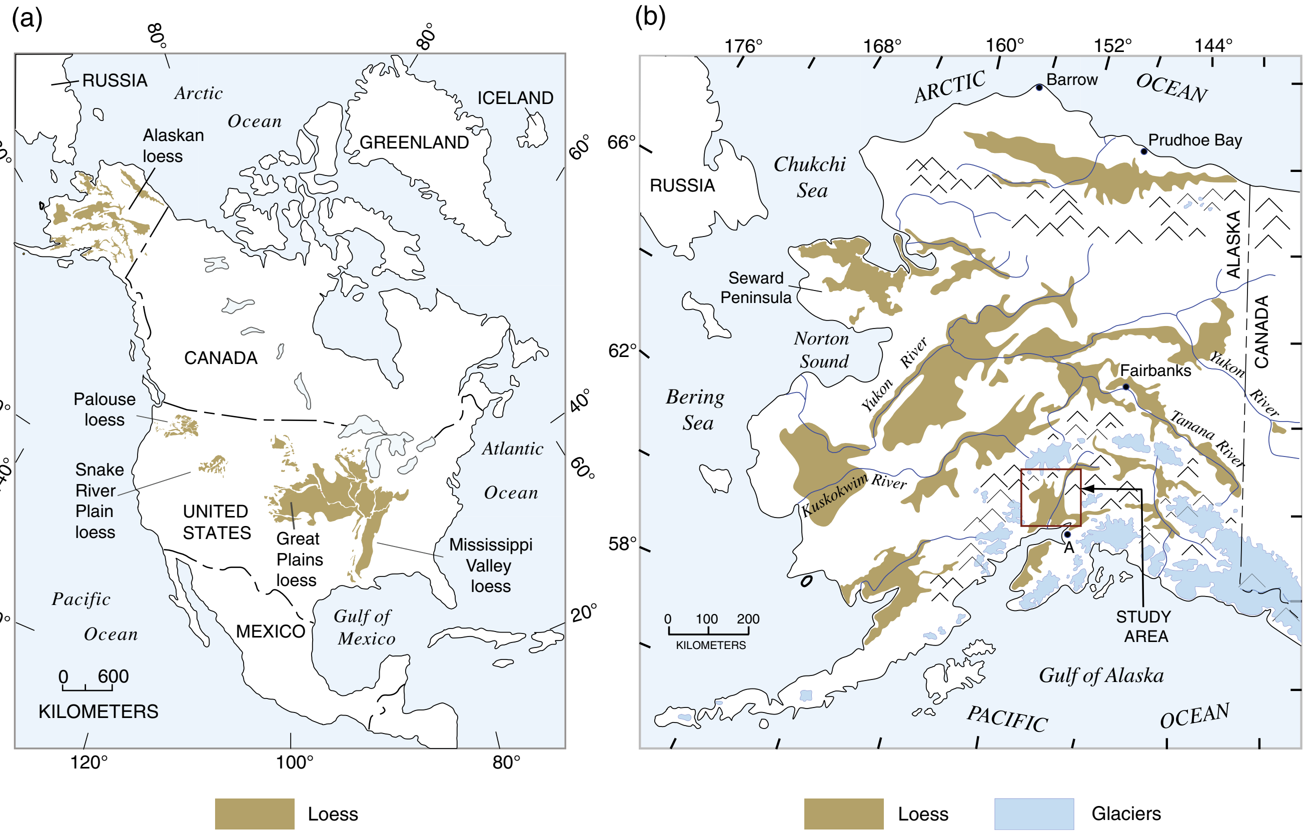

Fig. 1. (a) Map showing the distribution of loess (brown) in North America, from Bettis et al. (2003) and sources therein; (b) Map showing the distribution of loess deposits (brown) in Alaska, compiled from Hopkins (1963) and Sainsbury (1972) for the Seward Peninsula and Péwé (1975) for all other parts of the region. Most mapping from these sources has been field checked by the authors. Also shown is the present extent of glaciers (blue) in the region, taken from Péwé (1975) and Brown et al. (1997). Red box in (b) outlines Matanuska Valley study area; A, Anchorage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

accumulated during the Pleistocene (see reviews in Péwé, 1975; Muhs et al., 2003). Nevertheless, aeolian silt entrainment, transportation and deposition continue today because of extant glaciers (Fig. 1b) and abundant production of glaciogenic silt. Holocene loess accumulation has been observed at numerous locations within central and southern Alaska (Péwé, 1975; Muhs et al., 2003, 2004, 2013; Crusius et al., 2011).

The Matanuska Valley of southern Alaska is a good example of an area where there is documentation of historical and Holocene glaciogenic loess (Figs. 1b, 2, and 3). Radiocarbon ages reported by Muhs et al. (2004) indicate that deposition has been ongoing for the past ~7500 cal yr BP (calibrated years before present) and continues to the present day. Nevertheless, identification of the dominant source of loess in the Matanuska Valley has been controversial for more than half a century. Tuck (1938) thought that the loess in this area was derived primarily from the Knik River, whereas Black (1951) considered that various rivers in the area were likely sources. Stump et al. (1956) noted the physical similarities of silts in the Matanuska Valley to those of loess in Iowa, but did not specifically identify the Matanuska Valley silts as loess. Indeed, later Stump et al. (1959) questioned the aeolian origin of the silts in the Matanuska Valley. These investigators acknowledged the observations of modern dust storms from both the Matanuska and Knik Rivers and considered that an aeolian origin was possible, but left open the possibility that silts in the Matanuska Valley could be lacustrine. Rieger and Juve (1961), studying soils in the region, accepted Tuck's (1938) proposition that the Matanuska Valley silts are loess. These workers thought that the Knik River was the most important source at present, but offered the proposition that the Matanuska River was a more important source in the past. Trainer (1961) also considered that the silts of the region were indeed loess deposits and felt that both the Knik and Matanuska Rivers were sources. Schoephorster (1968) noted that both the Matanuska and Knik Rivers generate large dust storms at present (see his Fig. 2) and implied that these were both sources, but also pointed out that in the western part of the region, the Susitna River and its tributaries could be loess sources. Reger and Updike (1983) and Clark and Kautz (1998) also proposed that both the Knik and Matanuska Rivers were loess sources and noted that modern dust storms can be seen on the floodplains of both rivers (see Fig. 120 of Reger and Updike (1983) and Plate 1 of Clark and Kautz (1998)). Reger and Updike (1983), however, inferred from the loess thickness trends (Fig. 3) that the Matanuska River was the main source of loess immediately west of that river.

In this study, we report new stratigraphic, mineralogical, and geochemical data that provide a test of the various hypotheses that have been proposed about which river sources are the most important for the origin of Matanuska Valley loess. Our approach is similar to that used in determining the origin of Holocene loess in southeastern Alaska (Muhs et al., 2013) and Pleistocene loess of central Alaska (Muhs and Budahn, 2006). Understanding which river system provides the bulk of the loess to the Matanuska Valley is critical not only for determination of past wind direction but also for identifying the seasonality of aeolian silt transport. If loess in the region is derived from the Matanuska River, northern or northeastern winds are required. For the Knik River as a source of loess, southeast winds are required. Winds from both these directions occur in the region at the present, but at different times of the year. The Susitna River valley lies wholly to the west of the Matanuska Valley region (Fig. 2). Westerly winds are uncommon in this area

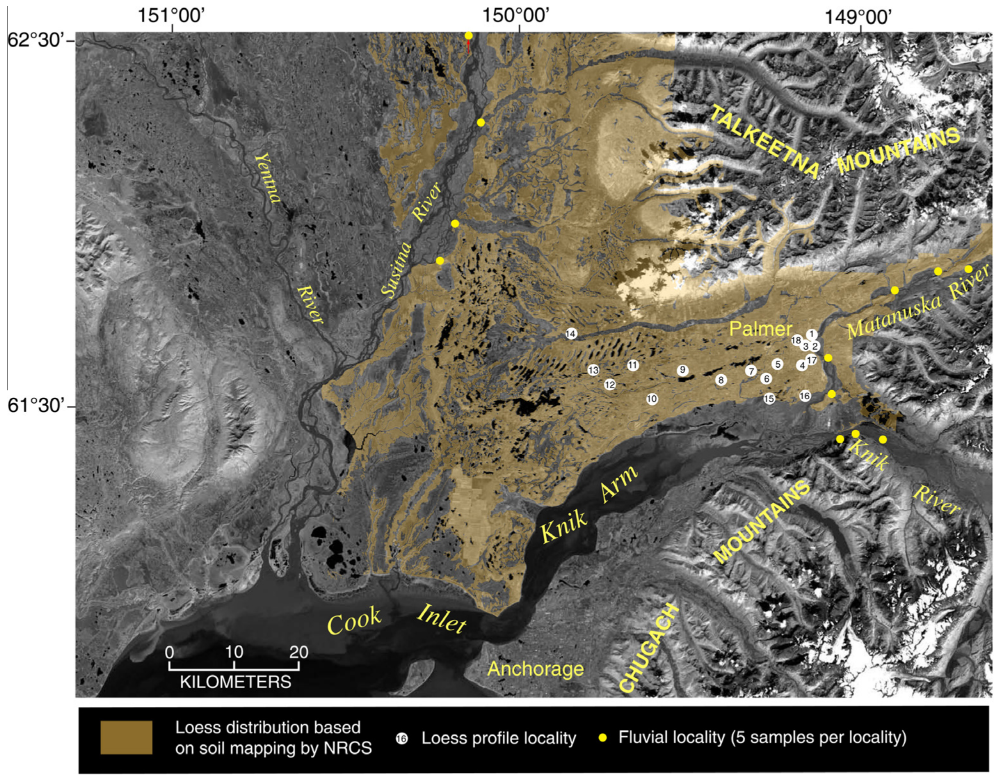

Fig. 2. Landsat ETM image (band nm 80; date of imagery is 2002) of southern Alaska, with the distribution of loess, shown with brown shading, derived from National Resources Conservation Service STATSGO files, in turn based largely on soil mapping from Schoephorster (1968) and Clark and Kautz (1998). Numbered white circles show locations of loess profiles studied by Muhs et al. (2004) and the present study; alluvial samples are shown by filled yellow circles and each locality represents five separate alluvial samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

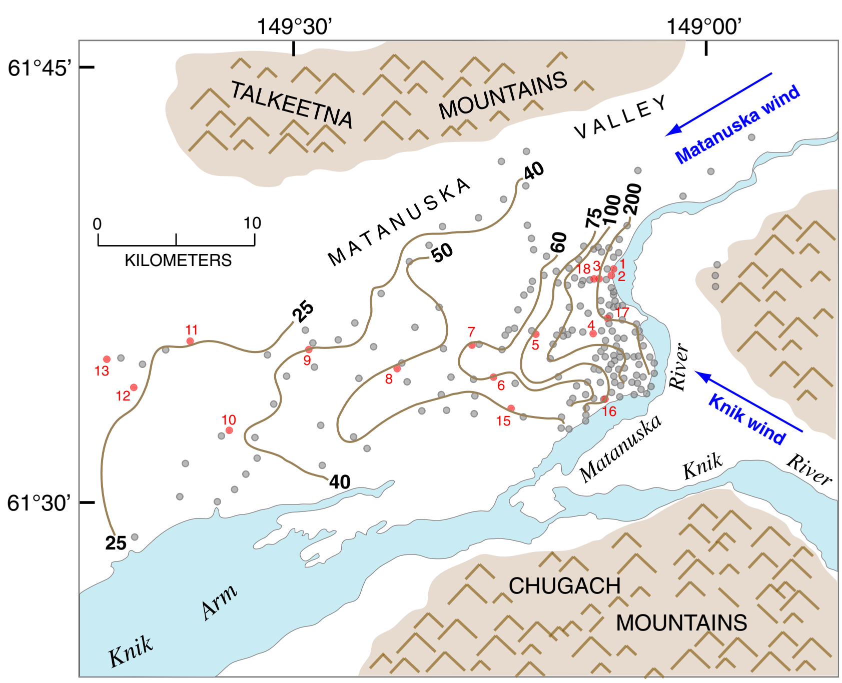

Fig. 3. Map of the lower Matanuska Valley and lower Knik River valleys and contours of loess thickness in centimeters. Contours hand-drawn by the authors from data in Trainer (1961), Muhs et al. (2004), and the present study. Numbered localities are loess profiles, as in Fig. 2. Note that immediately adjacent to the Matanuska River, loess and aeolian sand thicknesses are as much as 16 m, but contours of this thickness cannot be shown at this scale. Also shown are directions of "Matanuska" (northeasterly) and "Knik" (southeasterly) winds (Dale, 1956).

and thus a Susitna River source, if established, would require a very different paleowind regime from that of the present. If the mineralogical and geochemical compositions of sediments from these three rivers can be distinguished from one another, it should be possible to ascertain which river valley is the most important source of loess.

2. Geological setting and climate

The Matanuska Valley is a glacial-drift and loess-mantled topographic and structural trough surrounded by the rugged Chugach Mountains to the south and the Talkeetna Mountains to the north (Figs. 2 and 3). The mountains adjacent to the Matanuska Valley range as high as 1700–2100 m and host glaciers at the present time. The lower-elevation Matanuska Valley itself was glaciated during the late Pleistocene (Reger and Updike, 1983; Reger et al., 1995, 2007). The last glacial period in this part of Alaska is thought to have ended around 11,000 cal yr BP, according to Reger et al. (2007). Reger et al. (1995) report that upper Knik Arm, into which both the Matanuska and Knik Rivers terminate (Fig. 2), was deglaciated by ~9900 cal yr BP.

The climate of the Matanuska Valley is intermediate between the maritime (cool and humid) environment of southern Alaska and the continental (cold and dry) environment of central Alaska and is well summarized in a classic paper by Dale (1956). Mean annual precipitation at Palmer (Fig. 2) is 393 mm, with maximum precipitation occurring during the summer months. Winter precipitation is dominated by snowstorms that result from major frontal systems developing from the Aleutian low pressure cell to the south. Mean July temperature at Palmer is 15.7 °C, mean January temperature is −7.9 °C, and mean annual temperature is 3.8 °C, based on 1981–2010 averages from the U.S. National Climatic Data Center.

Wind direction and strength are crucial to understanding the aeolian history of the Matanuska Valley region. Winds from the northwest-to-northeast and the southeast are common in the region, but are distinctly seasonal (Fig. 4). From April through August, winds are dominantly from the southeast and high-velocity winds in this period are locally referred to as "Knik Winds." From October through February, winds are dominantly from the northwest-to-northeast and high-velocity winds are referred to locally as "Matanuska Winds." March and September are transitional months with biomodal wind regimes, including both northerly winds and southeasterly winds. Southwesterly winds are infrequent, and occur only during the months of April through August.

Aeolian movement of silt-sized particles by wind can take place either by direct entrainment by wind or by impact from saltating sand grains. Of these two mechanisms, it has long been thought that most silt particle movement is initiated by impact from saltating sand grains (Pye, 1987). The threshold velocity for entrainment of medium-sized (500–250 μm diameter) sand particles is ~5–6 m/s when considered at a height of 10 m, the standard height of wind speed measurement at most weather stations in the USA. At Palmer, Alaska (10 m height), mean wind speeds from the southeast are at or above this threshold for about 9 months of the year and mean wind speeds from the northeast are at or above this threshold for about 7 months of the year (Fig. 5). Thus, the potential for silt particle entrainment by saltating sand grains is high from both the southeast and the northeast during much of the year. Furthermore, Sweeney and Mason (2013) recently presented compelling field evidence that direct entrainment of silt-sized (63–2 μm) particles by wind is much more important than previously suspected and requires a threshold friction velocity significantly lower than that for sand.

In addition to wind velocity, the protective roles of vegetation, snow and ice, and water on the surface of a sediment source are important in determining the potential for particle entrainment by wind. On active floodplain surfaces, such as those of the Knik, Matanuska, and Susitna Rivers, plant cover may be minimal. Nevertheless, snow cover, flooding, and moist or frozen sediment can be important factors in limiting silt particle entrainment by wind. For example, in southern Alaska, the Copper River watershed can have a snow cover of 40–160 cm from November through May and is free of snow only during the months of June through September. As a result, dust storms from this floodplain are concentrated in the summer and early fall months (Crusius et al.,

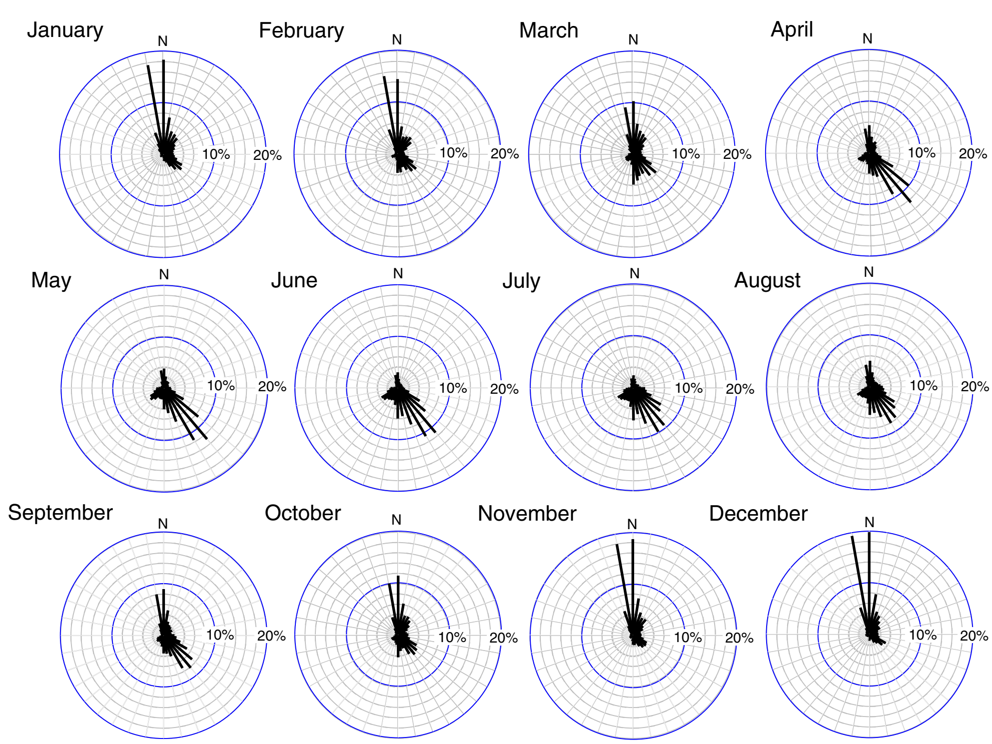

Fig. 4. Monthly wind roses for Palmer, Alaska, based on 1973–2002 NOAA records; arms point upwind. Note dominance of "Matanuska" (northeasterly) winds in fall and winter and dominance of "Knik" (southeasterly) winds in spring and summer.

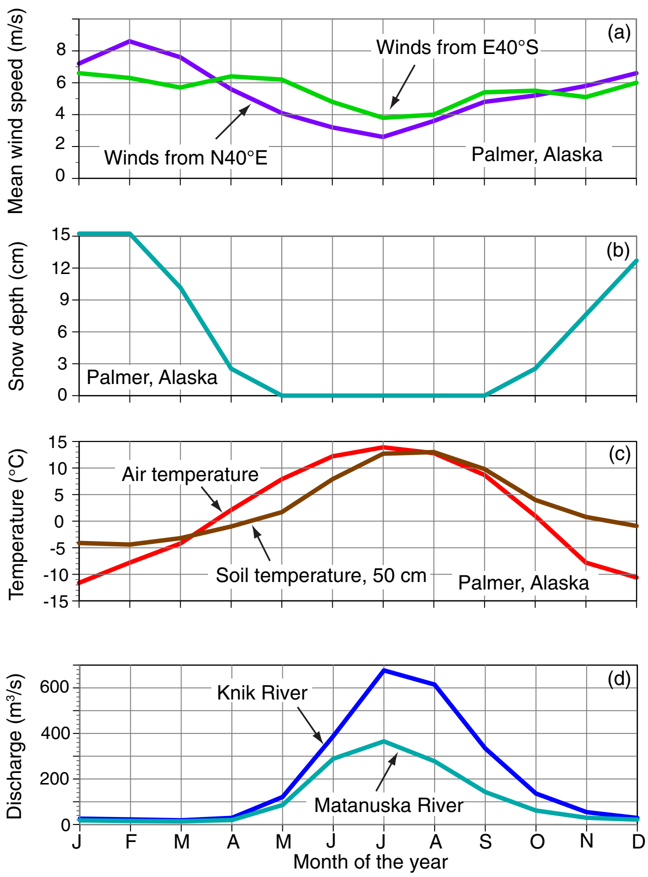

Fig. 5. Graphs showing climatology and hydrology of the Palmer, Alaska area: (a) mean monthly wind speeds for "Knik" winds, represented by winds from E40°S (1973–2002 records) and mean monthly wind speeds for "Matanuska" winds, represented by winds from N40°E (1973–2002 records); (b) average snow depth (cm) in the Palmer area (1948–2015 records); (c) mean air and soil temperatures (50 cm depth) at Palmer (1961–1983 records for air; 1962–1983 records for soil); (d) mean monthly discharge of the Knik and Matanuska rivers. Data for (a) and (b) are from National Oceanic and Atmospheric Administration (NOAA) records; data for (c) are from Ping (1987); data for (d) are from U.S. Geological Survey records.

2011). Snow depths in the lower Matanuska and Knik Rivers (based on data from Palmer) are much less, rarely exceeding 15 cm, and average 3 cm or less for 7 months of the year (Fig. 5). Dale (1956) points out that in mid-winter, thawing temperatures occasionally are experienced in the Matanuska Valley, which could remove snow cover altogether even during normally cold months. More than a century ago, Tarr and Martin (1913) pointed out that if silt-rich point bars in valleys of rivers that drain mountains with glaciers are a source of contemporary loess in Alaska, particle entrainment by wind is most likely during periods of low discharge, when the areal extent of exposed point bars is at a maximum. In a recent study in the Copper River basin of southern Alaska, Crusius et al. (2011) report that the time of lowest discharge is autumn, which is also a time with minimal snow cover and strong winds. A similar situation exists in the Matanuska Valley, where autumn is a time of low discharge of both the Matanuska and Knik Rivers, but snow cover is still minimal, soils and sediments are above freezing temperatures, and winds are strong (Fig. 5). The Matanuska and Knik Rivers drain terrain of the Chugach and Talkeetna Mountains where glaciers exist today (Fig. 6a) and unvegetated, dry, unfrozen, silt-rich point bars can be seen at their maximum extent during the period of low discharge in autumn (Fig. 6b).

3. Methods

Samples were collected from loess profiles 3, 4, and 5, previously studied by Muhs et al. (2004) and new loess profiles 15, 16, 17, and 18, presented here (Figs. 2, 3, 6c,d, and 7). No materials for radiocarbon dating were found in profiles 15, 16, and 18, but profile 17 yielded suitable material from four depths. Radiocarbon dating of wood and other plant fragments found in loess profile 17 was done by accelerator mass spectrometry (AMS) following McGeehin et al. (2001). Calibrated ages (Table 1), designated as calibrated years before present (cal yr BP), were derived using the CALIB v. 7.1 calibration software (Stuiver and Reimer, 1993) in conjunction with the IntCal13 calibration curve (Reimer et al., 2013).

In order to compare loess with possible alluvial sources, it is necessary to isolate the silt fraction from the alluvium, because loess is dominated by silt-sized particles. Sedimentologists put the sand/silt break at 63 microns, whereas soil scientists put the break at 50 microns. In consideration of both of these definitions, we used a 53 micron sieve to separate sand from silt. Mineralogy of silt (53-2 μm) fractions separated from alluvium was determined by X-ray diffractometry (XRD) on randomly oriented packed powders. For these analyses, pretreatments of bulk alluvial samples included removal of organic material with hydrogen peroxide, dispersion with sodium pyrophosphate, and ultrasonication. After pretreatments, sands (>53 μm particles) were removed by wet-sieving and clays (<2 μm particles) were removed by repeated sedimentation and siphoning. After removal of sands and clays, silts were pulverized prior to XRD analyses. Mineralogy of loess was determined on bulk samples, with pulverization being the only pretreatment. Mineral identification follows Moore and Reynolds (1989).

Concentrations (weight percents or ppm) of selected major and trace elements in bulk loess and silt fractions of alluvium were determined by instrumental neutron activation analysis (INAA), following Budahn and Wandless (2002). Selected samples were also analyzed for some major and trace element concentrations by energy-dispersive X-ray fluorescence (ED XRF).

Trace element geochemistry can be a powerful tool in loess or dust provenance studies (see review in Muhs, 2013a). We emphasize the use of the relatively immobile trace elements Sc, Th, Cr, Ta, Zr, Hf, As, Sb, and the rare earth elements. As shown by Taylor and McLennan (1985), ternary plots of Sc–Th–La easily identify sediments derived primarily from oceanic crust (OC) in contrast to those derived from upper continental crust (UCC). This discriminating ability is ideal for Alaska, where the mountains that provide the source material for glaciogenic loess are landforms within accreted terrains with highly variable compositions. Plots of La_N/Yb_N vs. Eu/Eu*, and Gd_N/Yb_N vs. Eu/Eu* are also effective discriminators for rocks from different crustal sources (McLennan, 1989) and have been used to distinguish different possible alluvial sources for loess in central Alaska (Muhs and Budahn, 2006). The latter investigators also used Zr/Hf as a zircon index and As/Sb as a magnetite index (Onishi and Sandell, 1955) and demonstrated the ability to discriminate alluvial sources using these ratios, as well as Cr/Sc and Th/Ta.

4. Results and Discussion

4.1. Stratigraphy of Matanuska Valley loess

Examination of river cuts shows that aeolian deposits are very thick close to two of the hypothesized sediment sources. On the banks of the Matanuska River, aeolian sediment is as much as ~16 m thick and consists of horizontally interbedded silts and fine sands (Profiles 1 and 2 in Figs. 2, 3 and 7). Aeolian sediment

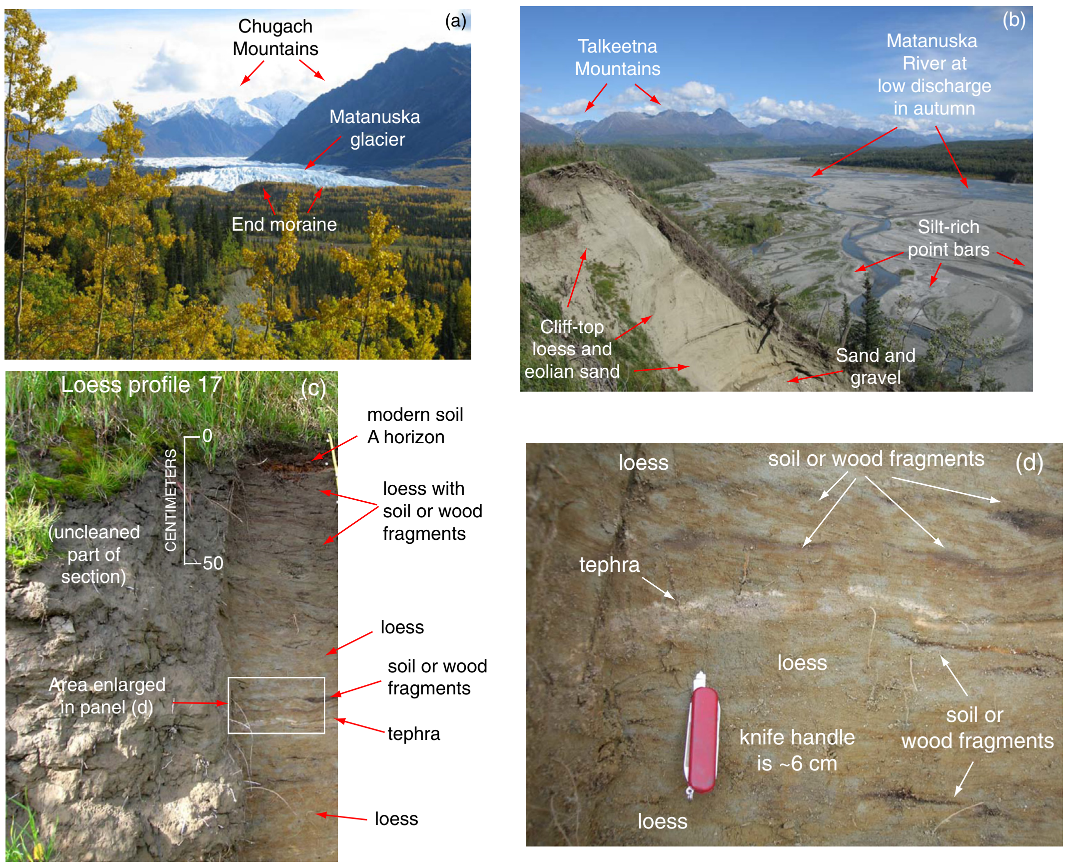

Fig. 6. Photographs of: (a) the downvalley end of the Matanuska glacier and the Chugach Mountains; (b) the Matanuska River at low discharge in autumn, with silt-rich point bars exposed subaerially, adjacent cliff-top loess and aeolian sand near loess profile 2 (see Figs. 2 and 3 for location), and Talkeetna Mountains in background; (c) loess profile 17 (see Figs. 2 and 3 for location), showing modern soil, loess, buried soil or wood fragments, and tephra; (d) detail of a portion of (c) showing loess, buried soil or wood fragments, and tephra. All photos by D.R. Muhs.

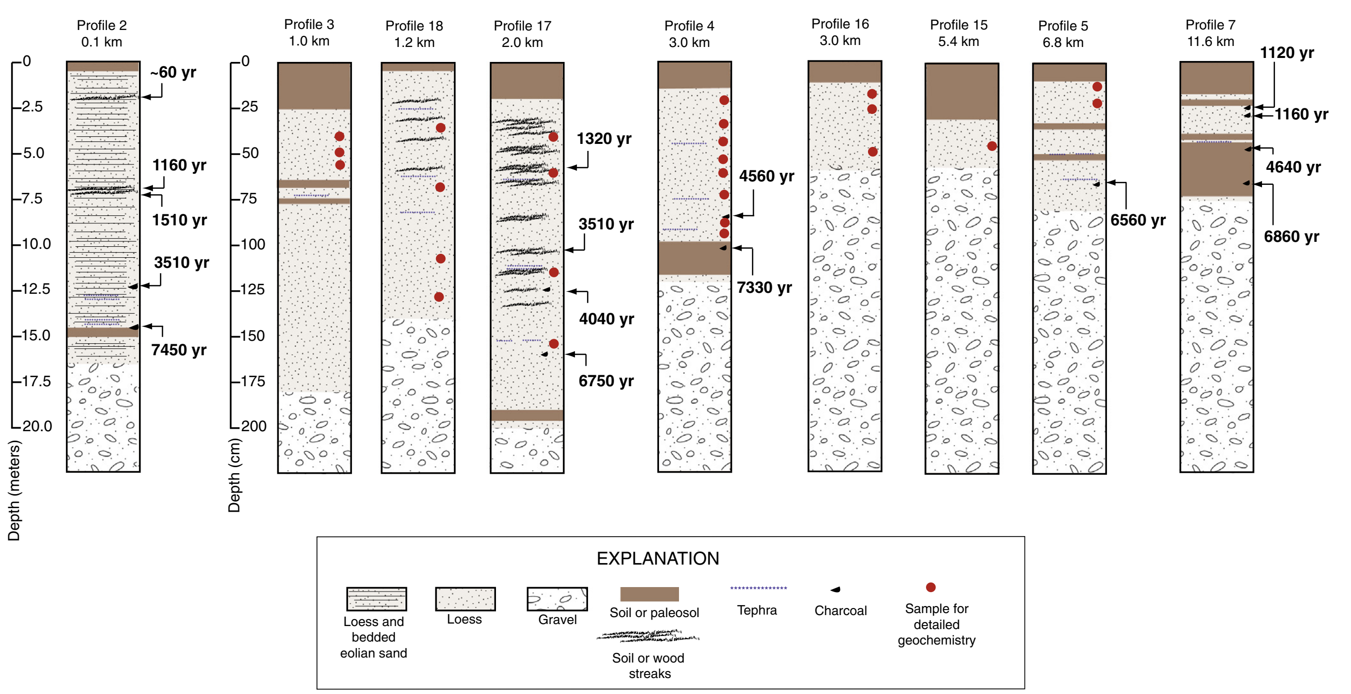

Fig. 7. Stratigraphy of loess profiles (see Figs. 2 and 3 for locations) and depths sampled (filled red circles) for detailed geochemical analyses in the present study. Numbers given below each profile number are distances west of the Matanuska River. Stratigraphy and calibrated (median) radiocarbon ages of profiles 2, 3, 4, 5, and 7 are from Muhs et al. (2004); profiles 15, 16, 17, and 18 are from the present study. Note scale change for Profile 2 compared to all other profiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Radiocarbon ages from Loess Profile 17, Palmer Alaska (N61°36.071′; W149°06.196′).

Lab#	Field #	Material	Depth (cm)	$\delta^{13}C$ (‰)	^{14}C Age (yr)	±	Dated on	Med age	Min	Max	*P*
WW8463	AK2625A	Wood	55	−26.5	**1415**	25	05-10-11	**1318**	1290	1352	1
WW8464	AK2630A	Wood	105	−25.1	**3275**	25	05-10-11	**3507**	3450	3564	1
WW8465	AK2632A	Charcoal	125	−24.7	**3705**	30	05-10-11	**4040**	3933	3940	0.008
									3971	4102	0.874
									4110	4148	0.118
WW8466	AK2636A	Charcoal	160	−23.2	**5925**	40	05-10-11	**6748**	6661	6807	0.895
									6811	6856	0.105

Notes:
• Samples were processed at the ^{14}C laboratory of the U. S. Geological Survey in Reston, Virginia.
• AMS^{14}C ages were determined at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory, Livermore, California.
• ^{14}C ages (bold type) are given in radiocarbon years with 1-sigma uncertainties using the Libby half life of 5568 years and following the conventions of Stuiver and Polach (1977).
• The WW number is the identification assigned to a sample by the USGS ^{14}C laboratory.
• $\delta^{13}C$ analyses were done at the University of California, Davis Stable Isotope Laboratory. Values are given in per mil (‰) relative to V-PDB.
• Calibrated ages were calculated using CALIB v. 7.1 in conjunction with the IntCal13 dataset. Calibrated ages are reported as the median (Med age, in bold type) and the 2-sigma calibrated age range (Min–Max). *P* = probability of the calibrated age falling within the reported range as calculated by CALIB.

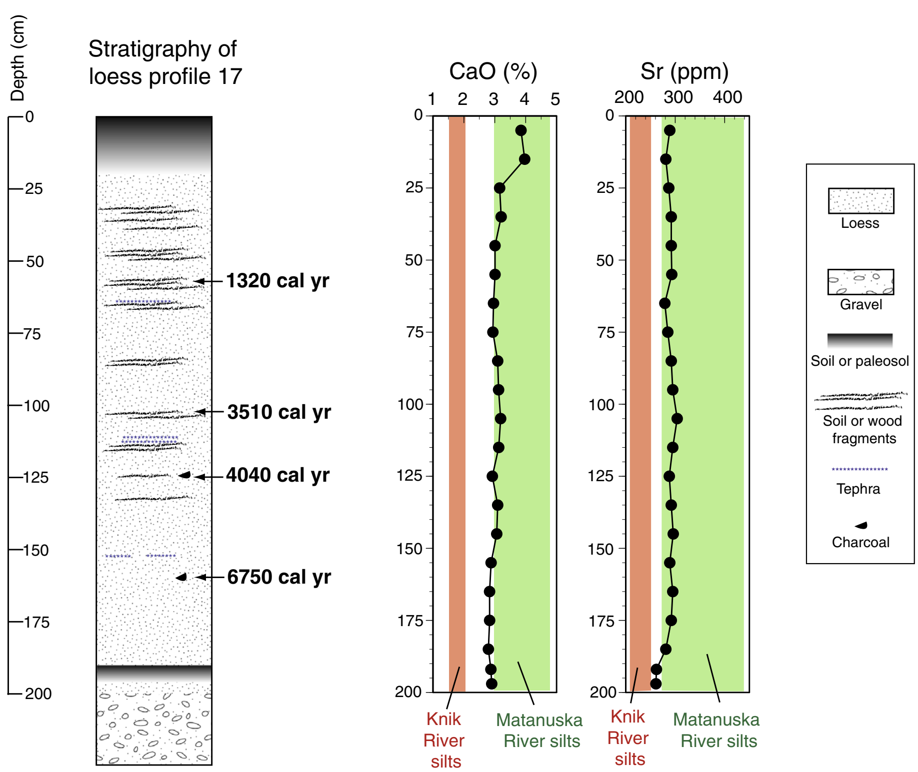

Fig. 8. Stratigraphy, calibrated (median) radiocarbon ages (see also Table 1) and CaO and Sr contents in loess profile 17, situated ~2 km west of the Matanuska River, and exposed near the corner of the Glenn Highway and Arctic Avenue in downtown Palmer, Alaska. Shown for comparison (green and pink bands) are the ranges of CaO and Sr concentrations in the silt fractions of competing loess sources, alluvium from the Matanuska River and Knik River. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thickness decreases rapidly with distance from the Matanuska River and Knik River valleys (Fig. 3). Thus, loess profiles 3, 18, 17, 4, 16, 15, and 5, between 1 and 8 km from any river source, are less than 200 cm thick (Fig. 7). Earlier studies showed that particle size decreases in a westward direction from both the Matanuska and Knik Rivers (Stump et al., 1959; Trainer, 1961; Muhs et al., 2004).

Previous radiocarbon analyses, from materials collected near the lower parts of profiles 1, 4, 5, and 7 (Fig. 7), indicate that aeolian sediment deposition began in the mid-Holocene, about 7500–6500 cal yr BP (Muhs et al., 2004). New radiocarbon analyses from profile 17 (Table 1; Figs. 7 and 8) are consistent with previous ages from nearby profiles. Charcoal collected in loess ~30 cm above the last-glacial-age gravels in this profile yielded a radiocarbon age of 5925 ± 40 yr, equivalent to a median calibrated age of ~6750 cal yr BP. Three other radiocarbon ages on materials collected above this depth resulted in median calibrated ages of ~4040 cal yr BP, ~3510 cal yr BP, and ~1320 cal yr BP, from deepest to shallowest, and maintain stratigraphic order (Table 1; Fig. 8). From previous ages given in Muhs et al. (2004) and those presented here, we retain an interpretation that loess accumulation likely began sometime between ~7500 and 6500 cal yr BP.

4.2. Mineralogy of river alluvium and loess

Mineralogical analyses indicate that the dominant silt-sized particles in unaltered alluvial sediments from the Matanuska, Knik, and Susitna rivers are quartz, plagioclase, mica, chlorite, and an amphibole mineral, likely hornblende (Fig. 9a). The mineral K-feldspar was detected with certainty only in silts of the Susitna River. The assemblages of minerals reflect derivation of the various river silts from rocks of the mountain ranges they drain. The Knik River drains only the Chugach Mountains, and the specific parts of the mountains drained by the river are composed largely of metasedimentary rocks of the Valdez Group (Late Cretaceous) and to a lesser extent the highly variable lithologies of the Mesozoic McHugh Complex (Winkler, 1992; Wilson et al., 2012).

The Matanuska River also drains Valdez Group and McHugh Complex rocks of the Chugach Mountains, explaining the similar mineralogy of silts from this river to silts of the Knik River. In addition, however, the Matanuska River also drains the Talkeetna Mountains (Figs. 2, 3 and 6), which contain a wide variety of rocks, including formations with mafic-to-felsic volcanic rocks (e.g., the Talkeetna Formation), felsic crystalline rocks, and metasedimentary rocks (Winkler, 1992; Wilson et al., 2012).

The Susitna River drains the Talkeetna Mountains, but also drains parts of the Alaska Range in its headwaters, much farther to the north of our study area. The Talkeetna Mountains and the parts of the Alaska Range that are drained by the Susitna River include a wide variety of igneous, sedimentary, and metamorphic rocks (Beikman, 1980). This likely explains the wide range of mineralogical variability found in silts of the Susitna River (Fig. 9a).

Loess from the Matanuska Valley also contains quartz, plagioclase, mica, amphibole, and chlorite. The relative abundance of these minerals in loess is similar to what is found in Matanuska and Knik River alluvium, but the loess does not have the compositional variability found in Susitna River alluvium (Fig. 9a). Thus, based on these data alone, the loess could be derived from either or both of the Matanuska and Knik Rivers, but not likely the Susitna River.

Considering just the metamorphic-rock-derived minerals (mica, amphibole, and chlorite), there is a greater differentiation of the three rivers. Both the Matanuska and Knik Rivers have abundant chlorite, but Knik River silts contain much less amphibole (Fig. 9b). Susitna River silts again have the greatest compositional variability, but in general are lower in chlorite than either the Matanuska or Knik Rivers. Matanuska Valley loess is closest, compositionally, to silts of the Matanuska River. Based on all mineralogy, we infer that the Susitna River is not a likely contributor to loess of the Matanuska Valley, consistent with the thickness trends (Fig. 3) and particle size trends (Muhs et al., 2004).

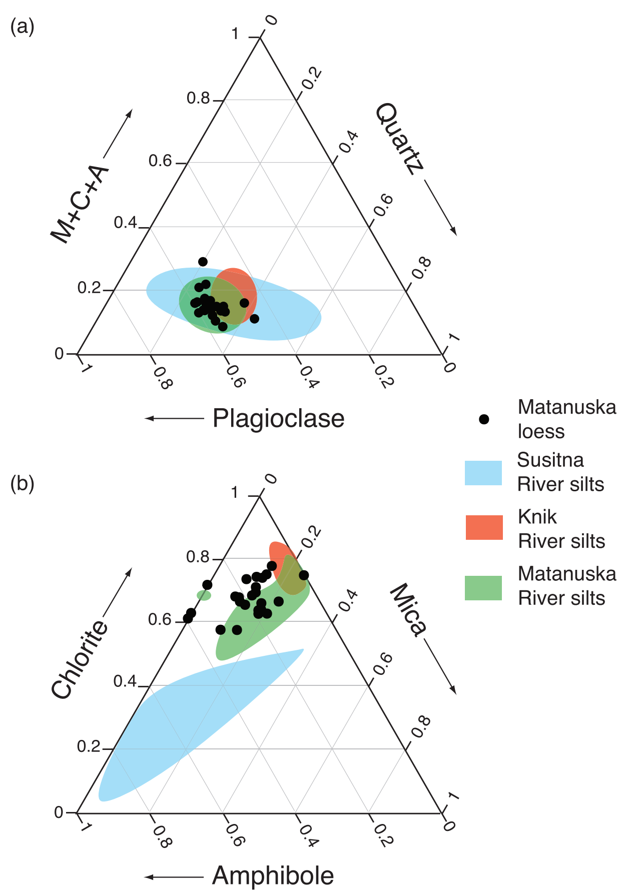

Fig. 9. (a) Ternary diagram of bulk mineralogy from the silt (53-2 μm) fractions of southern Alaskan alluvium (Matanuska, Knik, and Susitna rivers) compared to Holocene loess from the Matanuska Valley. Relative mineral abundances taken from the 20.8° 2-theta peak height for quartz, 27.8° peak for plagioclase, and 8.9°, 10.5°, and 12.5° peaks for mica (M), amphibole (A), and chlorite (C), respectively. (b) Ternary diagram of bulk mineralogy from dominantly metamorphic rock minerals (micas, chlorite, and amphiboles) from the silt fractions of southern Alaskan alluvium (Matanuska, Knik, and Susitna rivers) compared to Holocene loess from the Matanuska Valley. Relative abundances taken from the 8.9°, 10.5°, and 12.5° peaks for mica, amphibole, and chlorite, respectively.

4.3. Major element geochemistry as a function of mineralogy

Major element geochemistry of rocks and sediments is a direct reflection of mineralogy and such data are highly complementary to mineralogical analyses. The INAA and XRF methods employed herein yield concentrations of the major elements CaO, K_2O, TiO_2, MnO, and Fe_2O_3, as well as the trace elements Sr and Rb, which commonly substitute for CaO and K_2O, respectively. Given the mineralogical results summarized above for the Matanuska and Knik River silts, CaO and Sr are likely hosted primarily by plagioclase and to some extent amphibole (if we are correct that hornblende is the dominant species). Because there is little or no detectable K-feldspar in the silts of these two rivers, K_2O and Rb are likely hosted by micas (biotite and muscovite). Both Fe_2O_3 and MnO (which tends to follow Fe_2O_3) are probably hosted primarily by chlorite, but could also be found in amphibole and biotite.

The major element geochemistry reported here is in broad agreement with the semiquantitative mineralogy described earlier (Section 4.2) for the Matanuska and Knik River silts. The higher plagioclase and amphibole contents of Matanuska River silts, compared to Knik River silts (Fig. 9), is reflected in the higher CaO and Sr contents of the former (Figs. 8 and 10a). Mica contents in silts of the two rivers do not differ appreciably (Fig. 9b), and thus K_2O contents are similar, although Rb is somewhat higher in Knik River silts (Fig. 10b). Chlorite and amphibole abundances in Matanuska River silts are much more variable than in Knik River silts, and this may explain the more variable Fe_2O_3 and MnO contents in the former compared to the latter (Fig. 10c). With the exception of CaO and Sr, however, major element geochemistry does not provide distinctive geochemical "fingerprints" for silts of the Matanuska and Knik Rivers.

4.4. Trace element geochemistry

The concentrations of trace elements studied here are consistent with the inferred rocks that provide the glaciogenic silt found in the Matanuska and Knik Rivers. Valdez Group rocks, dominant in the Chugach Mountains, plot close to the composition of average upper continental crust on a Sc–Th–La diagram (Fig. 11a). In contrast, Talkeetna Formation rocks, found in the Talkeetna Mountains, have a mafic composition, are enriched in Sc and plot very closely to the composition of average oceanic crust. The Knik River drains only a part of the Chugach Mountains, an area dominated by rocks of the Valdez Group (Winkler, 1992), as discussed earlier.

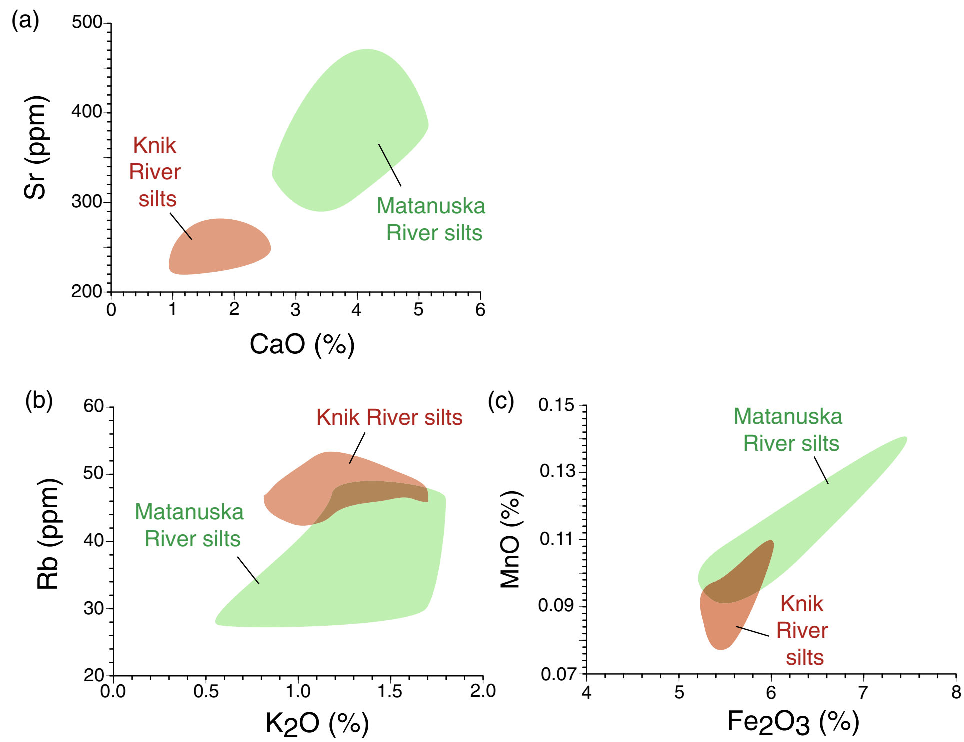

Fig. 10. Plots showing ranges of concentrations of major elements and trace elements that follow them found in Matanuska River (green) and Knik River (pink) silt-sized (53-2 μm) minerals, including (a) CaO, and Sr (plagioclase and amphiboles), (b) K_2O and Rb (micas and K-feldspar), and (c) Fe_2O_3 and MnO (chlorites, amphiboles, and some micas). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Thus, on a Sc–Th–La plot, Knik River alluvial silts fall near the center of the field of values defined by rocks of the Valdez Group (Fig. 11a). In contrast, the Matanuska River drains not only Valdez Group rocks in the Chugach Mountains, but also rocks of the Talkeetna Mountains. Thus, whereas Matanuska River alluvium falls largely within the range of composition of Valdez Group rocks for Sc–Th–La, it has a slightly more mafic composition than Knik River silts, perhaps the result of inputs from mafic rocks such as the Talkeetna Formation (Fig. 11a). With an ability to distinguish between Knik River silts and Matanuska River silts using Sc–Th–La, we compare Matanuska Valley loess compositions with those of the two possible river sources. Matanuska Valley loess does not overlap any part of the range of Knik River silts, but has almost precisely the same range of variation as that of Matanuska River silts (Fig. 11b).

On a plot of La_N/Yb_N vs. Eu/Eu*, it is also possible to differentiate Knik River silts and Matanuska River silts. Mafic rocks, including those dominated by oceanic crustal materials, tend to have relatively low La_N/Yb_N values, whereas more silicic, continental crustal rocks have higher La_N/Yb_N. The dominance of Valdez Group rocks in the composition of Knik River alluvium is easily seen in a La_N/Yb_N vs. Eu/Eu* plot, whereas Matanuska River alluvium again shows some likely input from a mafic source, such as the Talkeetna Formation (Fig. 12a). Matanuska Valley loess falls mostly within the Matanuska River field and no loess samples plot within the Knik River field. For Gd_N/Yb_N vs. Eu/Eu*, only two Matanuska Valley loess samples fall within the range of Knik River silts, although both of these also fall within the range of Matanuska River silts (Fig. 12b). Slightly more than half of the Matanuska Valley loess samples fall within the range of Matanuska River silts, and the other half are close to it.

Muhs and Budahn (2006) found Cr/Sc vs. Th/Ta to be a useful discriminator between three competing alluvial sources for loess in central Alaska. In southern Alaska, discrimination between Matanuska River silts and Knik River silts is poor using Th/Ta, but good using Cr/Sc. All but two Matanuska loess samples fall within the compositional range of Matanuska River silts and no loess samples plot within the range of Knik River silts (Fig. 13a). Because Zr and Hf are hosted almost exclusively by zircon, Zr/Hf is potentially a useful zircon geochemical fingerprint. Unfortunately, Zr/Hf values for both rivers overlap, and thus we can make no inferences regarding sources of loess using zircon compositions (Fig. 13b). On the other hand, As/Sb (both elements found in magnetite) shows good discrimination between the Matanuska and Knik Rivers (Fig. 13b). Almost all Matanuska Valley loess samples fall within the range of Matanuska River silts for As/Sb, and no loess samples plot within the range for the Knik River.

5. Discussion

The oldest radiocarbon ages of loess inferred here are substantially younger than the estimated times of glacial recession in the Matanuska Valley. As discussed earlier, Reger et al. (1995) report that upper Knik Arm was deglaciated by ~9900 cal yr BP. Thus, assuming conservatively that ice had left the lower part of the now-loess-mantled Matanuska Valley by about this time, ~3400–2100 cal yr could have passed before the first loess deposition. The hiatus in sedimentation between glacial recession and loess deposition may be represented by the paleosols developed above the glacial/outwash gravels in loess profiles 4, 5, 7 and 17 (Figs. 7 and 8). Another possibility is deflation by strong katabatic winds, a process that has been inferred elsewhere in Alaska (Thorson and Bender, 1985; Muhs and Budahn, 2006). Such a process would not explain the presence of paleosols, however.

New data presented here on the thickness of Matanuska Valley loess are consistent with earlier studies (Stump et al., 1959; Trainer, 1961; Muhs et al., 2004). Four new loess sections have

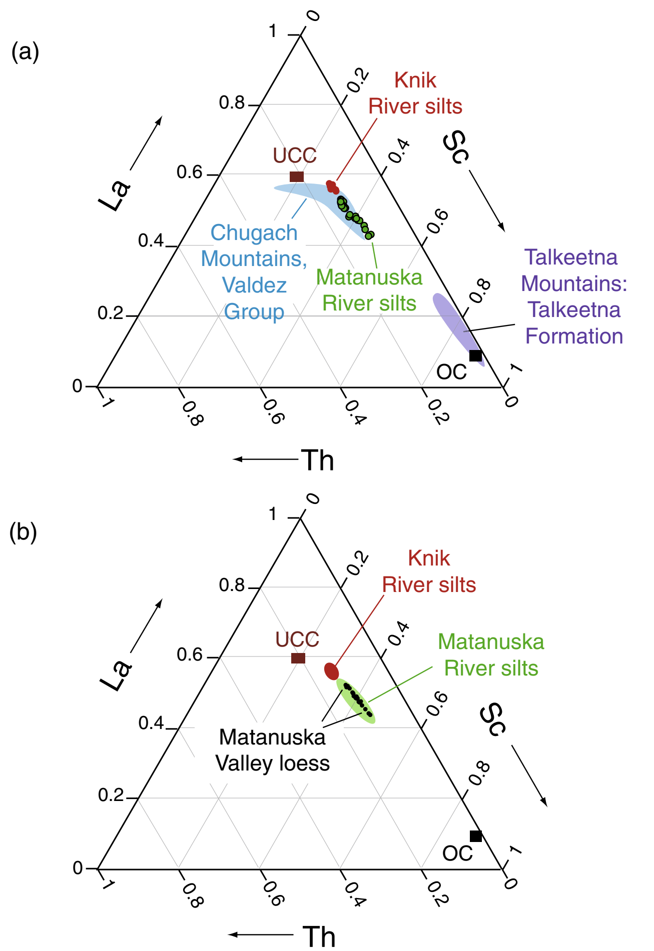

Fig. 11. (a) Sc–Th–La abundances of silt-sized (53-2 μm) particles from the Knik River (filled red circles) and Matanuska River (filled green circles), along with the ranges of these values for possible bedrock sources. Data for alluvial silts are from this study; bedrock geochemical data are from Plafker et al. (1989) and Barker et al. (1994). UCC, upper continental crust; OC, oceanic crust (values from Taylor and McLennan, 1985). (b) Sc–Th–La abundances for Matanuska Valley loess (filled black circles) compared to ranges of these elements in Knik and Matanuska River silts, derived from plot in (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

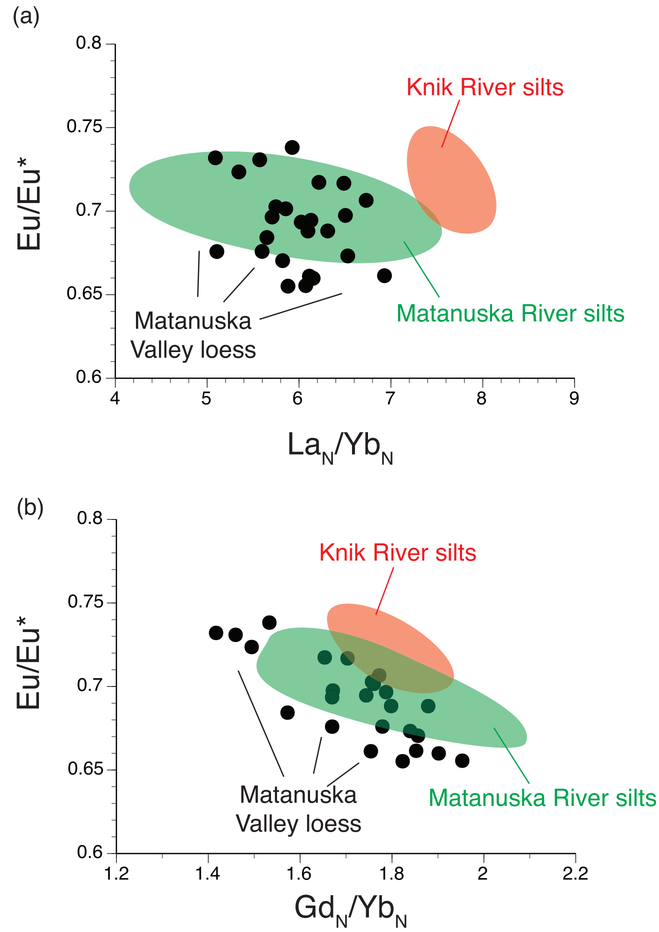

Fig. 12. (a) La_N/Yb_N vs. Eu/Eu* plot for Matanuska Valley loess (filled black circles), compared with ranges of compositions for Knik River (pink shading) and Matanuska River (green shading) alluvial silts. (b) Gd_N/Yb_N vs. Eu/Eu* plot for Matanuska Valley loess (filled black circles), compared with ranges of compositions for Knik River (pink shading) and Matanuska River (green shading) alluvial silts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thicknesses that are in good agreement with the regional trend of decreasing loess thickness to the west of the Matanuska and Knik Rivers (Fig. 3). Thus, the loess source or sources must be situated to the east of the lower Matanuska Valley. Mineralogical data are consistent with the thickness data that imply loess source or sources to the east rather than to the west. Silts of both the Knik and Matanuska Rivers, to the east of the loess body, have a mineralogy that is similar to that of Matanuska Valley loess, dominated by quartz and plagioclase, with smaller amounts of mica, chlorite, and amphibole. The major potential loess source to the west of the loess body is the Susitna River. In contrast to the other rivers, Susitna River silts have a much more variable mineralogy, including K-feldspar in all samples, lower amounts of plagioclase relative to quartz, and relatively higher amounts of amphibole relative to mica and chlorite. Thus, mineralogical data support the loess thickness trend that the Susitna River likely is not an important source of Matanuska Valley loess.

Although there are only minor differences in mineralogy between the Knik and Matanuska Rivers, certain trace element ratios (Sc–Th–La, La_N/Yb_N vs. Eu/Eu*, Cr/Sc, and As/Sb) are distinctive for silts of the two rivers. The trace element geochemistry shows that the Matanuska River is unquestionably the more important of these two as a loess source. Loess samples fall well within (or close to) the compositional fields for Matanuska River silts for Sc–Th–La, La_N/Yb_N vs. Eu/Eu*, Th/Ta vs. Cr/Sc, and Zr/Hf vs. As/Sb, and none falls within the compositional fields for these elements for the Knik River. Our results, therefore, support the proposal by Reger and Updike (1983) that the Matanuska River is the most important source and challenge the hypothesis of Tuck (1938) that the Knik River is the primary source. Some of our samples were collected at various depths within profiles 4, 17, and 18 (Fig. 7), yet all fall within the trace-element compositional fields of the Matanuska River, suggesting that this source has been the only important one over the course of loess accumulation history. Nevertheless, in order to test this more rigorously, we resampled loess profile 17 in more detail, at 10-cm depth intervals, to see if a Knik River signature could be detected in any loess deposited over at least the past ~6750 cal yr represented by the profile (Fig. 8). Concentrations of both CaO and Sr (thought to represent mostly amphibole and Ca-plagioclase) at all but the two lowermost depths fall within or close to the range of Matanuska River silts and none falls within the range of Knik River silts. Thus, even if there had been syndepositional leaching of CaO and Sr, concentrations of both elements are too high to permit any significant contribution from the Knik River. We conclude that the Matanuska River has been the major source for the loess not only at all localities studied,

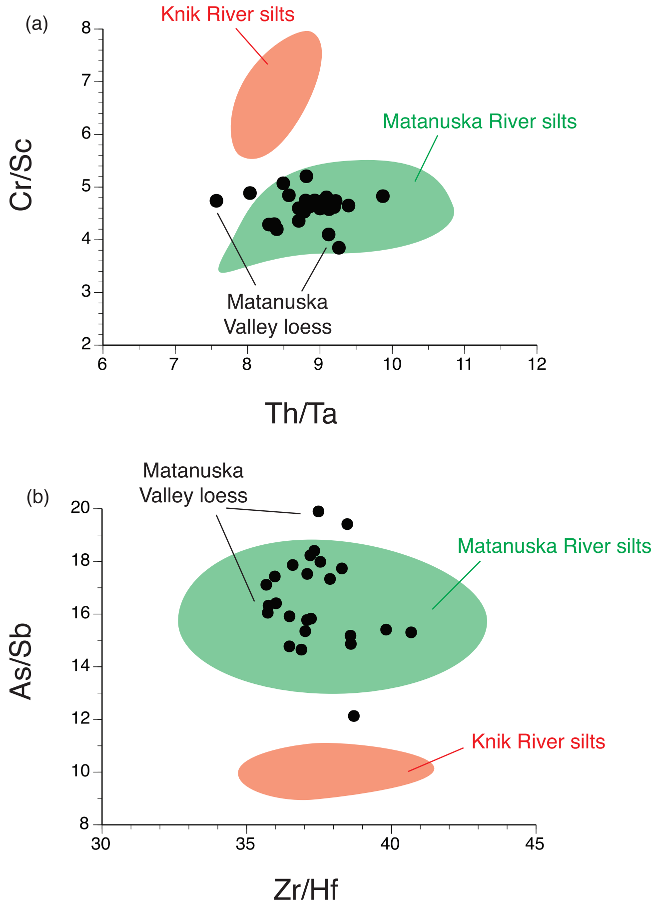

Fig. 13. (a) Th/Ta vs. Cr/Sc and (b) Zr/Hf vs. As/Sb for Matanuska Valley loess (filled black circles) compared with ranges of compositions for Knik River (pink shading) and Matanuska River (green shading) alluvial silts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

but also over all or most of the period of loess accumulation in the Matanuska Valley, at least close to the river.

Identification of the Matanuska River as the primary source for loess in the Matanuska Valley raises interesting questions about the controls on aeolian particle entrainment in the region. As pointed out by Schoephorster (1968), Reger and Updike (1983), and Clark and Kautz (1998), modern dust storms occur at present from both the Knik and Matanuska River floodplains, and winds that blow over both drainages are strong enough to entrain significant amounts of dust (Fig. 5a). However, the dominant time of dust entrainment differs for the two drainages. Matanuska winds, from the north or northeast, occur primarily during October through February, cold months, whereas Knik winds occur primarily during April through August, warm months. Thus, identification of the Matanuska River as the major loess source, with dust generated during cold months, seems counterintuitive. During cold months, floodplain silts can be frozen and/or snow-covered, which would inhibit particle entrainment. We note, however, that average snow depth in winter in the region is not as high as one might expect (Fig. 5b), due to the fact that mountains surrounding the Matanuska Valley (Figs. 2 and 3) block many air masses that could otherwise deliver precipitation as snow to the region (Dale, 1956). Furthermore, soil temperatures in the Palmer area, at least as measured at 50 cm depth (Fig. 5c), on average remain above freezing through November (Ping, 1987). Finally, as pointed out more than 100 years ago by Tarr and Martin (1913, p. 300) and recently by Crusius et al. (2011), in their studies of dust storms in the Copper River basin of southern Alaska, the optimum time for particle entrainment by wind is when the floodplain of a river system is at its lowest discharge, and silt-rich point bars are exposed. In the Copper River basin, this occurs in the autumn. In both the Knik and Matanuska River systems, the lowest discharge (during months when the ground is not frozen) also occurs during autumn (Fig. 5d), when northerly winds become frequent (Fig. 4).

In summary, during autumn, four factors become very critical in determining the source of aeolian particle entrainment for the Matanuska Valley: (1) discharge is very low and silt-rich point bars become exposed in both rivers; (2) snow cover has not yet become significant; (3) soils and sediments are not yet frozen; and (4) due to synoptic-scale climatic controls, the wind regime has shifted from a southeasterly (Knik) pattern to a northern or northeasterly (Matanuska) pattern. We infer, therefore, that much of the loess accumulation over the past ~7500 cal yr in the Matanuska Valley may have taken place during autumn, with perhaps some additional accumulation during favorable warm periods in winter. It is interesting to note that Arnalds et al. (2012) report that some of the highest dust fluxes in Iceland also occur in autumn (see their Table 4). Using more than a half-century of historic records, Dagsson-Waldhauserova et al. (2013) report that significant dust storms in northeastern Iceland occur primarily in summer *and* early autumn.

The observations presented here have implications for understanding possible seasonal controls on glaciogenic aeolian silt transport in the Pleistocene. Seasonal controls on Pleistocene aeolian silt transport in Asia are reasonably well understood based on modern, synoptic-scale controls on dust transport (Porter and An, 1995). For Europe, New Zealand, South America, and North America, there is far less information about possible seasonal controls on Pleistocene silt transportation by wind. A traditional inference for mid-continental North America (Fig. 1a), for example, is that most aeolian silt transport occurred in summer, during the glacial ablation season (Flint, 1971, p. 255). On the other hand, *both* summer and autumn have also been proposed as seasons of aeolian silt transport by Pye (1987), and recent studies have also suggested the possibility of aeolian silt transport in spring (Bromwich et al., 2005; Muhs et al., 2008). Study of modern aeolian silt transport in Alaska and other regions (see Bullard, 2012) may provide insight on controls for Pleistocene aeolian silt transport in other parts of the world.

6. Conclusions

(1) New stratigraphic sections measured for Matanuska Valley loess are consistent with loess thickness trends based on previous work and show a general westward thinning, implying a source or sources situated to the east, either the Knik or Matanuska Rivers.
(2) Knik and Matanuska River silts have only slight differences in mineralogy, except Matanuska River silts contain slightly more plagioclase and considerably more amphibole, mirrored by higher CaO and Sr contents. Both have mineralogical compositions similar to Matanuska Valley loess. The Susitna River, to the west of the study area, has a very different mineralogy than either of the other two rivers, and does not match Matanuska Valley loess. Elimination of the Susitna River as a loess source is consistent with thickness and particle size data that indicate the loess source is situated to the east of the Matanuska Valley loess body.
(3) Despite only minor differences in mineralogy, Knik and Matanuska River silts have significant differences in trace element geochemistry, and can be distinguished using Sc–Th–La, La_N/Yb_N vs. Eu/Eu*, Cr/Sc, and As/Sb. Matanuska Val-

ley loess falls clearly within the range of Matanuska River silt and does not appear to have a significant component of Knik River silt.

(4) Dust storms from the Matanuska River coincide with a time in autumn when river discharge is at a minimum and silt-rich point bars are exposed, wind speed from the north is beginning to increase after a low-velocity period in summer, snow depth is still minimal, and soil temperatures are still above freezing.

(5) Seasonal changes in climate and hydrology, identified as critical factors in the timing of loess accumulation in southern Alaska, could be applicable to understanding seasonal controls on Pleistocene glaciogenic aeolian silt transportation in Europe, South America, New Zealand, and North America.

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