Continuous Late Quaternary proxy climate records from loess in Beringia

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Abstract

Loess deposits in eastern Beringia contain continuous proxy records of the effects of past climatic change on terrestrial landscapes at high latitudes. Variations of environmental magnetism and sedimentology of high-latitude loess deposits indicate that the timing and pattern of responses to local variations in wind intensity, storminess, and pedogenesis in eastern Beringia closely resemble the pattern of global climate change during the Late Quaternary deduced from studies of marine and ice core records. The age of paleoclimatic fluctuations, permafrost features, volcanic ash horizons, buried forest layers and paleosols, and other features of the eastern Beringian loess record can be determined using a variety of Quaternary dating methods. Tephrochronologic correlations between the loess record and the glacial history of eastern Beringia indicate the Delta Glaciation occurred during marine isotope stage 6. Several other middle and Late Quaternary glaciations across eastern Beringia can be tephrochronologically tied to the loess record, and appear to have been in phase with episodes of global cooling recorded in deep-sea records. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Surprisingly little direct evidence exists documenting the continuous and progressive effects of Quaternary climate changes on terrestrial landscapes across Beringia and other areas around the world. For more than 40 years marine geologists have obtained literally hundreds of records of global patterns of Pleistocene climate changes by coring and studying deep-sea sediments (e.g., Emiliani, 1955; Martinson et al., 1987), and similar records have been obtained from lacustrine sediments, glacier ice and speleothems (Karabanov et al., 1998; Taylor et al., 1993; Winograd et al., 1992). However, until recently there have been no comparable continuous proxy climate records from terrestrial sediments directly recording changes in terrestrial environments. The need for continuous proxy climate records in terrestrial sites is considerable, as such data provide an independent check on marine-based models of Quaternary climate change. Also, because long-term changes in terrestrial plant and animal life, soil and permafrost development, and human evolution and prehistory are fundamentally terrestrial and not marine phenomena, there is a clear need to understand more about the history of climate change in terrestrial areas.

Loess (eolian dust) deposits, found in many areas around the world, are one potential source for continuous records of local paleoclimates and terrestrial paleoenvironments. Loess in Beringia typically accumulates very slowly, so that thick sequences of loess literally preserve a record of the burial of innumerable ancient ground surfaces (Begét, 1990). In rare cases tree trunks and branches, leaves, peat, and even the bodies of mammoths and other animals have been rapidly buried and preserved within permafrost in Arctic and sub-Arctic loess and reworked loess (Guthrie, 1990; Pewe et al., 1997).

In the last few decades proxy climate records from the 120 to 400 m thick loess in China have been shown to closely resemble global marine records over the last 2.4 Ma (Heller and Liu, 1982; Kukla et al., 1988), and similar but shorter loess records have been described from the Great Plains of the central United States and from Europe (Rosseau and Kukla, 1994; Frechen et al., 1997; Rosseau et al., 1998). In Beringia, loess studies in Siberia (Chlachula et al., 1997) and in central Alaska

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Fig. 1. Localities discussed in the text, including in Alaska (F) Fairbanks area loess and tephra, (GB) Goose Bay Peat, Knik drift, and Stampede tephra, (L) Lignite Creek drift and Stampede tephra, (D) Delta and Tanana Rivers, Delta drift, and Old Crow and Sheep Creek tephra, (M) Mirror Creek drift and Old Crow tephra, (R) Reid drift and Sheep Creek tephra, and in Siberia (K) the Kurtak loess site. The distribution of tephra-producing volcanoes in the Aleutian arc, Wrangell Mountains, Bering Sea, and Kamchatka is shown schematically by solid triangles.

(Begét, 1991, 1996) have also reconstructed long, continuous paleoclimatic records similar to those found in marine and other environments (See Fig. 1).

2. Origin of Beringian loess deposits

Most modern Beringian loess appears to be derived from glacial outwash streams which transport glacial silt for hundreds of kilometers across Alaska and part of Siberia. Dust storms (and concomitant loess deposition) usually occur only within the five- to six-month snow-free period during spring, summer and early fall, although in some local areas river bars are exposed to the wind in winter and dust may accumulate during winter in the snowpack before melting out in the spring (Péwé, 1955).

Loess depositional processes are very active in eastern Beringia today. A recent dust storm in eastern Beringia, sampled at a distance of 10 km from a river floodplain, contained more than 180,000 5–60 μm particles in each cubic meter of air, and a continuous background concentration of approximately 2000–60,000 dust particles was found to be present between dust storms (Begét, 1996). This suggests that loess deposits in Beringia are composed of dust derived from both the semi-continuous background dust flux and individual, discrete dust storms.

Quaternary loess deposits appear to have formed in environments similar to those associated with modern dustfalls and Holocene loess deposits. Random samples of late and middle Quaternary loess and late Tertiary to early Quaternary loess from eastern Beringia were mounted on aluminum stubs, coated with gold, and viewed in a JOEL JSM-T330 scanning electron microscope (SEM) at 15 keV. While most loess grains are sub-rounded, reflecting a history of fluvial and eolian transport, a significant number of grains, from both massive loess correlated with full glacial conditions and from paleosols recording interglacial and interstadial warm conditions, show SEM surface textures indicative of past crushing and abrasion (Fig. 2). Mechanical abrasion features, including conchoidal fractures, straight and arcuate steps, plates, irregular depressions, and the presence of angular, fresh breakage at grain margins, reflect a history of mechanical weathering most consistent with glacial comminution (Krinsley and Doornkamp, 1973; Margolis and Krinsley, 1974). These SEM surface textures suggest that the long history of loess deposition in interior Alaska indirectly records the presence of glaciers in the Alaska Range since late Pliocene time. Similar SEM features have been identified in Siberian loess, although the documented history of loess deposition in western Beringia is much shorter (Chlachula et al., 1997).

In Alaska and Siberia, the thickest deposits of loess usually occur near major silt-rich rivers (Begét, 1988; Chlachula et al., 1997). Sedimentation rates of eastern Beringian loess deposits are between 0.05 and 1.0 mm/yr, with the highest rates occurring near rivers which are loess sources, and lower rates at increasingly distal and higher sites (Begét, 1990). The longest loess records generally occur in areas of low sedimentation rate, while shorter records with higher resolution can be found on younger geologic surfaces nearer to loess sources.

Loess deposition in most middle-latitude regions such as the central United States or China slowed or completely stopped and soils formed during warm interglacial and interstadial intervals (Pye, 1987). In contrast, some Beringian loess deposits span the last glacial cycle and appear to be essentially continuous (Begét and Hawkins, 1989; Begét, 1996; Chlachula et al., 1997). Radiocarbon dating of organic material and paleosols in loess shows that loess deposition has been active throughout the Holocene in Alaska (Begét, 1990, 1991). Similarly, proxy climate records from Alaskan loess and Siberian loess clearly contain records of the previous interglaciation and prior warm periods (Begét, 1996; Chlachula et al., 1997). At least in Alaska, glaciers were apparently continuously present in the Alaska Range and other mountains throughout both glacial and interglacial periods of the Quaternary, so the production of glacial silt and the generation of loess were never interrupted.
Fig. 2. Scanning electron microscope (SEM) photomicrographs of surface textures on loess particles in eastern Beringia: (A) typical loess particles from loess in eastern Beringia, consisting mostly of sub-angular feldspar and quartz grains ca. 10–30 μm in diameter with mineral coating and numerous small adhering particles; (B) highly angular quartz grain, showing effects of abrasion and fracturing thought to record a sub-glacial environment; (C) close-up of lower part of grain in B, showing parallel steps and curved, conchoidal fractures characteristic of glacial environments; (D) high magnification view of aligned chemical dissolution pits, found on both Fe–Ti oxide grains and feldspar grains from loess paleosols in eastern Beringia. The weathering pits range from 0.1 to 1.0 μm in diameter, suggesting that some ultra-fine Fe–Ti oxide particles may have completely dissolved in the reducing conditions characteristic of gleyed Arctic and sub-Arctic soils.

Consequently, Alaskan loess can be used to reconstruct changes in Arctic environments during both past glacial and interglacial ages.

Fossils are common in Alaskan loess, and in several instances entire large Pleistocene mammals such as mammoths and bison have been preserved in excellent condition in permafrost in reworked loess, providing important information on the paleoecology and paleoenvironments of high-latitude areas (Guthrie, 1990). There are also numerous examples of frozen peat and wood layers, including perfectly preserved logs, plants, and leaves thought to date from the last interglaciation (Muhs et al., 2001). Such deposits provide an unparalleled direct record of ancient high-latitude vegetation during previous interglaciations (Edwards and McDowell, 1990; Hamilton and Brigham-Grette, 1991; Begèt et al., 1991). Many important archeological sites and artifacts have also been found in Alaskan loess (West, 1996).

3. Continuous proxy climate records from Alaskan loess deposits

Magnetic susceptibility records in both eastern and western Beringia are characterized by higher values during glaciations, and lower susceptibilities during warmer periods (Begèt and Hawkins, 1990; Begèt, 1996; Chlachula et al., 1997). The maximum and modal grain size, mineral content, deposition rate, magnetic susceptibility, and other characteristics of eastern Beringian loess deposits change with distance away from river floodplains, and vary through time at a single site in response to changes in the intensity or direction of
predominant winds and the frequency of dust storms versus background dust deposition (Begét et al., 1990; Begét, 1996).

Fine-grained river alluvium across much of eastern Beringia is characterized by high susceptibilities, reflecting high magnetite contents in metamorphic and volcanic rocks found widely in Alaskan mountain ranges, and susceptibilities of loess become progressively lower with distance from floodplains. Loess composed principally of dust entrained and transported by high-velocity winds is hypothesized to be coarser and characterized by higher dust fallout. The susceptibility record in Beringia is therefore thought to reflect windier conditions during ice ages, an interpretation consistent with reconstructions of ice-age climates in Alaska (Begét, 1996; Hopkins et al., 1982).

Pedogenic processes have also affected the magnetic susceptibility of Beringian loess deposits. While pedogenic processes are thought to increase the magnetic susceptibility of modern soils in temperate areas (Maher and Thompson, 1991), soils and paleosols in the Arctic and sub-Arctic typically show little sign of pedogenic enrichment of magnetite. Paleosols in high-latitude loess deposits are generally weak and low in susceptibility, although studies of the magnetic signal carrier in eastern Beringian loess demonstrate that augmentation of the primary susceptibility signal has occurred (Crumley, 1992; Rosenbaum et al., 1997).

New data suggest that pedogenic processes in central Alaska have actually lowered the magnetic susceptibility of some paleosol horizons in eastern Beringian loess. Chemical weathering pits as much as a micron in diameter have been observed using the scanning electron microscope (SEM) on large Fe–Ti oxide particles magnetically separated from loess paleosols near Fairbanks (Fig. 2). In addition to solution pits in large grains, chemical weathering may have removed some smaller Fe–Ti oxide particles (Rosenbaum et al., 1997). Superparamagnetic Fe–Ti oxide grains less than one μm in diameter are a significant component of the magnetic susceptibility signal in sediments and paleosols (Maher and Thompson, 1991; Oldfield, 1992). However, it is precisely the fine-grained superparamagnetic component of the magnetic signal carrier that would be preferentially removed by chemical processes associated with pedogenic gleying in high-latitude environments across Beringia.

The pedogenic dissolution of Fe–Ti oxides occurs in reducing environments associated with wet soils and gleying. Any pedogenic reductions in susceptibility in paleosols would tend to increase the primary differences in environmental magnetism between glacial and periglacial loess in eastern Beringia. Other processes, including changes in glacier cover and hydrologic parameters, may also have had some effect on the loess susceptibility signal and interpretations of continuous loess proxy paleoclimatic records in Beringia.

4. Geochronology of loess paleoclimate records in Eastern Europe

The pattern of the loess susceptibility records from Beringia appears to be broadly correlative with the standard global marine record of late Quaternary climate change (Fig. 2), but questions remain about the timing and duration of high-latitude climate events versus the global marine record. The age of the last interglaciation (stage 5e) in the marine record was 118,000–128,000 yr BP, based on recent U-series dates on corals (Chappell and Shackleton, 1986; Gallup et al., 1994; Edwards et al., 1997). One method of dating the complete late Quaternary global climate proxy record from the deep sea is based on “orbital tuning”, i.e., statistically based correlations with high-latitude insolation patterns (Berger, 1978; Martinson et al., 1987). Spectral power corresponding to orbital frequencies is also present in the loess magnetic susceptibility time series from eastern Beringia (Begét and Hawkins, 1989; Begét, 1996), suggesting that orbital tuning or direct matching of loess and other proxy climate wiggle curves can also be used to date the loess record.

A more direct approach to dating late Quaternary loess deposits is to utilize numerical, radiometric methods. The radiocarbon method has been applied back to its limit at ca. 35,000 BP (Begét, 1990), and a range of techniques have been applied to older sediments. These Quaternary techniques have often been utilized to directly or indirectly estimate the age of the volcanic ash horizons (tephras) found in Beringian loess.

The Old Crow tephra is the most widespread and important geochronologic datum in Alaska (Westgate et al., 1990). Its age as determined by the isothermal plateau fission track (ITP-FT) method is 147,000 ± 19,000, 118,000 ± 23,000, and 120,000 ± 20,000 BP, 145,000 ± 24,000, 156,000 ± 26,000 and 160,000 ± 20,000 yr BP based on analyses of six different samples of the tephra. The dates have been averaged to 140,000 ± 10,000 yr BP (Westgate, 1988, 1989).

The thermoluminescence method has also been widely used to date loess and intercalated tephras across Beringia. A thermoluminescence (TL) date directly on Old Crow tephra glass suggested an age of 170,000 ± 27,000 yr BP (Berger, 1991), while later dates of 110,000 ± 32,000 and 128,000 ± 22,000 yr BP were obtained from loess above the tephra, and 140,000 ± 30,000 and 144,000 ± 22,000 yr BP on loess from under the tephra (Berger, 1992, 1994). Earlier TL dates on loess intercalated with Old
Crow tephra suggested an age of $86,000 \pm 8,000$ yr BP (Wintle and Westgate, 1986), although this date is based on thermoluminescence laboratory techniques which may produce ages which are too young in sediments more than ca. $100,000$ yr BP (Péwé et al., 1997). The Sheep Creek Ash has also been dated by the thermoluminescence method to $190,000 \pm 20,000$ yr BP (Berger et al., 1996).

The paleomagnetic dating method has also been used to delineate the 2.5–3.0 million year long history of loess deposition in eastern Beringia (Westgate et al., 1990). Short-lived magnetic excursions are also recorded in Beringian loess. The Blake Event, dated to ca. $114,000–120,000$ yr BP (Fang et al., 1997) or a previously unknown excursion occurs below the Old Crow tephra (Wintle and Westgate, 1986).

The $^{40}$Ar/$^{39}$Ar dating method can be applied to single volcanic grains using laser technology, and has great potential for dating tephras and loess across Beringia. Dates on mafic tephras found in loess on the Seward Peninsula show that this technique can be used on tephras as young as ca. $75,000$ yr BP in Alaska (Begét et al., 1997). The average of three $^{40}$Ar/$^{39}$Ar dates on a coarse ash layer intercalated with the Stampede tephra suggests an age of ca. $378,000 \pm 67,000$ yr BP for this tephra layer. Recently, an $^{40}$Ar/$^{39}$Ar date of $1.1 \pm 0.1$ ma was obtained on the WP tephra (Schaefer et al., 1997), in excellent agreement with earlier ITP-FT dates.

It is interesting to compare the ages of fossils and other geologic features preserved in the loess with the radiometric age dates and with orbitally tuned global climate records. Much attention has focused on deposits of the penultimate interglacial and the Old Crow tephra in eastern Beringia (Hamilton and Brigham-Grette, 1991). Recently, the Eva Creek Forest Bed (ECFB), a deposit of logs and peat layers found in loess near Fairbanks, has been directly correlated with the peak of isotope stage 5e and assigned an age of $125,000$ yr BP (Péwé et al., 1997). The Sheep Creek, Old Crow, and Dome tephras occur in trenches excavated near the wood-rich loess of the ECFB, and it has previously been

Fig. 3. Normalized, dimensionless plots of proxy paleoclimate records showing proposed correlations between magnetic susceptibility profiles through loess sections in the Fairbanks area, eastern Beringia (Begét, 1996), magnetic susceptibility of loess in the Kurtak area of Siberia (Chlachula et al., 1997), averaged deep-sea isotopic record of global climate change during the late Quaternary; and the Devil's Hole, Nevada isotopic record. Ages versus depth are shown for the Devil's Hole site based on Uranium series dating (Winograd et al., 1992, 1997) and for the marine isotopic record based on orbital tuning (Martinson et al., 1987).
believed that all three tephras underlie the ECFB (Péwé et al., 1997). However, Muhs et al. (2001) have shown that the Old Crow tephra does not underlie the ECFB but instead occurs in the lower parts of the forest bed layer, and the Dome tephra actually overlies the ECFB at the type locality. These stratigraphic relationships indicate the climatic amelioration from full-glacial to interglacial conditions in Beringia, a climatic transition dated to ca. 125,000–128,000 yr BP in orbitally tuned global records, was well advanced prior to the deposition of the Old Crow and Dome tephras.

The discovery that the Old Crow tephra occurs above spruce macrofossils at the type locality of the Eva Creek Forest Bed suggests a younger age than previously thought for this tephra, as spruce were probably absent from interior Alaska prior to the insolation maximum at 125,000 yr BP (Muhs et al., 2001). This suggests the magnetic excursion in loess below the Old Crow tephra is correlative with the 114,000–120,000 yr BP Blake event (Wintle and Westgate, 1986). The averaged ITP-FT date of 140,000 ± 10,000 yr BP and thermoluminescence dates on the Old Crow tephra are, of course, consistent with an age of ca. 110,000 to 125,000 yr BP if the reported standard error is taken to two or three standard deviations.

Alternatively, the correlation of the Eva Creek Forest Bed with marine isotope stage 5e and an age assignment of 125,000 yr BP by Pewe et al. (1997) may be incorrect. If the Old Crow tephra was actually deposited close to ca. 140,000 yr BP, then the timing of the transition from full-glacial to interglacial conditions and associated last interglacial deposits in Alaska are older than previously assumed, and would be broadly correlative with the Uranium series dates on Termination II from the Devil's Hole site in Nevada (Winograd et al., 1992, 1997; Bégét, 1996). The penultimate transition from full-glacial to interglacial conditions is dated at approximately 140,000 ± 3000 yr BP at Devil's Hole, close to the generally accepted averaged fission-track date of 140,000 yr BP on the Old Crow tephra.

In addition to the Eva Creek Forest Bed, the Old Crow has now been found associated with last interglacial sediments at more than 20 sites across eastern Beringia (Bégét et al., 1990, 1991; Edwards and McDowell, 1990; Hamilton and Brigham-Grette, 1991; Bégét, 1996). In loess sections, the Old Crow tephra typically occurs above full-glacial loess and just below interglacial loess as reconstructed from magnetic susceptibility profiles (Fig. 3). Climatic amelioration from full-glacial conditions had clearly begun in Alaska prior to the deposition of this tephra, while maximum warming of the last interglaciation was attained very soon after the tephra was deposited. Improved dating of the Old Crow tephra, with concomitant reductions in standard errors, is clearly desirable to constrain the age of Termination II and the intercalated last interglacial sediments, and to determine if the timing of the penultimate glacial-to-interglacial transition in eastern Beringia occurred at the same time as the uranium-series dated Devil's Hole site, or if it supports orbitally tuned models of climate history (Bégét, 1996).

5. Correlation of the continuous loess record and discontinuous glacial record in eastern Beringia

In some cases, discontinuous records of climate change, such as the intermittent deposition of glacial moraines, can be correlated with the continuous loess proxy climate record through tephrochronology and direct radiometric dating. In the case of tephras, it is possible to obtain limiting age dates from the tephra stratigraphy, and also to directly correlate the glacial history in eastern Beringia with the paleoclimate record in loess and with global proxy climate records (Fig. 4).

A direct tephrostratigraphic connection exists between loess deposits near Fairbanks and glacial events just upstream in the Delta and upper Tanana River drainages in eastern Beringia. Reworked pods of Sheep Creek Ash have been reported from alluvial sediments correlative with the penultimate Delta Glaciation (Berger et al., 1996). Although previously interpreted as providing an upper limiting age on the Delta Glaciation, we propose that this tephra deposit actually comprises a maximum age limit for the Delta-age outwash, as the Sheep Creek tephra deposits are reworked and hence must be approximately the same age or older by some unknown amount than the glacial outwash sediments in which they are found.

Primary deposits of the Old Crow tephra occur in loess overlying the Delta-age terrace farther downvalley, so that tephras provide both upper and lower limiting age dates on the Delta Glaciation. The discovery of the Old Crow site proves that the Delta Glaciation cannot be of early Wisconsin age (i.e., marine isotope stage 4) as that event is dated in the marine record and the Devil's Hole record to between 65,000 and 75,000 yr ago (Martinson et al., 1987; Winograd et al., 1992). Similarly the Delta Glaciation cannot be older than marine isotope stage 6, as it postdates the Sheep Creek tephra.

The position of the Old Crow and Sheep Creek tephras in loess proxy climate records are consistent with the glacial stratigraphy. The Old Crow occurs above magnetic susceptibility inflections recording the peak of isotope stage 6, while the Sheep Creek tephra occurs early in stage 6, but lies above paleosols which appear to be correlative with stage 7 (Fig. 3). The available radiometric dates on the tephras and correlations with the continuous loess record both support the hypothesis that the Delta Glaciation occurred during marine isotope stage 6, and so is broadly correlative with the global record of colder climate and ice advance at that time (Fig. 4).

The Old Crow tephra has previously been recognized overlying drift of the Mirror Creek Glaciation in the Yukon Territory, and the Mirror Creek Glaciation
Fig. 4. Proposed correlations between marine isotope stages and the continuous paleoclimatic record obtained by magnetic susceptibility profiling through loess sections in the Fairbanks area (Beget, 1996), and the discontinuous morainal record of glacial fluctuations during the middle and late Pleistocene at sites across eastern Beringia based on regional tephrochronology. The stratigraphic position of tephras in the loess and relative to glacial deposits are shown by stipled bars, with D = Dome, OC = Old Crow, SC = Sheep Creek, and S = Stampede. Also shown is the stratigraphic position of the Eva Creek Forest Bed (ECFB) within the Fairbanks loess sequence.

therefore may have occurred during marine isotope stage 6 (Hughes et al., 1989). Deposits of the Reid Glaciation of the Yukon Territory are overlain by the Sheep Creek Ash (Hughes et al., 1989; Berger et al., 1996), and so must be older than the Delta Glaciation, and may date to marine isotope stage 8 or an even older climatic event.

The Stampede tephra is incorporated in the type Lignite Creek moraine, indicating this glacial advance post-dates the tephra eruption (Beget and Keskinen, 1991). Stampede tephra underlies Dome tephra in loess sections in eastern Beringia (Beget, unpublished data). It also occurs in the Goose Bay Peat of upper Cook Inlet, where thermoluminescence dates of ca. 181,000 ± 19,000 and 175,000 ± 12,000 yr BP were obtained on loess associated with the tephra (Reger et al., 1996). Also, as discussed above, 40Ar/39Ar dates on coarse tephra in the same horizon yielded an age of 378,000 ± 67,000 yr BP. The TL dates may constitute upper limiting ages, as the depositional history of the dated sediments is not well understood. Unfortunately, the 40Ar/39Ar date on the Stampede tephra is also problematical, as the analysis was run on composite feldspar separates and so may be contaminated by older material. Taken together, the available tephrochronologic age control overlaps at two standard deviations, and suggests the Stampede tephra is probably at least as old as stage 7 (175–230,000 yr BP) and may be older. The Lignite Creek glaciation in the Nenana Valley of central Alaska is younger than the tephra, while till of Knik glaciation age which underlies the tephra must be older (Fig. 4).

The tephrochronologic evidence provides an objective basis for making correlations between glacier sequences mapped in Alaska, and those across the international border in northwest Canada, with the detailed proxy climate record of the last glacial cycle found in central Alaskan loess deposits and with similar orbitally tuned global paleoclimatic records. The tephrochronologic correlations suggest that glaciations occurred across eastern Beringia during times correlative with major global episodes of glaciation, i.e., marine isotope stages 2, 4, and 6 (Fig. 4). This does not preclude the possibility that glaciations occurred at other times, including during
interglacial periods, in other parts of Beringia (Karabanov et al., 1998).

The comparison of the loess and glacial records reveals that very different and discordant histories of glaciation have been recognized across different areas of eastern Beringia. It is not clear if all of these differences are real, or if some might reflect problems in the preservation, recognition, or dating of Pleistocene moraines in different settings. However, it is evident that a particularly valuable feature of the continuous loess proxy climate record is its ability to provide a local paleoclimatic template with which more discontinuous records of climate change, such as records of glaciation, can be compared and correlated.

6. Summary and conclusions

Loess deposits provide a unique opportunity to reconstruct the chronology and pattern of climate change in terrestrial areas. Alaskan loess deposits, which in some cases have remained frozen for tens of thousands of years after deposition, contain uniquely well-preserved plant and animal fossils that reflect the paleoecology of past environments. Variations in the primary sedimentological and geophysical properties of Beringian loess reflect climatic regimes and their effects on surface processes at the time of deposition, and can be used to reconstruct continuous proxy climate curves analogous to those obtained from ice sheets or deep-sea sediments. Proxy climate data sets from high-latitude loess provide continuous paleoclimatic records of late Quaternary climate history in local areas and regions of Beringia. The pattern of climate change across Beringia as recorded in loess appears similar to global paleoclimatic histories and retrdictions of high latitude insolation. Questions still remain about the precise age of events and climatic transitions.

More accurate and precise dating of the Old Crow and other tephras and careful stratigraphic studies of their position in loess are a high priority for future paleoclimatic studies of loess in Beringia. Both the fission-track and thermoluminescence dates available at present are consistent with an age for the Old Crow tephra of about 140,000 ± 10,000 BP. The Old Crow occurs in the last interglacial Eva Creek Forest Bed and near loess records of Termination II, the penultimate transition from full-glacial to interglacial conditions in Beringia. These results are consistent with the Devils Hole record from Nevada, but apparently predate increases in Milankovitch insolation and the orbitally tuned date assigned to Termination II in the marine record. It is important to note that the generally accepted ITP-FT date on the Old Crow tephra overlaps the orbitally tuned age for Termination II and stage 5e (ca. 125,000–128,000 yr BP) when two or more standard deviations of counting error are included.

The continuous proxy climate records from Alaskan loess provide a valuable, independent paleoclimatic template which, through tephochronologic correlations, can yield information about the timing and significance of more discontinuous data sets produced by Quaternary glaciation.

Correlation between several glaciated areas in eastern Beringia and the proxy climate record obtained from loess suggests that local glacier records are very different and discordant in different areas of eastern Beringia. The tephochronological dating also suggests that the last several major glaciations in eastern Beringia were in phase with major cold periods recorded in the loess record, and with the periods of global glaciation designated as marine isotope stages 2, 4, and 6 in the orbitally tuned deep-sea record.

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