Geochemical evidence for the origin of late Quaternary loess in central Alaska

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Abstract: Loess is extensive in central Alaska, but there are uncertainties about its source and the direction of paleowinds that deposited it. Both northerly and southerly winds have been inferred. The most likely sources of loess are the Tanana River (south), the Nenana River (southeast), and the Yukon River (north). Late Quaternary loess in central Alaska has immobile trace-element compositions (Cr/Sc, Th/Ta, Th/Sc, Th/U, Eu/Eu*, Gd_N/Yb_N) that indicate derivation mostly from the Tanana River. However, other ratios (As/Sb, Zr/Hf, La_N/Yb_N) and quantitative modeling indicate that the Yukon River was also a source. During the last glacial period, there may have been a longer residence time of the Siberian and Canadian high-pressure cells, along with a strengthened Aleutian low-pressure cell. This would have generated regional-scale northeasterly winds and explains derivation of loess from the Yukon River. However, superimposed upon this synoptic-scale circulation, there may have been strong, southerly katabatic winds from expanded glaciers on the northern flank of the Alaska Range. These winds could have provided eolian silt from the Tanana River. Yukon River and Tanana River sediments are highly calcareous, whereas Fairbanks-area loess is not. This suggests that carbonate leaching in loess kept ahead of sedimentation and that late Quaternary loess in central Alaska was deposited relatively slowly.

Résumé : Il existe encore de l'incertitude quant à la source du lœss largement présent dans le centre de l'Alaska et à la direction des paléovents qui l'y ont déposé. On a pu inférer l'action de vents du nord et du sud. Les sources les plus probables du lœss sont les rivières Tanana (au sud) et Nenana (au sud-est), ainsi que le fleuve Yukon (au nord). Le lœss de l'Holocène dans le centre de l'Alaska contient des compositions immobiles d'éléments traces (Cr/Sc, Th/Ta, Th/Sc, Th/U, Eu/Eu*, Gd_N/Yb_N) qui indiquent une dérivation prépondérante à partir de la rivière Tanana. Cependant, d'autres ratios (As/Sb, Zr/Hf et La_N/Yb_N) et la modélisation quantitative désignent le fleuve Yukon comme autre source. Il est possible qu'au cours de la dernière glaciation le temps de séjour des cellules de haute pression de la Sibérie et du Canada ait été plus long et la cellule de basse pression des Aléoutiennes, renforcée. Ces conditions auraient engendré des vents régionaux du nord-est et pourraient expliquer la dérivation à partir du fleuve Yukon. Il est par ailleurs vraisemblable que, superposés à cette circulation atmosphérique générale, de forts vents catabatiques aient soufflé du sud, en provenance des glaciers s'étendant sur le flanc nord de la chaîne de l'Alaska. Ces vents auraient transporté du silt depuis la rivière Tanana. Les sédiments du fleuve Yukon et de la rivière Tanana sont hautement calcaires, tandis que le lœss de la région de Fairbanks ne l'est pas. Cela laisse penser que le lessivage du carbonate du lœss aurait devancé la sédimentation et que le lœss de l'Holocène dans le centre de l'Alaska aurait été déposé relativement lentement.

[Traduit par la Rédaction]

Introduction

Loess is one of the most extensive Quaternary deposits on the surface of the Earth and forms some of the world's most highly productive soils. Thick loess is now recognized as an important paleoclimate archive and is sometimes presented as a terrestrial equivalent to the deep-sea oxygen isotope record of Quaternary glacial–interglacial cycles (Porter 2001; Muhs and Bettis 2003). Because loess is an eolian sediment, it is also one of the few direct records of paleowinds, which can aid greatly in reconstructing synoptic-scale paleoclimatology (Porter and An 1995; Muhs and Bettis 2000). In addition, however, atmospheric scientists are now examining the potential role of the fine-grained component of loess (aerosolic dust) in bringing about climate change (see reviews in Mahowald et al. 1999; Kohfeld and Harrison 2001; Harrison et al. 2001). Aerosolic dust can change climate through radiative forcing (Tegen 2003) or as fertilizer to the world's oceans, where enhanced phytoplankton blooms can draw down atmospheric carbon dioxide (Hutchins and Brunland 1998).

To utilize loess for paleowind studies and for assessing the importance of the fine-grained, far-traveled component for radiative forcing or oceanic additions, it is essential to identify the source sediments. On landscapes of some glaciated

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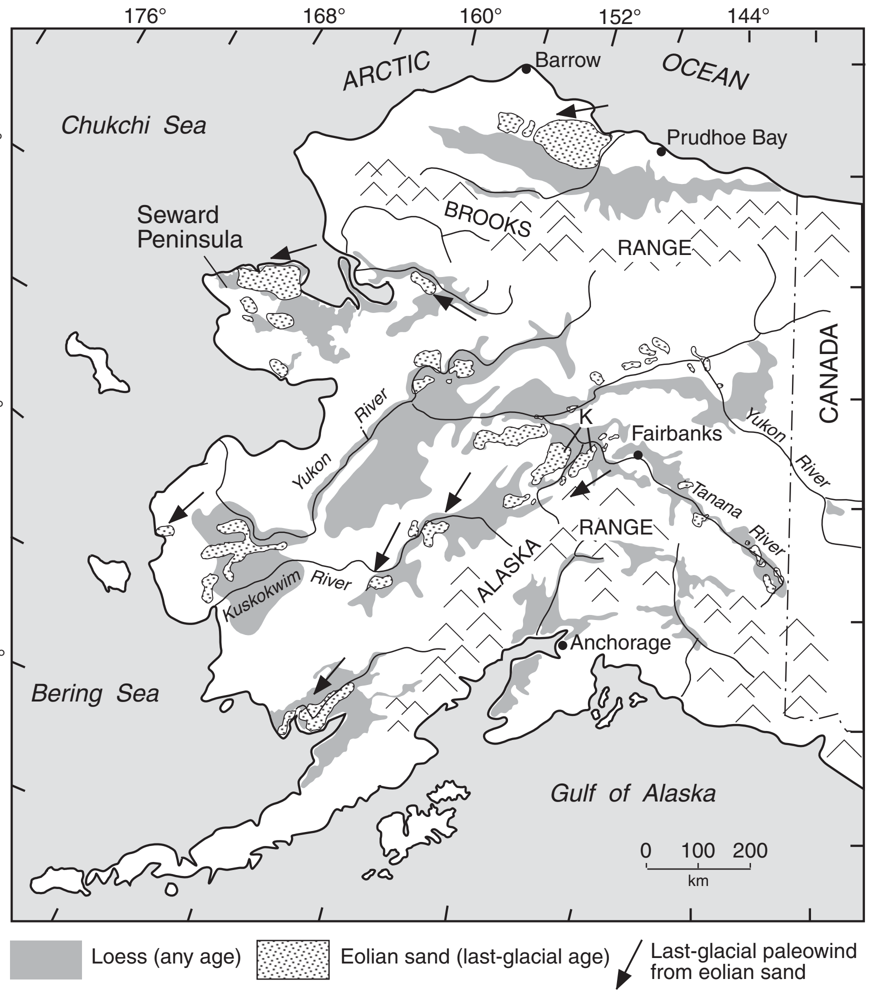
Fig. 1. Map showing the distribution of loess and eolian sand in Alaska, along with inferred last-glacial paleowinds derived from eolian sand bodies and dunes. Loess compiled from Hopkins (1963) and Sainsbury (1972) for the Seward Peninsula, and Péwé (1975) for all other parts of the region. Eolian sand distribution from Hopkins (1982) and Lea and Waythomas (1990). K, Kantishna sand sea.



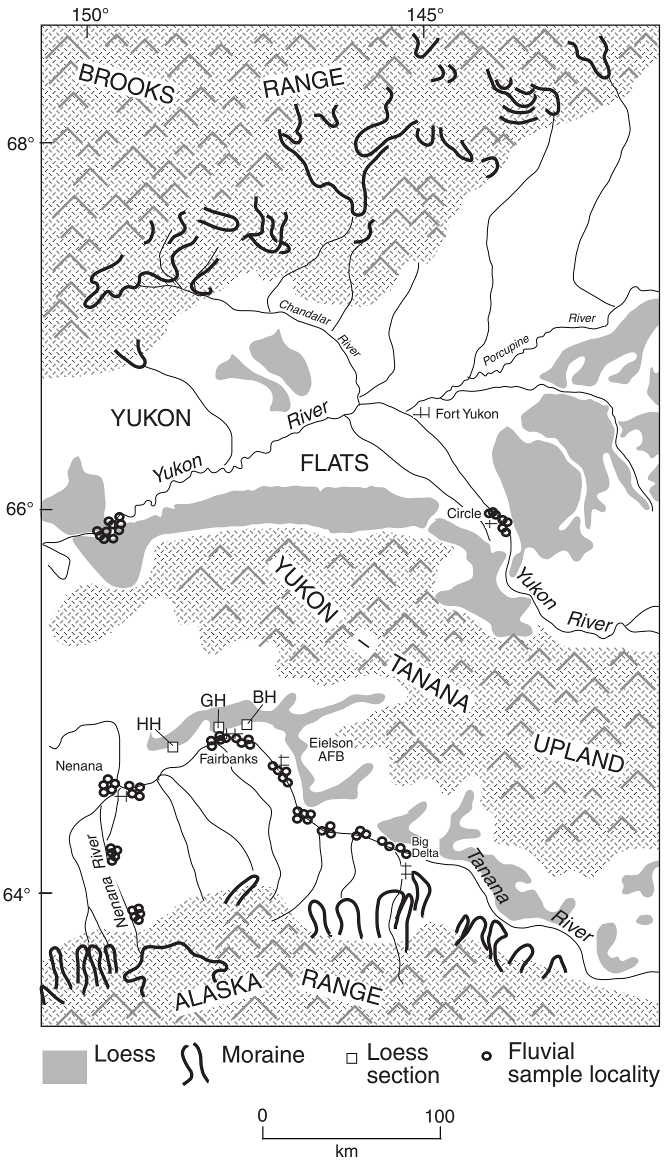
Northern Hemisphere continents, loess deposits have obvious links to glaciogenic sources, such as the Mississippi, Missouri, and Ohio rivers in North America and the Danube and Rhine rivers in Europe (Ruhe 1983; Smalley and Leach 1978). On other continents, such as Asia (particularly China), loess has upwind desert basins as its immediate sources (Sun 2002). However, the ultimate source of the silt particles (glaciogenic or desert-derived) is not agreed upon, and there is considerable debate over the origin of eolian silt in those regions (Liu 1985; Smalley 1995; Derbyshire et al. 1998; Wright 2001; Sun 2002).

Alaska is one part of North America where loess is extensive (Fig. 1), and there have been a significant number of studies of its stratigraphy, intercalated paleosols, and links to the global record of Quaternary glacial–interglacial cycles (Péwé 1975; Begét 1990; Begét et al. 1990; Vlag et al. 1999; Preece et al. 1999; Lagroix and Banerjee 2002, 2004; Berger 2003; Muhs et al. 2003). The Alaskan loess records offer an unusual opportunity to assess past climates at high latitudes because the region is within a very sensitive zone with respect to atmospheric circulation over the north Pacific and Arctic oceans. Previous workers have attempted to reconstruct paleowinds from sand dune orientations and the locations of sand sheets in Alaska, particularly for the last glacial period (25 000 – 12 000 years BP). These studies conclude that last-glacial paleowinds were dominantly from the northeast (Hopkins 1982; Lea and Waythomas 1990). In contrast, younger eolian sheet sands, with basal radiocarbon ages of ~10 000 – 11 000 ^{14}C years BP, are found on the north side of the Yukon River elsewhere in central Alaska (Froese et al. 2005). If the ages are maximum-limiting estimates and if the sands were locally derived, these deposits imply sand-transporting winds from the south by the start of the Holocene.

Loess deposits have also been utilized for paleowind reconstructions in Alaska. A recent study concludes that, on the basis of magnetic mineral fabric, both glacial and interglacial paleowinds were from the north (Lagroix and Banerjee 2002). In contrast, other studies suggest that last-glacial paleowinds in central Alaska were from the south, based on reported diminishing loess thickness away from the Tanana River near Fairbanks (Péwé 1955) and on hypothesized katabatic winds from the Alaska Range (Thorson and Bender 1985; Guthrie 1990).

In this paper, we test the opposing hypotheses of northerly

Fig. 2. Map showing the distribution of loess in central Alaska, moraines thought to date from the last glacial period, major river systems, mountain ranges, loess section localities, and geochemical sample localities along the Tanana, Nenana and Yukon rivers. Loess distribution from Péwé et al. (1966) and Williams (1962), and minor new mapping by Muhs et al. (2003). Moraine positions are from Karlstrom et al. (1964). AFB, Air Force Base; BH, Birch Hill; GH, Gold Hill; HH, Halfway House.



versus southerly paleowinds for the origin of late Quaternary loess in central Alaska. Our approach is to determine the most likely source sediments for central Alaskan loess using rare-earth elements (REE) and other immobile trace elements (Cr, Sc, Th, U, Ta, Zr, Hf, As, Sb) as provenance indicators. We analyzed deposits from a loess belt in central Alaska near Fairbanks (Figs. 1, 2), using that part of the stratigraphic record that is thought to date from the latest Quaternary, specifically the last glacial period and (or) the Holocene.

Composition of Alaskan loess, geologic setting, and synoptic climatology

Sedimentology and mineralogy of central Alaskan loess

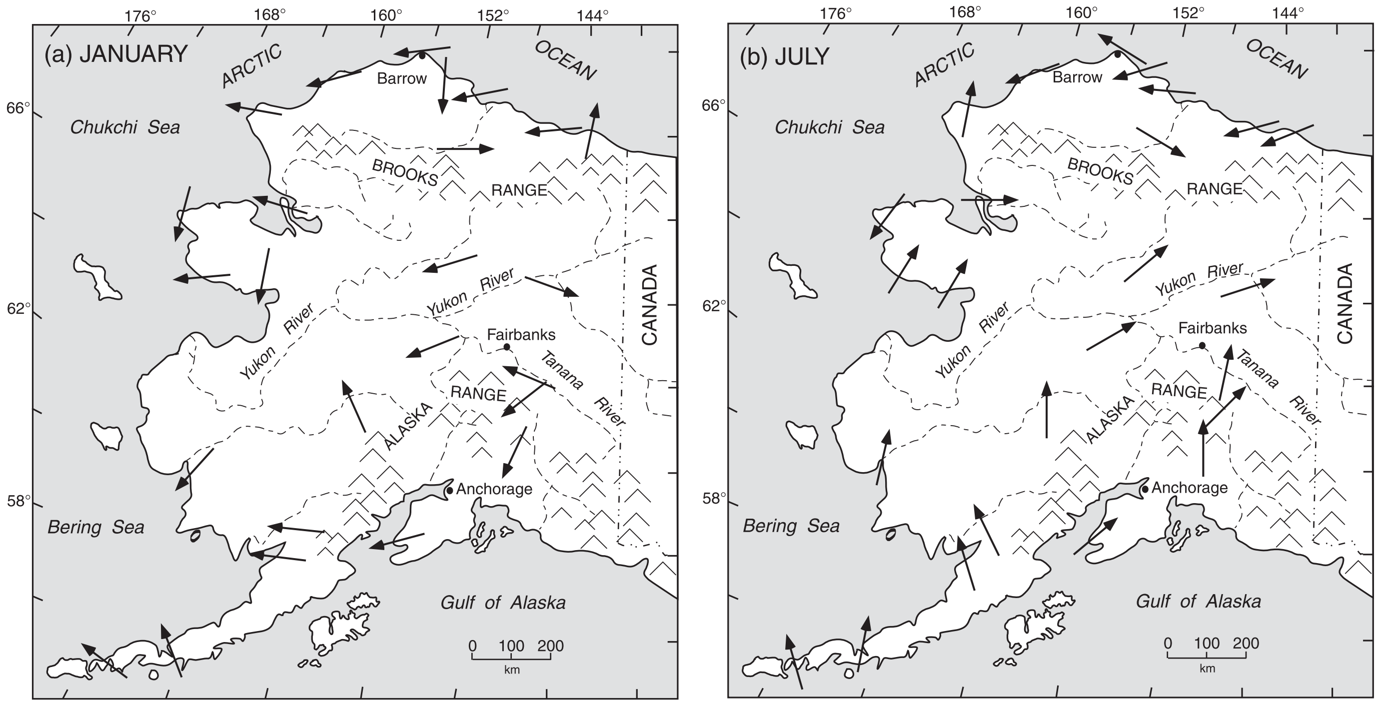
Loess in the Fairbanks area (Fig. 2) is often many tens of metres thick and the oldest loess may exceed an age of 3.0 Ma (Westgate et al. 1990; Preece et al. 1999). Central Alaskan loess sections are thick deposits of eolian silt, separated by paleosols (Begét et al. 1990; Muhs et al. 2003). The loess is dominated (~50%–70%) by coarse silt (53–20 μm), but also contains significant (~15%–35%) fine silt (20–2 μm). In contrast, sand (>53 μm) and clay (<2 μm) contents are almost always < 5% each (Muhs et al. 2003). Bulk mineralogy of central Alaskan loess, based on X-ray diffraction analysis, is quartz, plagioclase, mica, and chlorite. K-feldspar is present in some samples, but concentrations are not high. Based on analyses of ~100 samples, we found small amounts of calcite in only a few samples, which distinguishes Alaskan loess from highly calcareous, midcontinental North American loess, Chinese loess, and European loess. Studies of magnetic susceptibility show that central Alaskan loess has significant quantities of magnetite (Begét 1990; Begét et al. 1990; Vlag et al. 1999; Lagroix and Banerjee 2002). Péwé (1955) also reported the presence of small quantities of heavy minerals such as epidote, garnet, hypersthene, rutile, sphene, and tourmaline. In addition to these heavy minerals, our own trace-element geochemistry indicates that zircon is present in all samples. Based on analyses of selected loess samples by three-treatment X-ray diffraction (air dry, glycolated, and heated to 550 °C), clay minerals in central Alaskan loess consist of chlorite, mica, and kaolinite, with smaller amounts of smectite, as well as clay-sized quartz and feldspars; the latter are dominated by plagioclase (Muhs et al. 2003).

Geologic setting and possible sources of loess

There are at least four potential sources of Fairbanks-area loess. One is the local schist bedrock, formerly called the Birch Creek schist and now called, informally, the Fairbanks schist (Robinson et al. 1990). Taber (1943, 1953, 1958) considers this rock to be the main source of silt in the Fairbanks area, via frost shattering and downslope movement to valley bottoms. In his studies, Taber is not referring to silts that occur on uplands or interfluves, but strictly to silts found in valley bottoms and side slopes. Unlike other researchers, Taber does not report upland silts of any significant thickness in the area (Taber 1958, p. 133). Péwé (1955) rejects Taber's (1943, 1953) hypotheses about the origin of silts in the Fairbanks area and presents several lines of evidence supporting an eolian origin. All subsequent investigators, with the exception of Taber (1958), agree with Péwé (1955) that upland silts in the region are true loess deposits.

The most important potential source sediments to the north of the Fairbanks-area loess are fluvial deposits of the Yukon River (Figs. 1, 2). The Yukon River drains the southern flank of the eastern Brooks Range (Paleozoic clastic carbonate and metasedimentary rocks, and Paleozoic and Mesozoic mafic volcanic rocks) and the northern flank of the Yukon–Tanana Upland (Precambrian and Paleozoic gneiss and schist, and Mesozoic felsic intrusive igneous rocks). Few glaciers exist in the Brooks Range today, but during the last glacial period,

Fig. 3. Map of Alaska showing seasonal wind directions for wind velocities > 5 m/s for (*a*) January and (*b*) July. Computed by the authors using WERIS wind data from the National Climatic Data Center, Asheville, North Carolina, following the methods outlined in Fryberger and Dean (1979).



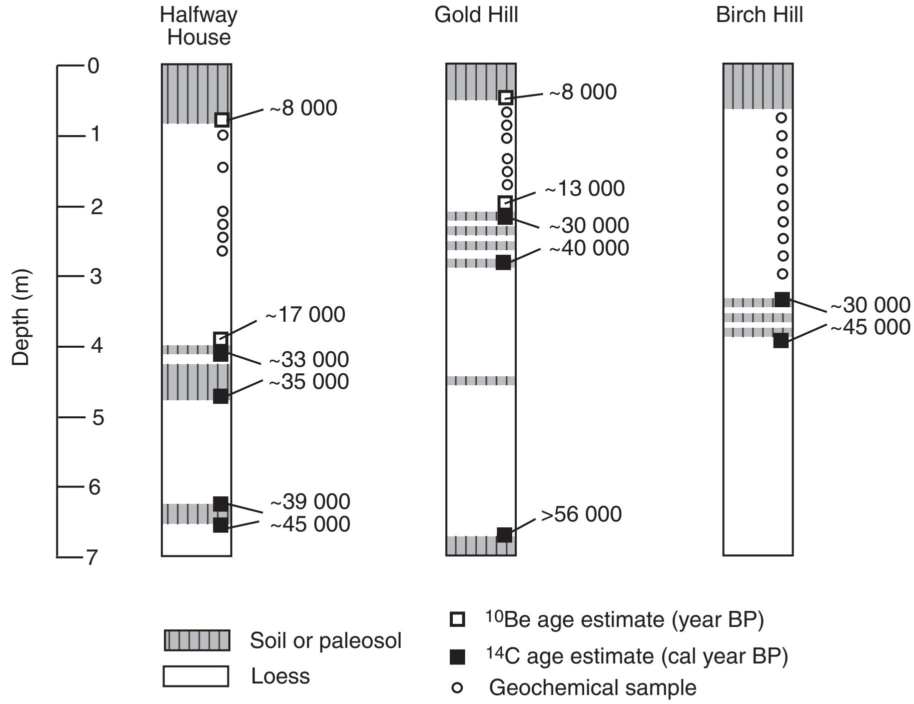
ice was extensive on both the northern and southern flanks of the range (Hamilton 1982, 1994). To the south, the most important potential source sediments are fluvial deposits of the Tanana and Nenana rivers (Figs. 1, 2). The Nenana River heads in the Alaska Range and flows south to north, draining a limited portion of the Alaska Range only. In contrast, the Tanana River flows east to west and drains the southern flank of the Yukon–Tanana Upland (Precambrian and Paleozoic gneiss and schist, and Mesozoic felsic intrusive igneous rocks), the Wrangell Mountains (Tertiary and Quaternary volcanic rocks of intermediate composition), and the northern flank of the Alaska Range (Precambrian and Paleozoic gneiss and schist, and Tertiary clastic sedimentary rocks). The Yukon–Tanana Upland is not presently glacier covered and had limited ice extent during the last glacial period (Péwé et al. 1967; Hamilton 1994). In contrast, both the Wrangell Mountains and the Alaska Range have glaciers at present, and had much more extensive ice during the last glacial period (Hamilton 1994).

Synoptic climatology of central Alaskan dust storms

Modern surface winds in central Alaska exhibit seasonal changes in direction as a result of synoptic-scale shifts in pressure systems across the region and their interactions with topography (Mock et al. 1998). In winter, two high-pressure cells are situated to the north of central Alaska. The Siberian high-pressure cell extends from central Asia to Siberia, and a smaller but prominent high-pressure center is located over northern Canada (Bryson and Hare 1974). At the same time, the Aleutian low-pressure cell is well developed over much of the North Pacific Ocean, corresponding with the location of the jet stream, well south of Alaska. In contrast, the Pacific subtropical high-pressure cell is weak and is situated south of about 40°N. Thus, relatively strong northeasterly surface winds occur over central Alaska in winter, driven by the pressure gradient between the Canadian high and the Aleutian low (Fig. 3). In summer, the Canadian high and Aleutian low weaken, and the Pacific subtropical high strengthens and migrates northward. The northward migration of the subtropical high corresponds with increased jet stream activity and a trough centered on Bering Strait. Thus, in summer over much of southern and central Alaska, there is southwesterly airflow at the surface (Fig. 3), as well as in the upper atmosphere. The southerly summer surface winds in Alaska are, in general, weaker than the northerly winter winds.

Modern dust-transporting winds in Alaska follow the overall seasonal shifts in wind direction. Based on observations of modern dust storms derived from entrainment of silt-sized glaciofluvial sediment in central Alaska and Yukon, wind velocities of at least 4–14 m/s (at standard weather station measuring heights) are required for transport of loess-sized particles (Péwé 1951; Nickling 1978). We compiled wind data for various localities in Alaska from the WERIS (Wind Energy Resource Information System) database of the National Climatic Data Center (Asheville, North Carolina, USA) and generated vector summations of resultant wind direction and strength for those velocities > 5 m/s, following the methods given in Fryberger and Dean (1979). The resultant dust-transporting winds are dominantly from the north or northeast in winter and from the south or southwest in summer (Fig. 3), consistent with the broad synoptic pattern sketched earlier in the text. We have observed eolian entrainment of

Fig. 4. Portions of three loess sections from the Fairbanks loess belt of central Alaska, showing loess (unshaded portions), paleosols (shaded portions), sample depths, and age estimates in calendar years before present. Stratigraphy and ages for all sections are from Muhs et al. (2003).



dust from the modern floodplains of the Delta, Tanana, and Nenana rivers during periods of relatively strong, southerly winds in summer and fall.

Methods

We sampled loess deposits from three localities near Fairbanks, Alaska, (Fig. 4) that have been studied by numerous investigators (Begét 1990; Preece et al. 1999; Vlag et al. 1999; Lagroix and Banerjee 2002, 2004; Berger 2003; Muhs et al. 2003). Radiocarbon and ^{10}Be inventory methods suggest that loess that underlies the modern surface soil at the three localities (Halfway House, Gold Hill, Birch Hill) could date to either the latest part of the last glacial period and (or) the Holocene (Fig. 4). We emphasize that better age control is needed at all these sites because the radiocarbon estimates are uncertain. For example, all of the radiocarbon ages at Halfway House and Gold Hill are based on humic acid extractions, which could very well underestimate the true ages. The ^{10}Be ages are dependent on assumptions about both ^{10}Be production rates and amount of inheritance. The global ^{10}Be production rate is not known with certainty and estimates vary by a factor of two (see range of estimates in Muhs et al. 2003). Following Curry and Pavich (1996), Muhs et al. (2003) use a value of 1.3×10^6 atoms/cm^2/year in estimating ages of central Alaskan loess. Because there are few first-cycle sediments on the Earth's surface, the probability is high that some of the measured ^{10}Be is inherited from a previous period of pedogenesis and surface accumulation. Muhs et al. (2003) estimate what this "background" ^{10}Be concentration might be for central Alaska by measuring the abundance of ^{10}Be in a radiocarbon-dated Holocene loess section near Delta Junction, Alaska.

Samples were taken at various depths from the estimated late Quaternary portions of each loess section (Fig. 4). Samples of modern, silt-rich alluvium were also collected from a number of reaches of the Tanana River, between Delta Junction and Nenana (a total of 38 samples). For the Yukon River, we collected modern silt-rich alluvium from the two road-accessible localities available, near Circle and at the Yukon River crossing on the Dalton Highway (a total of 17 samples). Along the Nenana River, we collected 15 silt-rich alluvial samples, five at each of three localities between the towns of Nenana and Healy. We also collected 12 samples of the Fairbanks schist, the local bedrock that underlies the Fairbanks loess belt in the Yukon–Tanana Upland.

All loess and schist samples were analyzed in bulk (i.e., as "whole rocks") without pre-treatments. For the alluvial sediments, samples were first treated with hydrogen peroxide to remove organic matter. Sodium hexametaphosphate was then added as a dispersant and left overnight. The samples were then treated by ultrasonic shaking to aid dispersion of clays. Sands and gravels were removed by wet-sieving (using a 53 µm sieve) and clays (<2 µm) were removed by repeated settling and decantation. We chose 53 µm for the sand–silt break (as opposed to 63 µm) and 2 µm for the silt–clay break (as opposed to 4 µm) for two important reasons: (1) particle size data in Muhs et al. (2003) indicate that the majority of Fairbanks-area loess deposits consist of particles between 53 and 2 µm, and (2) the majority of loess deposits that have been studied elsewhere in North America (particularly in the midcontinent) have used these particle size breaks or breaks close to them (e.g., the 50 and 2 μm breaks used by soil scientists). The resulting 53–2 μm silt separate, which closely duplicates the texture of loess, was then analyzed for geochemistry. It should be noted that carbonates, if present, are retained by this process.

Sedimentary petrologists have shown that virtually all shales have lower Na_2O/Al_2O_3 values than the lowest limits for this ratio found in igneous rocks, whether mafic or felsic (Garrels and MacKenzie 1971). Such observations have been interpreted to mean that particles in shale have undergone considerable depletion of Na-plagioclase, compared with the original content of feldspar in the protolith. Moreover, shales show a trend toward increasing K_2O/Al_2O_3 values, which reflects increasing amounts of illite accumulation over time (Garrels and MacKenzie 1971). Gallet et al. (1998) use Na_2O/Al_2O_3 vs. K_2O/Al_2O_3 plots for a wide range of loesses sampled worldwide. They show that, as with shales, loess deposits have lower Na_2O/Al_2O_3 compared with all igneous rocks. Gallet et al. (1998) interpret the trends to indicate that most or all loesses are derived from protoliths that have undergone at least one cycle (and probably *many* cycles) of weathering, pedogenesis, or diagenesis prior to eolian entrainment, transport, and deposition as loess. In contrast to the concept of simple, first-cycle glacial grinding of crystalline rocks, their results argue for a greater role played by "preweathered" sediments or sedimentary rocks in the origin of loess, with at least some degree of Na-plagioclase depletion inherited by loess. We applied this method to central Alaskan loess, measuring major elements using X-ray fluorescence. In addition, we generated similar plots for loesses in other regions using data from the literature.

Concentrations of certain major elements, trace elements, and REE were determined by instrumental neutron activation analysis, as described by Budahn and Wandless (2002). For provenance studies, we used only those elements that are considered, on the basis of high ionic potential, to be immobile in low-temperature, near-surface environments. The suite of elements chosen includes Cr, Sc, Ta, Th, U, Zr, Hf, As, and Sb, as well as the REE La to Lu. Based on the mineralogy of bulk central Alaskan loess, the host minerals for Cr and Sc are probably micas, amphiboles, and clay minerals. U, Th, and Ta could be hosted by micas, amphiboles, zircon, sphene, and clay minerals; in addition, Ta could be found in magnetite or ilmenite. Zircon is the exclusive host of Zr and Hf. Both As and Sb most likely occur as substitutes for Fe in magnetite (Onishi and Sandell 1955). The REE could be hosted by micas, chlorite, clay minerals, amphiboles, zircon, feldspars (in small amounts), and apatite. Although we did not observe apatite directly by petrographic or X-ray methods, its presence is inferred from measurable amounts of P in these loesses (Muhs et al. 2003).

The upper continental crust (UCC) has a very distinctive composition with regard to REE (McLennan 1989; McLennan et al. 1980; Taylor and McLennan 1985, 1995; Taylor et al. 1983). On chondrite-normalized REE plots, sediments from the UCC are characterized by enriched light REE (LREE), a negative Eu anomaly, and depleted heavy REE (HREE) (expressed on plots as a "flat" curve). Loesses from a variety of regions worldwide have a typical UCC composition based on REE abundances (Taylor et al. 1983; Gallet et al. 1996, 1998; Jahn et al. 2001), as does modern dust collected in the southwestern United States (Reheis et al. 2002). One advantage of the REE over other immobile trace elements for provenance studies is that they are found in a broad suite of minerals. Whereas Zr and Hf and As and Sb are found in heavy minerals (zircon and magnetite, respectively), the REE are found in both heavy and light minerals (amphiboles, micas, zircon, chlorite, clay minerals, apatite, and even trace amounts in feldspars). Thus although Zr, Hf, As, and Sb may be biased somewhat towards indicators of heavy minerals that reflect nearby sources, the REE potentially can reflect both proximal and distal loess sources.

Geochemistry of central Alaskan loess and possible source sediments

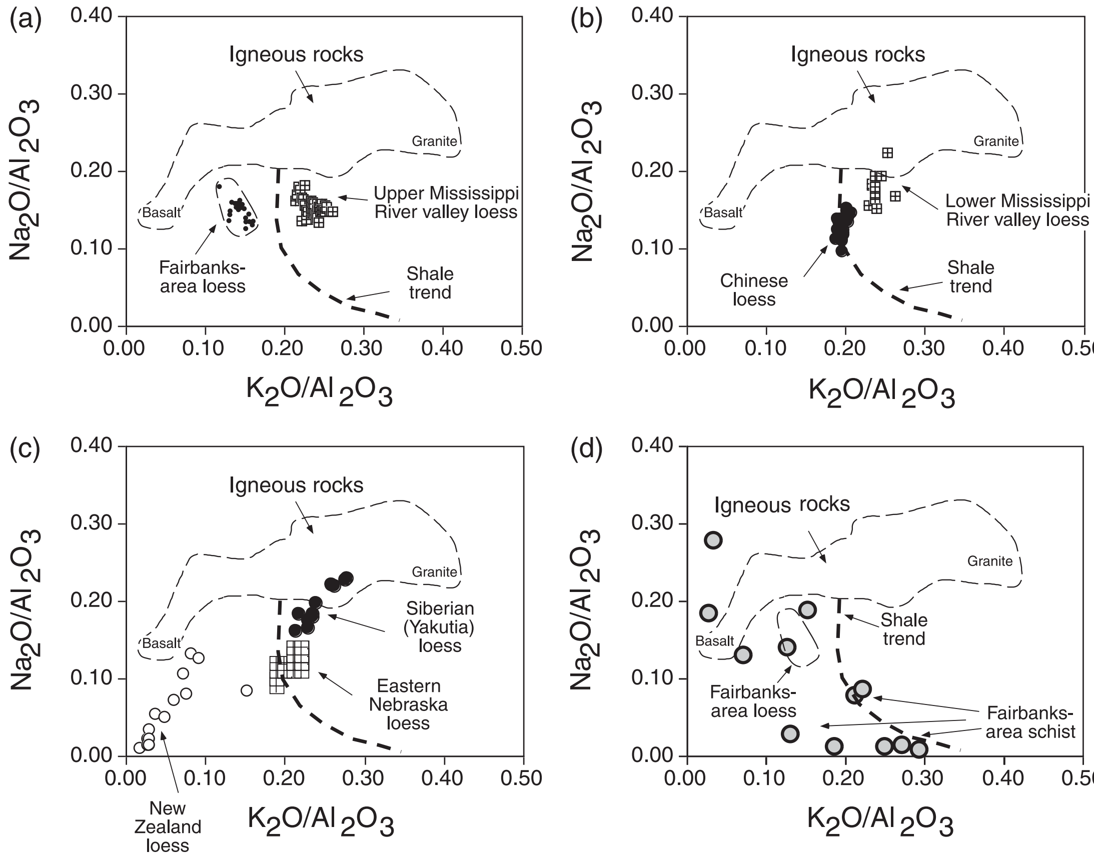
Major-element concentrations in Alaskan loess and implications for sources

Major-element geochemistry shows that Alaskan loess also has been derived, at least in part, from sediments that have undergone one or more cycles of weathering and Na-plagioclase depletion (Fig. 5). Loess in Alaska, as elsewhere, appears to have a large component of particles that have undergone previous cycles of weathering and specifically Na-plagioclase depletion. Such particles could be derived from weathered soils, sedimentary rocks that have experienced a significant degree of diagenetic alteration, highly altered metamorphic rocks, or some combination of these protoliths. Given the dominance of sedimentary and metamorphic rocks in the Alaska Range, the Yukon–Tanana Upland, and the Brooks Range, glaciers and rivers draining Alaska's mountain ranges are likely to be carrying silt-sized particles that are depleted in Na-plagioclase relative to most igneous rocks.

Local bedrock of the Fairbanks area (the Fairbanks schist) shows a wide range of compositions on a Na_2O/Al_2O_3 vs. K_2O/Al_2O_3 plot, and only a few samples overlap those of loess deposits (Fig. 5). Abundances of Na_2O and K_2O with respect to Al_2O_3 in schist span a range of protolith compositions from relatively unaltered felsic rocks to highly Na-depleted mafic rocks. This range of variability is far greater than that shown for Fairbanks-area loess, and implies that the local bedrock is not likely to have been an important source for the loess, which is in agreement with the earlier conclusion of Péwé (1955).

We also examined Na_2O/Al_2O_3 vs. K_2O/Al_2O_3 for loess from a variety of regions (China, New Zealand, Siberia, midcontinental North America), using data presented by previous workers (Fig. 5). Chinese loess derived from desert basins to the northwest of the Loess Plateau (Sun 2002) also exhibits depletion of Na_2O, as shown by Gallet et al. (1998). Loess from midcontinental North America, both from the upper and lower parts of the Mississippi River valley, is derived from outwash sediments of the Mississippi River, which in turn are derived from till of the Laurentide ice sheet. Mississippi River valley loess also shows evidence of previous weathering and Na-plagioclase depletion. Eastern Nebraska loess may be derived from a combination of glacial and non-glacial sources (see Aleinikoff et al. 1999, and Muhs and Bettis 2000) and shows considerable depletion of Na-plagioclase compared with the range of igneous rocks. Loess from the Yakutia region of Siberia has a composition similar to that of lower Mississippi River valley loess, but shows the lowest

Fig. 5. Plots of Na_2O/Al_2O_3 vs. K_2O/Al_2O_3 for (*a*) Fairbanks-area loess (this study) and upper Mississippi River valley loess from Illinois (data from Muhs and Bettis 2000); (*b*) lower Mississippi River valley loess from Mississippi (data from Pye and Johnson 1988) and Chinese loess (data from Gallet et al. 1996 and Jahn et al. 2001); (*c*) eastern Nebraska loess (data from Muhs and Bettis 2000), New Zealand loess (data from Graham et al. 2001), and Siberian loess (data from Péwé and Journaux 1983); and (*d*) Fairbanks-area loess and local schist bedrock (this study). Also shown for all plots are the trend line for shales and the field occupied by unaltered igneous rocks, compiled by Garrels and MacKenzie (1971).



degree of mineralogical maturity of any loess examined here. Loess from New Zealand shows a wide range of values for Na_2O/Al_2O_3, suggesting multiple protoliths that have varying degrees of plagioclase depletion, although all appear to have a mafic origin. Although Alaskan loess does not show the same degree of plagioclase depletion as New Zealand loess, it is similar with regard to low K_2O/Al_2O_3 values, suggesting somewhat more mafic source rocks compared with loess from Siberia, China, or elsewhere in North America. We conclude, in agreement with Gallet et al. (1998), that loess from a wide variety of regions, including Alaska, is not the simple result of glacial grinding of crystalline rocks to produce silt.

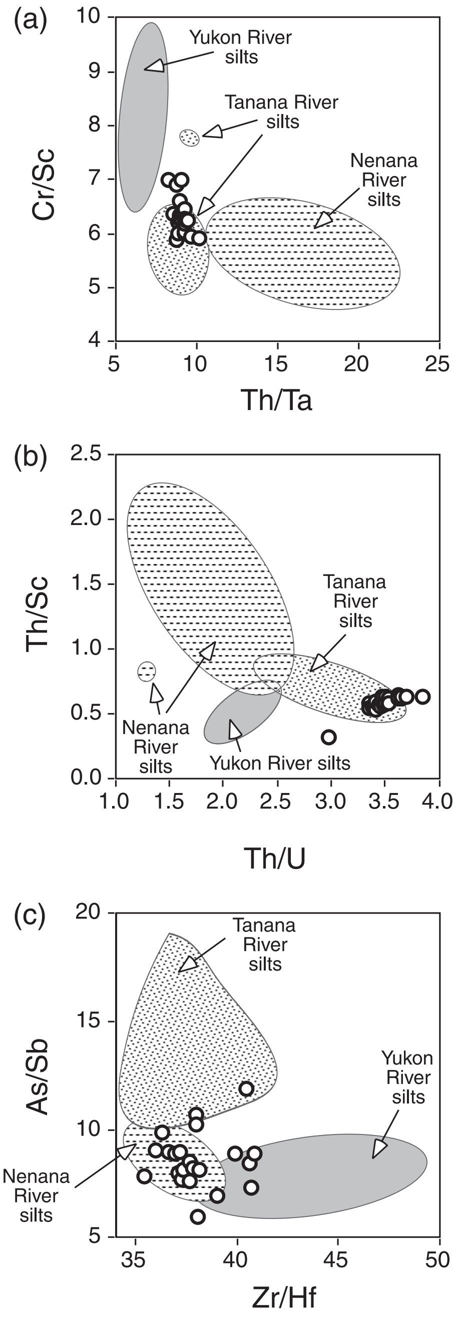
Immobile trace-element composition of river silts and loesses

Ratios of certain immobile trace-element ratios can provide useful indicators of probable loess source sediments. There is good discrimination among silts from all three central Alaskan rivers for Th/Ta and differentiation between the Yukon River and the other two rivers for Cr/Sc (Fig. 6). Fairbanks-area loesses, with one exception, plot mostly in the Tanana River field defined by these element pairs. A plot of Th/Sc vs. Th/U also defines three separate fields for the various river sources, and again Fairbanks-area loesses plot mostly within the field defined for the Tanana River silts. These four element pairs (Cr/Sc, Th/Ta, Th/Sc, Th/U) reflect the trace-element compositions in a wide variety of minerals, such as micas, amphiboles, zircon, sphene, and clay minerals. Other element ratios are provenance indicators for specific minerals. As/Sb and Zr/Hf are proxies for magnetite and zircon, respectively. These two element ratios define three fields for the heavy mineral component of the three river sources. Fairbanks-area loess samples plot mostly in the Nenana River field, but some plot in the Yukon River field (five samples) and a few plot in the Tanana River field.

Rare-earth element compositions of river silts and loesses

Chondrite-normalized plots of REE abundances show that Tanana, Nenana, and Yukon river silts have typical upper-crustal compositions, with enriched LREE, negative Eu anomalies, and depleted HREE (Fig. 7). Nevertheless, there are differences among the three sediment groups when the REE curves are examined in detail. In general, REE abundances are greater in Tanana River and Nenana River sediments than they are in Yukon River sediments. For concentrations of La, Nenana River silts are 100–400 times chrondrite, Tanana

Fig. 6. Plots of (*a*) Cr/Sc vs. Th/Ta, (*b*) Th/Sc vs. Th/U, and (*c*) As/Sb vs. Zr/Hf values in Fairbanks-area loess (shown by circles) and fields for these values defined by the range of values in Tanana, Nenana, and Yukon river silts.



River sediments are 100–200 times chondrite, and Yukon River sediments are 80–150 times chondrite. The differences are due, in part, simply to carbonate dilution because of higher carbonate contents in Yukon River sediments. Although sediments from the Tanana River are also calcareous, Yukon River sediments effervesce much more violently when treated with HCl, and the greater abundance of carbonates is reflected in higher overall CaO and Sr contents (Fig. 8). Concentrations of CaO and Sr are lower in loess than in sediments from either of the Tanana or Yukon rivers, an observation we discuss in more detail later in the text.

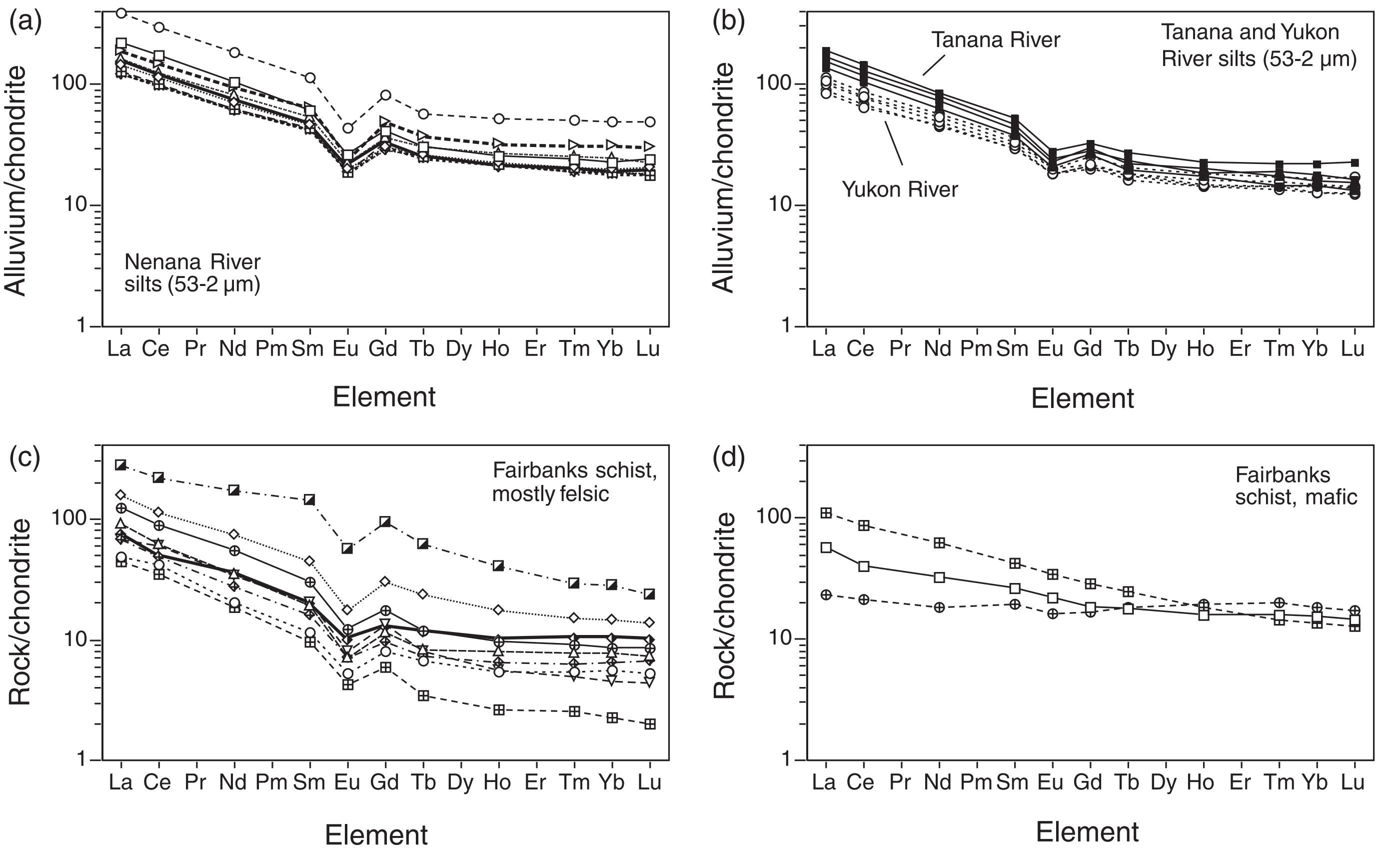
Fairbanks-area loesses also show typical UCC compositions on REE plots (Fig. 9). Samples at all depths in all sections show enriched LREE, negative Eu anomalies, and relatively flat HREE curves. The Alaskan loess REE trends are in agreement with those reported by investigators who have studied loess deposits from other regions (Taylor et al. 1983; Gallet et al. 1996, 1998; Jahn et al. 2001). Concentrations of La in Fairbanks-area loesses are ~100 times chondrite for La; these are similar to those of Chinese loesses (Gallet et al. 1996; Jahn et al. 2001) and somewhat higher than loess from either Europe or Argentina (Gallet et al. 1998).

When using REE in sedimentary geochemistry, it is helpful to reduce the data to certain key elemental ratios (chondrite-normalized) that give a quantitative measure of parts of the REE suite. The sign and degree of any Eu anomaly can be quantified by the Eu/Eu* value, where Eu is the chondrite-normalized Eu concentration (Eu_N), and Eu* is $(Sm_N \times Gd_N)^{0.5}$. Basalts that reflect a relatively pure mantle origin typically have no Eu anomaly (see examples from Hawaii in Budahn and Schmitt 1985). Values < 1.0 indicate negative Eu anomalies; values > 1.0 indicate positive Eu anomalies. Because of differing crustal histories, Archean sedimentary rocks usually have positive Eu anomalies, but post-Archean sedimentary rocks typically have negative Eu anomalies. In post-Archean sedimentary rocks, typical Eu/Eu* values range from 0.6 to just under 1.0 (McLennan 1989; Taylor and McLennan 1985, 1995). Chinese loess of Quaternary age has Eu/Eu* values that range from 0.61 to 0.66 (Gallet et al. 1996; Jahn et al. 2001). Two other measures of REE composition reflect abundances of LREE and HREE. La_N/Yb_N is a measure of the overall enrichment of LREE, where high values reflect significant LREE enrichment. Gd_N/Yb_N is a measure of HREE depletion, where high Gd_N/Yb_N values indicate significant depletion of the HREE.

The three river silts have a wide range of Eu/Eu* values (Fig. 10). Yukon River silts have Eu/Eu* ranging from about 0.63 to 0.77, but Tanana River silts show more Eu depletion with Eu/Eu* ranging from 0.55 to 0.68. Nenana River silts have Eu/Eu* that are generally lower than the other two rivers (0.44 to 0.56) and overlap the range for the Tanana River only slightly. Tanana River silts show the greatest enrichment of LREE, based on La_N/Yb_N and are distinct from Yukon River silts. Yukon River and Nenana River silts show about the same amount of depletion of HREE, based on Gd_N/Yb_N values. On a Eu/Eu* vs. Gd_N/Yb_N plot, loess samples fall within the field defined by values from the Tanana River. However on the Eu/Eu* vs. La_N/Yb_N plot, loess samples fall between the fields defined by the three groups of river sediments.

The simple bivariate plots of element ratios seem to indicate that the Tanana River is the most important source of loess, but there have probably been contributions from the other rivers. To quantify the contribution of the three Alaskan river-silt sources to each of the loess compositions, multilinear regression analysis (MRA) calculations were performed using the approach described in Budahn and Schmitt (1985). The elements selected for these calculations were Cr, Sc, Ta, Th, Zr, Hf, As, Sb, and six REE (La, Sm, Eu, Gd, Tb, Yb). Preliminary calculations that used representative samples encompassing the entire range of Tanana and Nenana silt compositions indicated that only those silts characterized by

Fig. 7. Chondrite-normalized rare-earth element plots for (*a*) Nenana River silts, (*b*) Tanana River and Yukon River silts; (*c*) Fairbanks schist (mostly felsic), and (*d*) Fairbanks schist (mafic).



low overall REE abundances from these two rivers contribute to the loess compositions. However, there appears to be a variable contribution of the Yukon River from both low-REE and high-REE type silt components. On this basis, the MRA approach that we used defined four end-member silt components: Tanana River silt (average of two low-REE samples), Nenana River silt (average of four low-REE samples), Yukon River silt (average of two low-REE samples) and Yukon River silt (average of three high-REE samples). This approach shows that Fairbanks-area loess is dominated by contributions from the Tanana River, but also has significant components derived from the Yukon and Nenana rivers (Fig. 11).

Discussion

Eolian silts from the Fairbanks loess belt of central Alaska appear to have had a complex origin. Major-element ratios indicate that the local schist bedrock may have had minimal influence on the origins of these sediments, a conclusion that was also reached a half-century ago by Péwé (1955). Most element ratios (Cr/Sc, Th/Ta, Th/Sc, Th/U, Eu/Eu*, Gd_N/Yb_N) suggest a dominance of the Tanana River as a source. Nevertheless, As/Sb and Zr/Hf suggest the possibility of substantial contributions of the heavy mineral fraction (magnetite and zircon) from the Nenana River or the Yukon River. This result is unexpected, because the Yukon and Nenana rivers are farther from Fairbanks than the Tanana River, and we hypothesized that heavy minerals would travel shorter distances than light minerals. The La_N/Yb_N values suggest that some mix of the three river-sediment sources is possible, which is consistent with the MRA results (Fig. 11). We conclude that the Tanana River is probably the primary source for most of the late Quaternary loess in the Fairbanks area, but that this fluvial system alone cannot explain the observed compositions. In fact, MRA calculations indicate that the average loess compositions from Gold Hill, Halfway House, and Birch Hill contain 62%–43% Tanana River silt, 36%–20% Yukon River silt, and 21%–12% Nenana River silt (Fig. 11). It follows from this that paleowinds that deposited late Quaternary loess in the Fairbanks area were dominantly, but not wholly, from the south. Lagroix and Banerjee (2002) thought that Fairbanks-area loess, whether of glacial or interglacial age, was transported dominantly by northerly winds, a conclusion that is not supported by the data presented here.

Based on the modern pattern of southerly winds in summer and northerly winds in winter, it could be argued that a synoptic-scale pattern of circulation very similar to the present one occurred in central Alaska during the main period of loess deposition. If the uppermost deposits at Halfway House, Gold Hill, and Birch Hill are Holocene, then a dominant contribution from the Tanana River is consistent with the modern summer pattern of wind directions. Observations of modern dust storms in periglacial regions show that eolian silt entrainment can occur in both summer and winter in New Zealand (McGowan et al. 1996; McGowan 1997), but in Canada, Greenland, and elsewhere in Alaska, eolian silt transport occurs mostly in summer or early fall (Péwé 1951; Nickling 1978; Dijkmans

Fig. 8. Plots of CaO vs. Sr (carbonate indicators) for (*a*) Tanana, Nenana, and Yukon river silts, and (*b*) Fairbanks-area loesses superimposed on fields defined by CaO vs. Sr for the three river-sediment groups.

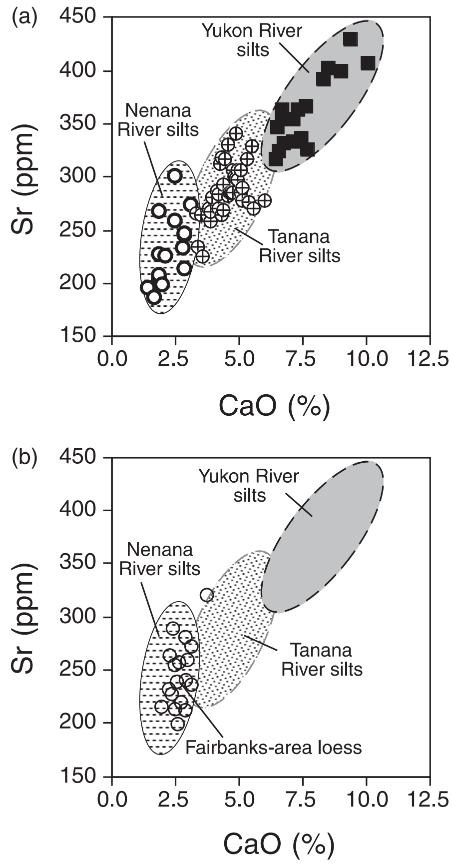
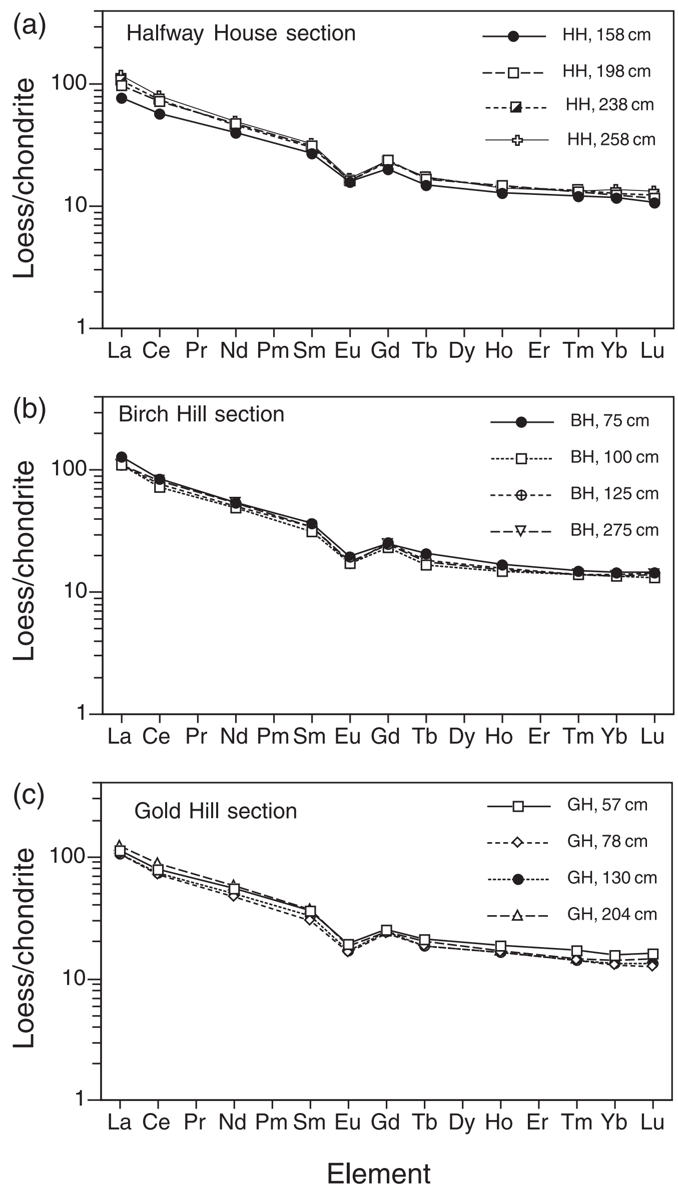


Fig. 9. Chondrite-normalized rare-earth element plots for Fairbanks-area loesses from (*a*) Halfway House, (*b*) Birch Hill, and (*c*) Gold Hill.



and Törnqvist 1991). During winter, eolian silt entrainment is inhibited because of low sediment availability as a consequence of frozen soils and sediments, as well as snow cover. We suspect that during modern (and earlier, but Holocene) winters in central Alaska, with river icings, frozen floodplain sediments, and widespread snow cover, there is little sediment available for eolian transport. If this is the case, however, then inputs from the Yukon River, to the north, are unexplained.

If, on the other hand, the uppermost loess at Halfway House, Gold Hill, and Birch Hill is of last-glacial age, then the inference of a dominantly Tanana River source presents some interesting complications. As discussed earlier in the text, orientations of sand dunes and locations of eolian sheet sands throughout much of Alaska indicate that regional-scale winds were likely from the north or northeast during the last glacial period (Fig. 1). Indeed, the Kantishna sand sea (K on Fig. 1), immediately to the west of the Fairbanks loess belt, dates to the late-glacial period (Lea 1996) and has parabolic dunes with arms that point to the northeast, indicating northeasterly paleowinds (Collins 1985). We interpret the origin of the Kantishna sand sea and other dune fields in Alaska that date to the last glacial period (Hopkins 1982; Lea and Waythomas 1990) to be the result of an increase in the strength or duration of the modern-winter type, synoptic-scale climatology over Alaska. Under such conditions, there may have been an increase in the strength or residence time of the Siberian and Canadian high-pressure cells over the region, along with a stronger Aleutian low-pressure cell, at least in winter. The Aleutian low has been simulated to be stronger in winter during the full-glacial and late-glacial periods compared with the present (Bartlein et al. 1998). This synoptic pattern would have enhanced the north-to-south regional pressure gradient and produced northerly or northeasterly winds that could have built many of the dune fields in Alaska, perhaps not in winter, but in fall and spring and possibly in full-glacial summers. If the synoptic-scale reconstruction presented earlier in the text is correct and if the late Quaternary loess around Fairbanks is actually of last-glacial age, then it is difficult to explain how northerly winds built dune fields just to the west of Fairbanks while southerly winds were depositing loess over Fairbanks.

Fig. 10. Plots of (*a*) Eu/Eu* vs. La_N/Yb_N and (*b*) Eu/Eu* vs. Gd_N/Yb_N for Fairbanks-area loesses and ranges of these values for Tanana, Nenana, and Yukon river silts.

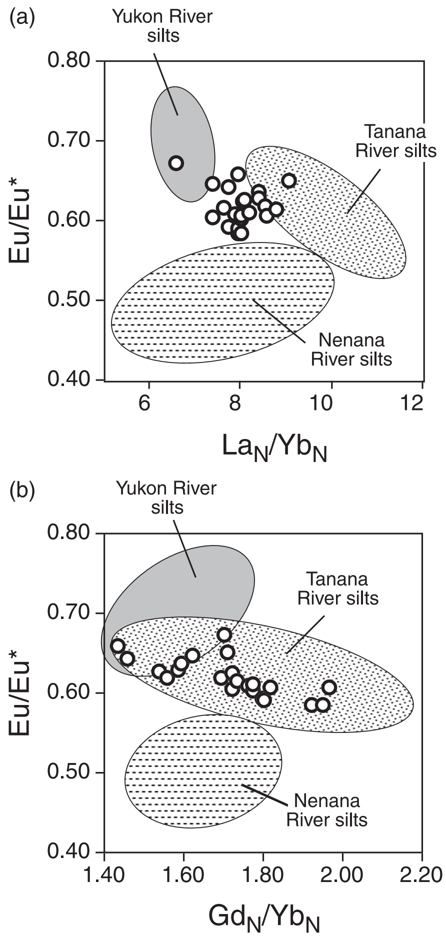
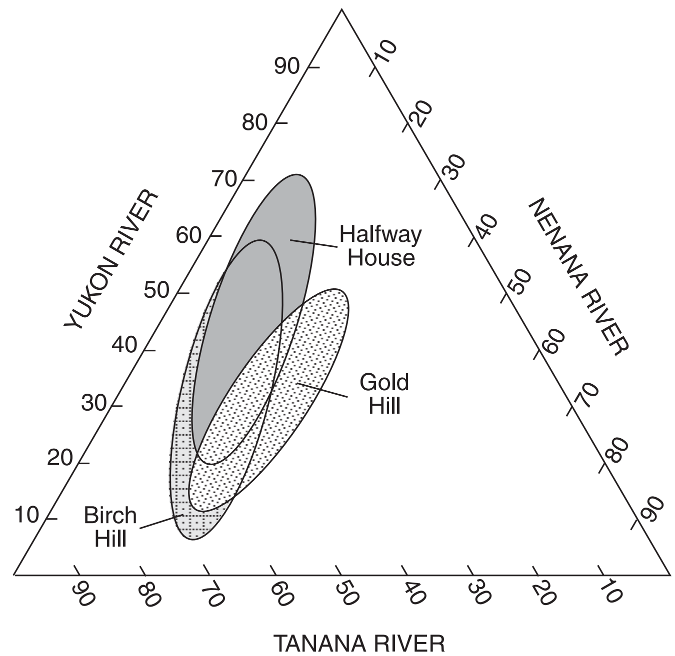


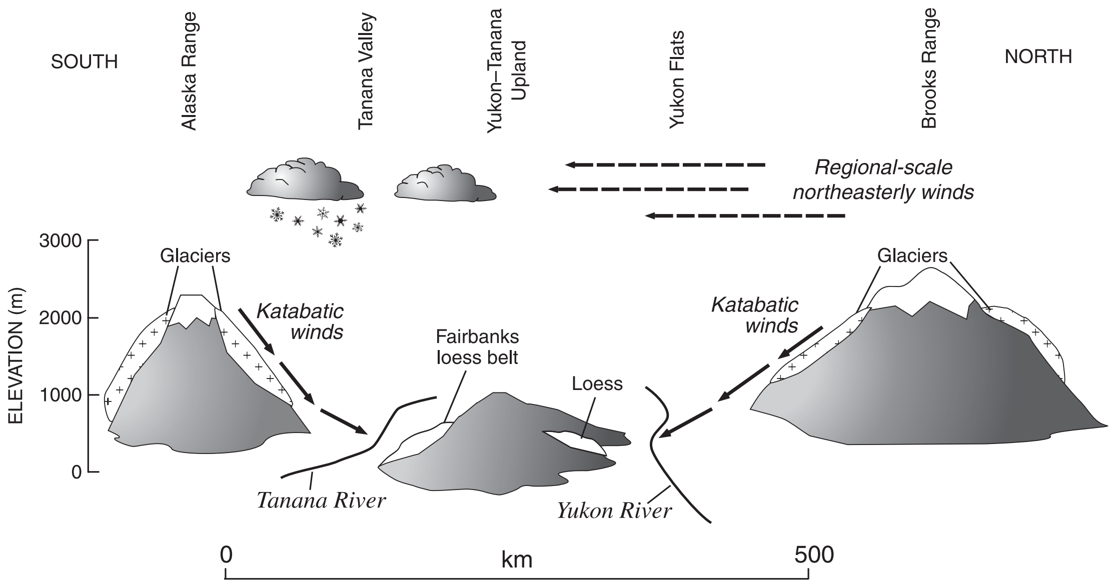
Fig. 11. Ternary diagram showing relative contributions of different river systems to Fairbanks-area loess, derived from multilinear regression analysis calculations using the model of Budahn and Schmitt (1985).



A possible reconciliation of the opposing dune-inferred and loess-inferred paleowinds can be sought in a consideration of the positions of ice fronts in central Alaska during the last glacial period. Glaciers on both sides of the Brooks Range and the Alaska Range were greatly expanded during the last glacial period compared with the present (Hamilton 1982, 1994). Glaciers on the northern flank of the Alaska Range advanced to within 80–100 km of Fairbanks. Theoretical considerations indicate that there could have been significant katabatic wind flow off these glaciers (Thorson and Bender 1985; Guthrie 1990), and the direction of air flow would have been to the north. Other studies, conducted where glaciers occur today in Canada and Greenland, have shown that katabatic winds can be strong enough to entrain silt-sized particles and produce visible dust storms (Nickling and Brazel 1985; Dijkmans and Törnqvist 1991). Based on these considerations and the data presented here, we propose a model that could explain the dual-source origin of Fairbanks-area loess if the loess is of last-glacial age (Fig. 12). During the last glacial period, increased strength and residence time of the Siberian and Canadian highs to the north and the Aleutian low to the south generated strong, regional-scale, northerly winds. In contrast to the present pattern of such winds occurring solely in winter, we suggest that during the last glacial period this synoptic pattern began earlier in the fall and lasted later in the spring. These synoptic-scale winds would have been responsible for the growth of many of central Alaska's dune fields and eolian sheet sands (Fig. 1), as hypothesized by Hopkins (1982) and Lea and Waythomas (1990). The same northerly or northeasterly winds would also have been responsible for the entrainment of a minor amount of silt from the Yukon River valley and transport of this sediment to the Fairbanks area. Superimposed on this northerly ("winter pattern") wind regime was a southerly flow of air, at lower levels, in the form of katabatic winds, which was the result of expanded glaciers on the north flank of the Alaska Range. Southerly winds would have entrained silt from the Tanana River and deposited sediment to the north, in the vicinity of present-day Fairbanks.

An unexpected result of our study is evidence for low concentrations of carbonates in central Alaskan loess, when compared with possible source sediments (Fig. 8). Silts we collected from both the Tanana River and Yukon River systems effervesce strongly when treated with dilute HCl, and both sediment groups show fairly high amounts of CaO, as well as Sr, which substitutes for Ca in Ca-bearing minerals, such as calcite. Yukon River sediments have CaO contents of 7%–10%, which implies calcium carbonate contents of as much as ~15%–20%, which are in broad agreement with data in Eberl (2004). Nenana River silts, in contrast, have lower CaO contents and generally lower Sr contents. Interestingly, all of the loess samples we analyzed have CaO contents lower than those found in Yukon River silts, and most have CaO contents lower than those found in Tanana River silts. A simple explanation, based only on the CaO and Sr data, would be that the loess is derived primarily from the Nenana River (Fig. 8). As discussed earlier in the text, however, immobile trace-element geochemistry does not support

Fig. 12. Model of loess deposition in the Fairbanks area by opposing winds during the last glacial period, modified from Thorson and Bender (1985), Guthrie (1990) and Muhs et al. (2003). Regional-scale northeasterly winds occur during periods other than just winter during the last glacial period and provide sediment from the Yukon River valley. Katabatic winds from expanded, north-flowing glaciers of the Alaska Range are southerly and entrain sediment from the Tanana River valley.



such an interpretation. If we are correct that central Alaskan loess is derived mainly from the Tanana and Yukon rivers, then loess was likely calcareous when it was first deposited.

Low-carbonate zones in last-glacial loess in Kansas, Iowa, and Illinois have been interpreted to be the result of syndepositional leaching under relatively low sedimentation rates (Swineford and Frye 1951; Kleiss 1973; Ruhe 1983; Muhs and Bettis 2000). Higher carbonate zones within the same midcontinent sections studied by these latter workers are interpreted to be zones of more rapid sedimentation rate. Thus, even though we were careful to avoid paleosols in our sampling scheme, our data show that what appears to be "unaltered" loess is in fact probably sediment that experienced a significant amount of leaching under a relatively low sedimentation rate. If loess deposition occurred during the Holocene, then it is possible that syndepositional leaching took place under acid litter from spruce- and birch-dominated boreal forest; this vegetation community arrived in central Alaska around 8000–9000 ^{14}C years BP (Ager and Brubaker 1985). If, on the other hand, the youngest loess in our sections is of last-glacial age, then loess deposition probably would have taken place under an herb tundra vegetation (Ager and Brubaker 1985). Herb tundra, depending on the composition of this community, may not produce as acidic a litter cover as boreal forest; if so, syndepositional carbonate leaching would require an even lower sedimentation rate.

Summary and conclusions

Loess in central Alaska, as with loess from many other regions, is not the simple result of glacial grinding of crystalline rocks as a first-cycle sediment. Plots of Na_2O/Al_2O_3 vs. K_2O/Al_2O_3 show that central Alaskan loess, like other loesses globally, has probably been derived from multiple source rocks and sediments, many of which have undergone several cycles of weathering, erosion, and transportation. Sediments of the Tanana, Nenana, and Yukon rivers integrate multiple rock and sediment sources from the Alaska Range, Yukon–Tanana Upland, and Brooks Range. The Na_2O/Al_2O_3 vs. K_2O/Al_2O_3 data are consistent with central Alaskan loess being derived from large fluvial sources that integrate and homogenize many rock types. These major-element data also indicate that the local schist bedrock, which has a highly variable composition, is not the main source of eolian silt.

Immobile trace-elements ratios show that the silt fractions of alluvium from the Tanana, Nenana, and Yukon rivers can be differentiated from one another. Thus, it is possible to assess the relative contributions of each river-sediment group to Fairbanks-area loess. Cr/Sc, Th/Ta, Th/Sc, and Th/U in loess imply a dominance of the Tanana River as a source, but As/Sb and Zr/Hf values in loess imply some influence from the Nenana and (or) Yukon rivers. Although loesses have Eu/Eu* and Gd_N/Yb_N values that fall mostly within the fields defined by Tanana River silts, they also have La_N/Yb_N values that plot between the fields defined by the three alluvial sources. We conclude from all these data and MRA calculations that central Alaskan loess has a complex origin, derived mostly from the Tanana River but also in part from the Yukon River and (or) Nenana River.

If late Quaternary loess in central Alaska is of Holocene age, then derivation mostly from the Tanana River is consistent with the modern synoptic-scale pattern of southerly winds in summer and early fall. Under a Holocene scenario, however, inputs from the Yukon River, to the north, are unexplained. If the loess is of last-glacial age, then derivation mostly from the Tanana River is not consistent with dune fields and sand sheets that imply last-glacial paleowinds in Alaska from the north. Superimposed upon this synoptic-scale pattern, however, there may have been strong, southerly katabatic winds from expanded glaciers that flowed north from the Alaska Range. These southerly winds could have transported silt-sized sediment from the Tanana River to the Fairbanks loess belt.

Central Alaskan loess is generally not calcareous, whereas both Tanana River and Yukon River silts are highly calcareous. This difference in carbonate content is mirrored in CaO and Sr contents, which are higher in the alluvial sediments than in central Alaskan loess. Depletion of carbonates in what appears to be unaltered loess implies syndepositional leaching, wherein leaching keeps ahead of sedimentation. This process also has been inferred from observations of leached loess in the lower parts of last-glacial-age loess of midcontinental North America. Thus, in addition to accumulation by complex winds, late Quaternary loess of central Alaska was deposited slowly.

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