The Palisades is a key reference site for the middle Pleistocene of eastern Beringia: new evidence from paleomagnetics and regional tephrostratigraphy

Britta J.L. Jensen a,*, Alberto V. Reyes a,†, Duane G. Froese a, David B. Stone b

a Department of Earth and Atmospheric Sciences, University of Alberta, 1-26 Earth Sciences Building, Edmonton, AB T6G 2E3, Canada
b Geophysical Institute, University of Alaska, Fairbanks, AK, USA

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ABSTRACT

The Palisades, in central Alaska, is one of the most prominent exposures of Quaternary sediments on the Yukon River. Perennially-frozen silt and sand at the Palisades are presently thought to preserve paleoenvironmental records from the Holocene to marine Isotope Stage (MIS) 8 and, beneath a major unconformity, the earliest Pleistocene (~2 Ma). We present new paleomagnetic and tephrachronologic constraints that substantially revise the age of the sediments at the Palisades. We describe 15 new tephra beds, including five beds below the prominent PAL tephra that correlate to known tephra with independent age control from other sites in eastern Beringia. These five known tephra include Chester Bluff tephra, which is present in east-central Alaska and the Yukon, and the newly named Alyeska Pipeline and Taylor Highway tephra from central Alaska; all are constrained to the middle Pleistocene. Paleomagnetic transects from the base of the bluff to the MIS 5e forest bed yield normal polarity, with the exception of a brief reversal event between Old Crow tephra (124 ± 10 ka) and the MIS 5e forest bed that is likely the first documentation of the Blake paleomagnetic event in Alaskan loess. The detailed tephrostratigraphy and paleomagnetic data collectively suggest that most of the sedimentary record at the Palisades is middle Pleistocene in age. The Palisades thus preserves a rare record of late to middle Pleistocene paleoenvironments with multiple regionally distributed tephra beds.

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1. Introduction

The Palisades, on the Yukon River in central Alaska (Fig. 1), is a steep, gullied exposure of perennially frozen loess with interbedded peat, forest beds, relic permafrost, and tephra beds (Begét et al., 1991; Matheus et al., 2003; Reyes et al., 2010a). Descriptions of this impressive bluff, known locally as “The Boneyard”, first appeared over a hundred years ago (e.g. Russell, 1890; Spurr and Goodrich, 1898). However, only relatively recently has it been examined in depth. Yeend (1977) presented a detailed study of Miocene sediments underlying Pleistocene silts at smaller bluff just west of the main Palisades exposure. Begét et al. (1991) discovered the Old Crow tephra (OCT; 124 ± 10 ka; Preece et al., 2011a) and an overlying wood-rich peat, which was identified as representing Marine Isotope Stage (MIS) 5. They also noted that there was likely an extensive middle Pleistocene record present since these units were generally found in the upper third of the exposure. Building on these earlier efforts, Reyes et al. (2010a, 2010b) documented relic ice wedges at the Palisades that persisted through MIS 5e and described an in situ tundra surface buried by OCT.

Of particular relevance to this study, Matheus et al. (2003) mapped the Palisades from river level to the forested surface at the top of the bluff. They found multiple tephra beds below OCT, including Sheep Creek-Fairbanks (SC-F; 190 ± 20 ka; Berger et al., 1996), PA (2.02 ± 0.14 Ma; Preece et al., 1999), Engineering Creek (EC; ~2 Ma; Westgate et al., 2003), Mining Camp (MC; ~2 Ma; Westgate et al., 2003), and a then-newly described tephra bed, the Palisades tephra (PAL). The petrologic and geochemical characteristics of PAL and EC are very similar to PA, thus Matheus et al. (2003) considered these tephra to be co-magmatic and of similar age. The 2.02 ± 0.14 Ma glass fission-track age of PA and the interpretation of PAL as co-magmatic with PA, together with the presence of PAL across the majority of the Palisades, prompted Matheus et al. (2003) to argue that the lower third of the Palisades is earliest
Pleistocene in age. Their "lower peat", stratigraphically associated with PAL, was therefore considered equivalent to the early Pleistocene Dawson Cut Forest Bed in Fairbanks, 260 km to the east (Matheus et al., 2003; Westgate et al., 2003; Péwé et al., 2009). The Palisades is thus a critical site for resolving these stratigraphic relations because the reference sites in the Fairbanks area are either destroyed or overgrown. In this paper we clarify and revise the chronostratigraphic framework for the Palisades through detailed paleomagnetic and tephrostratigraphic sampling. We show that the tephra record at the Palisades is much richer than previously thought; indeed, the new Palisades tephrostratigraphy is a critical link in the ongoing development of regional middle Pleistocene paleoenvironmental proxy records.

2. Site description

The Palisades are on the south bank of the Yukon River in Nowitna National Wildlife Refuge, ~70 km downstream of Tanana village. The site consists of two main exposures (Fig. 1): Palisades East is the main, 8 km long bluff, while Palisades West is a 3 km long bluff that is largely vegetated and has received relatively little attention (Yeend, 1977; Reyes et al., 2010b). We limit our attention here to Palisades East.

Palisades East forms a heavily gullied, cliff-like exposure that is generally ~40--45 m in height, but ranges from ~25 m high at Site E to ~55--60 m high at Site D (Fig. 1). It is difficult to access safely, with many near-vertical exposures and overhanging blocks of frozen sediment that frequently break free into the Yukon River.

3. Methods

3.1. Stratigraphy

We measured elevations of distinct stratigraphic features at accessible exposures using a Lasertech 200XL laser range finder, which has a nominal precision of 0.1 m. Elevations were also collected by repeated measurements with a barometric altimeter; agreement between sections measured by both methods are within 1--3 m. Additional error is also introduced because all measured sections are heights relative to river level at the time, which can vary by several meters over the course of a season, or even weeks.

The cliff-like configuration of the site and slump blocks present few opportunities to complete stratigraphic logs from the top to bottom of the section. Only one section was logged in detail from river level to a height of 32 m above river level (m.a.r.l.) (Figs. 1 and 2; Site B1). All other sections were generally less than 10 m in length. Several tephra samples were grab samples collected to track the continuity of deposits across Palisades East. Wherever possible, we collected OCT, SC-F and PAL to facilitate correlation among measured sections.

3.2. Paleomagnetic measurements

Paleomagnetic samples were collected in two transects: one at 10--20 cm intervals at Site B1 in 2005, and the other at ~5--15 cm intervals from 13 to 17 m above river level through a primary deposit of PAL at Site D1 in 2007 (Figs. 1 and 2; Site B1). All other sections were generally less than 10 m in length. Several tephra samples were grab samples collected to track the continuity of deposits across Palisades East. Wherever possible, we collected OCT, SC-F and PAL to facilitate correlation among measured sections.
(AF) demagnetization ending at 100 mT. The 2007 samples were measured at the California Institute of Technology, also using a 2G Enterprises cryogenic magnetometer. The resulting directions were then displayed on a Zijderveld (1967) three-dimensional plot to identify the magnetic component that decays to the origin. These characteristic magnetizations were determined using a line-fit technique (Kirschvink, 2003), and the tabulated results were then filtered using a maximum angular deviation (MAD) cut off value of 5 to remove unstable components and measurements.

3.3. Major-element glass geochemistry

Major-element glass geochemistry of individual glass shards was determined by wavelength dispersive spectrometry on a JEOL 8900 electron microprobe at the University of Alberta. Analytical conditions for the microprobe were 15 keV accelerating voltage, 6 nA beam current, and a beam diameter of 10 μm. A Lipari obsidian (ID 3506/UA 5831) and Old Crow tephra were used as secondary standards (Kuehn et al., 2011). Reported data are a compilation of multiple analyses. Most tephra samples that were considered potential correlatives to previously identified tephra beds were later analyzed concurrently with reference material to minimize potential variation caused by minor differences in calibration and standardization over time (c.f. Westgate et al., 2008). All samples are assigned a laboratory number during processing. Samples with UA prefixes were processed and analyzed at the University of Alberta, while those with UT prefixes are splits from reference material originally processed and analyzed at the University of Toronto tephrochronology laboratory by J. Westgate and S. Preece.

4. Results

4.1. General stratigraphy

We mapped multiple sections across Palisades East (Fig. 1). With the exception of Sites B2, F and D2, stratigraphic logs are composites of several smaller measured sections within ~200 m of each other. Fig. 3 presents a composite stratigraphic log of Palisades East, with all tephra beds and major organic horizons in relative stratigraphic order. Unless otherwise noted, all elevations are relative to river level at the time of description. We did not examine in detail the latest Pleistocene and Holocene deposits near the top of the Palisades, but rather focused on sediments between river level and the prominent MIS 5e “upper peat” of Matheus et al. (2003).

The stratigraphy of the lower third of the bluff is complicated by the presence of slumped blocks and colluvium, although two main features are traceable across most of Palisades East. The lowestmost traceable unit is a compressed peat that grades up into organic-rich silt, which commonly contains large woody macrofossils with ring-porous anatomy, Picea needle fragments, and tephra beds. This peat and associated tephra are generally at river level, but rise locally to ~6 m (e.g. Site IB4, Fig. 2). Hereafter, we term these deposits the “river-level” peats. At Site B1, it is not clear if the interbedded peat and organic-rich silt at ~6–7 m, which contains ice-wedge casts, is...
part of the river-level peat since no tephra were found to confirm the correlation (Figs. 2 and 4C).

The second traceable feature across much of Palisades East is the PAL tephra (Matheus et al., 2003) and an associated overlying peat and organic-rich silt up to 3 m thick, found at ~13–15 m (Fig. 2). PAL tephra is ~20 cm below or reworked into the base of this thick organic unit. We consider this unit to be equivalent to the "lower peat" of Matheus et al. (2003), and use the term throughout this paper. In some locations PAL has been found above a peat (e.g. Site B2), but the apparently conflicting stratigraphy is clarified at Site D1 where PAL is present below the lower peat, but also above another distinct organic-rich bed comprising organic-rich silt and large wood macrofossils (Figs. 2 and 4B). However, due to a lack of continuously exposed sections from PAL to river level, the stratigraphic relationship between the organic unit directly below PAL and the river-level peat is not clear. Available data suggests the river-level peat, the organic-rich silt below PAL, and the lower peat are discrete units (e.g. Fig. 3), but further mapping when the Yukon River is at low levels would help resolve this stratigraphy.

The ~190 ka SC-F tephra is commonly present within inorganic loess at ~20–23 m, between the lower peat and upper peat of Matheus et al. (2003) and stratigraphically above a semi-continuous organic unit that is probably equivalent to their "middle peat". With the exception of Sites B1 and D2, we did not map sections with prominent expression of the "middle peat". The SC-F tephra is present three meters above the middle peat at Site D2, with two additional new tephra just below or within the peat.

Old Crow tephra and the MIS 5e forest bed/peat are prominent and generally continuous, though at variable elevation above river level, across much of Palisades East (Matheus et al., 2003; Reyes et al., 2010a). The MIS 5e forest bed/peat, which locally contains rooted, upright Picea stumps, is typically separated from the underlying Oct by ~3–7 m of massive inorganic silt with some organic-rich siltly interbeds. At the upstream end of Palisades East (Site E; Fig. 1), the bluff is considerably lower, and OcT is ~7 m above river level. Here, thaw slumping reworked a mixed-age assemblage of organic detritus, spanning non-finite to middle Holocene 14C dates, into stratigraphic association with OcT (Reyes et al., 2011). Moving downstream, the Palisades rise in height to a maximum of ~60 m near Site D (Figs. 1 and 2), where OcT is ~45 m. More commonly, bluff height is 10–45 m, and OcT is present ~25–30 m above river level.

4.2. Tephrostratigraphy and major-element glass geochemistry

We collected and processed 68 tephra samples over two field seasons in 2005 and 2007. From these, we identified 19 unique tephra beds. Four have been identified in previous studies from the Palisades: OcT, SC-F, PAU and PAL (Begét et al., 1991; Matheus et al., 2003). We correlate two Palisades tephra to beds that are well known from other sites in Alaska: Halfway House tephra (HHt; MIS 5d?) and Chester Bluff tephra (CBt; >124 ± 10 ka, < 500 ± 100 ka) (Jensen et al., 2008, 2011a; Preece et al., 2011b). One of the Palisades tephra beds correlates to Valley Creek tephra in the Klondike area of central Yukon, where the stratigraphic context of this bed is poorly understood (Morison et al., 1998). Twelve tephra beds are described here for the first time. Of those, four can be correlated to previously undescribed beds at other sites in Alaska and are named formally here.

We classify each tephra bed according to a scheme, proposed by Preece et al. (1992, 1999), that divides Yukon-Alaska tephra beds into Type I, Type II, and "other" tephra. Type I tephra are derived from the Aleutian Arc, and can typically be identified by their predominantlyplaty glass morphology, and relatively low abundance of phenocrysts that are largely comprised of plagioclase, pyroxenes, and Fe–Ti oxides. In contrast, Type II tephra, derived from the Wrangell volcanic field and northern-most Alaska Peninsula volcanoes, have frothy, inflated pumice and >20% phenocrysts that are predominantly plagioclase, hornblende and Fe–Ti oxides. Geochemically, Type I tephra beds typically contain higher concentrations of FeO and TiO2, and lower Al2O3 and CaO, than Type II beds at the same SiO2 weight percent (wt%). Tephra that do not fit in this scheme are simply listed as 'other'. Here we describe each Palisades tephra bed from oldest to youngest. Complete major-element glass geochemical results for all glass shards, including reference samples, are provided in accompanying supplementary data; summary data are provided in Table 1.

4.2.1. Palisades-1 (P1)

This tephra, together with Palisades-2a/2b, -3, and -4, is found within multiple samples collected near river level at Site F, and in grab samples from Sites B2 and IB4 (Fig. 2); these are collectively...
termed the ‘river level’ tephra beds. All were small, reworked wisps of tephra within the river level peat, which at Site F is a compact peat at river level that grades upward into organic-rich silt with interbedded peat pods and abundant plant macrofossils. We identified two main glass geochemical populations in all samples; two minor glass geochemical populations were identified that, due to potential correlations to other tephra beds elsewhere in Yukon/Alaska, are considered unique tephra. All samples contained abundant detrital shards with no clear geochemical affinity to any of the identified populations. P1 is the most well-defined geochemical population in these samples, representing a high SiO$_2$ wt% rhyolite with relatively high FeO$_t$ and low Al$_2$O$_3$ wt% (Fig. 5;
Palisades-10

2084, 2110, 2162 (1), 2164;

a Type I classiﬁcation

Table 1. The glass geochemistry, together with morphology dominated by blocky bubble-walled shards and pumice, suggests a Type I classification.

The P1 tephra bed is correlative to several samples collected by one of us (B.J.L.J.) at other sites in Alaska. It was ﬁrst identiﬁed at the Alyeska Pipeline viewing site (UA 1679) on the Taylor Highway near Fairbanks. Later it was recognized in previously unreported samples from Chester Bluff (UA 1542; pop. 2 in UA 1070/71/72), and a newly documented sample (pop. 2 in UA 1448) from the river level samples. It is a Type I rhyolite with tight porous anatomy were collected above the tephra sample. The chemical populations in mixed samples from the Tetlin Junction site, and is the main population in that sample, this chemical population was identiﬁed at the Tetlin Junction site also partially plots within P2b.

Palisades-11

Mean 76.16 0.04 14.20 0.56 0.14 0.10 1.04 3.98 3.68 0.09 6.79 96
Stdev 1.30 0.09 0.55 0.17 0.04 0.15 0.94 0.24 0.81 0.01 0.98 25

Palisades-3

Mean 74.35 0.43 13.41 2.29 0.07 0.19 1.94 4.14 2.71 0.22 3.56 56
Stdev 0.56 0.05 0.24 0.24 0.09 0.14 0.23 0.24 0.10 0.06 1.06 5

Palisades-2b

Mean 67.83 1.11 14.73 4.44 0.07 0.11 0.73 4.13 3.50 0.08 2.12 13
Stdev 1.10 0.01 0.14 0.14 0.02 0.02 0.06 0.20 0.17 0.03 1.06 3

Palisades-5

Mean 74.48 0.39 13.60 2.03 0.08 0.15 0.73 3.94 3.16 0.20 5.43 10
Stdev 0.47 0.02 0.18 0.22 0.03 0.09 0.26 0.24 0.11 0.02 1.64 2

Palisades-7

Mean 77.52 0.33 11.88 1.59 0.03 0.28 0.73 3.67 2.77 0.17 5.80 15
Stdev 0.56 0.05 0.18 0.24 0.04 0.16 0.43 0.38 0.11 0.02 1.43 5

Palisades-6

Mean 71.05 0.43 14.49 3.27 0.12 0.28 1.58 5.26 3.21 0.22 5.82 29
Stdev 1.08 0.19 0.28 0.34 0.04 0.21 0.47 0.45 0.20 0.02 2.00 3

Palisades-2a/b (P2a/P2b)

P2a is the second major glass geochemical population extracted from the river level samples. It is a Type I rhyolite with tight geochemical populations, and glass morphology that is predominately tricuspate and bubble-walled shards with minor thick-walled pumice. The P2 glass shards also correlate to distinct geochemical populations in mixed samples from the Tetlin Junction site (pop. 1 in UA 1448) and Chester Bluff (pop. 2 in UA 1070/71/72, two shards in UA 1542) (Figs. 5 and 6; Tables 1 and 2). Because this geochemical population was ﬁrst identiﬁed in UA 1448, from the Tetlin Junction site, and is the main population in that sample, this regionally correlated bed is named the Taylor Highway tephra (THT).

P2b is a subpopulation of dacitic glass present in two of the river level samples. Trends exhibited in this subpopulation, particularly for K2O wt%, suggest that P2b may represent a lower SiO2 wt% population of P2a/THT, although it is geochemically plausible that it may be a unique tephra bed, or even a sub-population of P1/Apt. Several shards from Apt samples at Chester Bluff (UA 1542) and the Alyeska Pipeline viewing site (UA 1679) plot with this population. The third major geochemical population present in UA 1448 from the Tetlin Junction site also partially plots within P2b’s compositional range (Fig. 5C, D).

4.2.3. Palisades-3 (P3)

We identiﬁed a minor glass geochemical sub-population in several of the river level samples (Table 1), which was subsequently identiﬁed in the similarly mixed tephra sample from Chester Bluff.

Table 1 Major-element glass geochemistry (in wt%) of newly described tephra beds.

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<th>Sample</th>
<th>SiO2</th>
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<th>FeOt</th>
<th>MnO</th>
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</table>

Notes: composi-
Fig. 5. Bivariate plots of major-element glass geochemistry for newly identified ‘river-level’ tephra that have been correlated to other sites in Yukon and Alaska: A, B – Data from the Palisades ‘river-level’ tephra. C, D – Data from the Palisades ‘river-level’ tephra, together with reference samples of correlative tephra beds elsewhere in Yukon/Alaska. UA 1679 is the designated reference sample for the Alyeska Pipeline tephra (APt). UA 1542 is APt, but also contains several shards of Taylor Highway tephra (THt) and P2b. UA 1070, 1071, and 1072 contain all the rhyolitic ‘river-level’ tephra beds, and is the designated reference sample for Noyes tephra. UA 1448 is the designated reference sample for THt, but also contains P2b and APt. E, F – A close-up of the rhyolitic ‘river-level’ tephra beds, indicating discernable differences in major element geochemistry. G, H – Reference samples for VCt and LCCt plotted against P3 and UA 1885, a new sample collected at a placer mine in the Klondike goldfields south of Dawson City. Subtle differences in Al2O3 and Na2O wt% suggest that P3 and UA 1885 likely correlate to VCt, rather than LCCt.
These samples plot well with concurrent analyses of reference samples for the Valley Creek tephra (VCt, UT 1464, Preece et al., 2011b) and Last Chance Creek tephra (LCCt, UT 92, Preece et al., 2000, 2011b), both from the Klondike region of west-central Yukon. These two Klondike tephra have nearly identical major-element glass geochemistry and are more reliably distinguished by trace-element composition (c.f. Preece et al., 2011b). However, based on concurrent analyses of VCt and LCCt with some of the river level samples containing this population, subtle differences are present in Al₂O₃ and Na₂O wt% that suggest a more likely correlation with VCt (Fig. 5G, H; Tables 1 and 2). It is difficult to generalize about P3 glass morphology due to the low number of shards, but analyzed P3 shards were remarkably consistent with VCt glass morphology, which is largely a mixture of inflated and thick-walled platy glass. Thus, limited glass geochemistry and morphology support a correlation of P3 to VCt.

4.2.5. Palisades-5 (P5)

This tephra was collected as two samples (UA 2084, 2164) 75 cm above river level at Site F, in the river level peat complex (pop. 4 in UA 1070, 1071, 1072). These samples plot well with concurrent analyses of reference samples for the Valley Creek tephra (VCt, UT 1464, Preece et al., 2011b) and Last Chance Creek tephra (LCCt, UT 92, Preece et al., 2000, 2011b), both from the Klondike region of west-central Yukon. These two Klondike tephra have nearly identical major-element glass geochemistry and are more reliably distinguished by trace-element composition (c.f. Preece et al., 2011b). However, based on concurrent analyses of VCt and LCCt with some of the river level samples containing this population, subtle differences are present in Al₂O₃ and Na₂O wt% that suggest a more likely correlation with VCt (Fig. 5G, H; Tables 1 and 2). It is difficult to generalize about P3 glass morphology due to the low number of shards, but analyzed P3 shards were remarkably consistent with VCt glass morphology, which is largely a mixture of inflated and thick-walled platy glass. Thus, limited glass geochemistry and morphology support a correlation of P3 to VCt.

4.2.4. Palisades-4 (P4)

This minor sub-population of glass was identified on the basis of only four shards, though we interpret it as a unique tephra due to the geochemical correlation of these four analyses to the primary population in UA 1070, 1071, and 1072 from Chester Bluff, a suite of samples that also contains P1/APt, P2a, P3 (Fig. 5). The major-element glass geochemistry of this tephra bed is consistent with a Type II classification; it is similar to, but clearly distinct from, CBt, which is ~9 m above P4 at Chester Bluff (Fig. 6). Because of its apparent regional distribution, here we name this bed the Noyes tephra, for a historical cabin site on the Yukon River near Chester Bluff, where the bed was first discovered.

4.2.5. Palisades-5 (P5)

This tephra was collected as two samples (UA 2084, 2164) ~75 cm above river level at Site F, in the river level peat complex...
Samples UA 2084 and 2164 contain glass geochemical populations of several of the lowest tephra beds, but none of these lowest beds contain shards of P5. UA 2164 was sampled from a single mm-scale wispy layer. Sample UA 2084 was collected from several small creamy-white pods <0.5 cm thick and <5 cm long, which were reworked within organic-rich silt ~50 cm above the compact peat at river level. P5 is a Type I rhyolite with a tight distribution, similar to THt, but with higher Na2O and lower Cl and K2O wt% (Jensen et al., 2008). More importantly, the full range of major-element glass compositions of these deposits can be attributed to a single geologic event, and is not consistent with the presence of multiple tephra layers. The P6 bed is a lower SiO2 wt% rhyolite (Fig. 7; Table 1) with glass morphology that is almost exclusively thin tricuspate and bubble-walled shards, and mineralogy dominated by plagioclase and pyroxene, leading to a Type I classification. It does not correlate to any known tephra from Yukon or Alaska.

4.2.7. Palisades-7 (P7)

We collected one sample of P7 at Site D1 (UA 1308), where it was present as a wispy, white, discontinuous lamina <0.1 cm thick, reworked into the upper 20 cm of an organic-rich silt bed containing wood fragments up to 30 cm in length (Figs. 2 and 4B). Geochronologically it is a Type II tephra bed that is correlated to the Chester Bluff tephra (CBt) (Jensen et al., 2008).

The reference bed of CBt at Chester Bluff, on the Yukon River in east-central Alaska (Fig. 1; Jensen et al., 2008), is found either directly above or within a major organic unit. Primary deposits of CBt at Chester Bluff are thick (up to 30 cm) and complex, consisting of several layers that vary in glass morphology and geochemistry (Jensen et al., 2008). Shard morphology is predominantly thin-walled frothy pumice with some distinct thick-walled pumice. Blocky pumice with abundant microlites are generally limited to the lower, pink layer of CBt at the reference locale, which also contains a high SiO2 wt% population (i.e. CBt-2 of Jensen et al., 2008). Although mineralogical comparisons are complicated by the distinctly finer texture of the Palisades sample, glass morphology is strikingly similar to the Chester Bluff reference material. More importantly, the full range of major-element glass
geochemistry was noted in Palisades sample UA 1308, including several shards identical to the high SiO₂ wt% geochemical population attributed to CBt-2 (Fig. 8C, D; Tables 1 and 2). This tephra bed has recently been identified in a suite of samples from Thistle Creek, in the south Klondike, Yukon, greatly expanding its known distribution (S.J. Preece, pers. comm.).

4.2.8. PAL

Together with OCt, this strikingly pink tephra is one of the most prominent tephra beds found at the Palisades. We collected PAL at all logged sites across Palisades East, except Site F, and as two opportunistically collected samples while tracing the tephra laterally across the exposure. It was generally found below a peat, although organic-rich silt and peat deposits were also found below it at several sites (Fig. 2). Site D₅, which contains a primary bed of PAL complete with root casts and laminations (Fig. 4A), appears to be the least disturbed measured section. There, PAL is overlain by a 1 m thick peat bed, while organic-rich silt with large woody macrofossils is present ~2 m below the tephra (Figs. 2 and 4B). Primary beds of PAL are 2~5 cm thick, but locally the bed is reworked to thicknesses of 10~20 cm. The tephra was first described by Matheus et al. (2003) at the Palisades, with major-element glass geochemistry reported by Westgate et al. (2003). PAL is a Type I tephra bed, with a broad compositional range from ~69.5 to 74.5 SiO₂ wt%, with a slight gap around 72 wt% (Fig. 9; Tables 2 and 3). Glass morphology is diverse, and includes tricuspate and bubble-walled shards, and blocky to frothy pumice. Our analyses of six samples of PAL are indistinguishable from concurrent analyses of the UT 1201 reference material collected by Matheus et al. (2003) (Fig. 9). Our correlations are also supported by consistent stratigraphic context across the Palisades. PAL does bear striking morphological, geochemical, and mineralogical similarities to the PA and EC tephra beds of Fairbanks (Westgate et al., 2003), but they can be distinguished on the basis of SiO₂, Al₂O₃, and K₂O wt% (Fig. 9).

4.2.9. PAU

We have tentatively identified PAU tephra from a sample collected at Site B₁ (UA 1263). A pink tephra like PAL, it is 2~10 cm thick and was found cryoturbated into the upper contact of a 3 m thick wood-rich peat (Fig. 2). This tephra is geochemically indistinguishable from PAL, except that it appears to have a smaller geochemical range (Fig. 9A, B), and the average composition is similar to PAU as published by Matheus et al. (2003) (Tables 2 and 3). However, we did not have access to PAU reference material to confirm this correlation with concurrent microprobe analyses. Matheus et al. (2003) report PAU above a peat bed at several measured sections. In contrast, of the seven pink tephra that we collected from similar stratigraphic contexts, UA 1263 was the only tephra that was not identified as PAL.

4.2.10. Palisades 8 (P8)

This unique tephra bed (UA 1309) was sampled in the paleomagnetic transect at Site D₁, in a reworked peat ~2 m above PAL tephra. Palisades-8 is yellow-white and discontinuous, forming thin wisps up to 0.2 cm thick and 20 cm long. It has high SiO₂ wt% with relatively high FeOt and low Al₂O₃ wt% (Fig. 7C, D; Table 1), suggesting a Type I designation. However, glass morphology is inconclusive, consisting primarily of blocky, thick-walled pumice, with some frothy pumice and platy glass. It does not correlate to any known tephra from Yukon or Alaska.

4.2.11. Palisades 9 (P9)

This tephra (UA 1467, 1468) is present at two of the three gullies that comprise Site D₂, including one gully where it is ~10 cm below P10. The tephra is present as pink-orange semi-continuous pods...
Fig. 8. Bivariate plots of major-element glass geochemistry for newly identified Palisades tephra that are stratigraphically above the river level peat and correlate to other sites in Alaska; A,B – HHT reference sample (UA 1453) plotted against P15 (UA 1462, 2134), and the reference sample for P11 (Boneyard tephra, UA 1126) plotted against Fairbanks area samples from Halfway House (UA 1874) and Largent Mine, near Ester (UA 1609); C,D – CBt reference samples from Chester Bluff (UA 1049/1050, UT 1873/1894; Jensen et al., 2008) and P7 (UA 1308).

Fig. 9. Bivariate plots of major-element glass geochemistry of tephra previously described at Palisades East; A,B – Tephra previously described by Matheus et al. (2003); C,D – PAL plotted against reference samples of tephra of similar composition; EC (UA 351) and PA (UA 355, UA 1327, UT 497), and a PAL reference sample (UT 1201).
analyses are of abundant microlites that vesicles are deformed, and pure glass (2008; Jensen et al., 2008; Kaufman et al., 2012). Glass morphology Table 1). This is consistent with the many Type I tephra beds that have bimodal major-element glass geochemistry (e.g. Finney et al., 2008; Jensen et al., 2008; Kaufman et al., 2012). Glass morphology is distinct; the dominantly thick-walled pumice contains such abundant microlites that vesicles are deformed, and pure glass analyses are difficult. Some brown glass is present, and mineralogy consists of plagioclase, which is frequently zoned, and pyroxene. It does not correlate to any known tephra from Yukon or Alaska.

4.2.12. Palisades 10 (P10)

This tephra (UA 1469) was only found at one of three gullies that comprise Site D2 (Fig. 2). It forms white, discontinuous mm-scale wisps within organic-rich silt directly below the ~0.5–3 cm thick that are within, or up to 40 cm below, the base of the Matheus et al. (2003) middle peat (Fig. 2). Major-element glass geochemistry suggests a Type I classification. Most analyzed shards are dacitic, with rare rhyolitic shards that likely represent a second geochemical population from the same eruption (Fig. 7A, B; Table 1). This is consistent with the many Type I tephra beds that have bimodal major-element glass geochemistry (e.g. Finney et al., 2008; Jensen et al., 2008; Kaufman et al., 2012). Glass morphology is distinct; the dominantly thick-walled pumice contains such abundant microlites that vesicles are deformed, and pure glass analyses are difficult. Some brown glass is present, and mineralogy consists of plagioclase, which is frequently zoned, and pyroxene. It does not correlate to any known tephra from Yukon or Alaska.

4.2.13. Sheep Creek-Fairbanks

Originally described in the Fairbanks region, SC-F is a Type II tephra bed that is typically found several meters below OCT within inorganic loess (e.g. Berger et al., 1996; Preece et al., 1999). We collected SC-F ~6 m below OCT at Sites IB4, C, and D2 (Figs. 1 and 2), and earlier collected it in similar stratigraphic context at Palisades West (Reyes et al., 2010b), and Site B at SC-F found above the middle peat unit of Matheus et al. (2003). The six samples identified as SC-F were all analyzed concurrently with reference material, or a sample that had previously been identified as SC-F, to minimize the potential for miscorrelation stemming from the numerous late Quaternary Sheep Creek-type tephra beds known from elsewhere in eastern Beringia (Westgate et al., 2008). All Palisades samples had major-element glass geochemistry (Fig. 9A, B; Tables 2 and 3), glass morphology, and mineralogy consistent with SC-F.

4.2.14. Palisades-11 (P11)

This bed was found within inorganic loess 50–75 cm below OCT at two measured sections at Site B (UA 1126, 2082; Fig. 2). It is a diffuse, discontinuous, gray tephra with a maximum thickness of 0.3 cm. Its stratigraphic position relative to SC-F is uncertain since they have not been found in the same section. However, we tentatively place SC-F stratigraphically below P11 because at all sites where it is found, P11 is within 1 m of OCT, while SC-F is generally 2–6 m below OCT (Figs. 2 and 3). P11 has unique glass geochemistry, with relatively high Al$_2$O$_3$ wt% and low FeO wt% compared to other Yukon–Alaska tephra beds at this SiO$_2$ wt % range, including Type II beds. The glass morphology is also distinct, consisting almost entirely of blocky, thick-walled pumice, often elongate, with common microcrysts and small, evenly distributed vesicles. Phenocrysts are rare and are dominantly plagioclase with minor amphibole. Since our work at the Palisades in 2005 and 2007, one of us (B.J.L.) has sampled this tephra at two sites near Fairbanks: at Halfway House, a well studied site ~75 km west of Fairbanks (e.g. Preece et al., 1999), and a new Gold Hill Loess exposure at the Largent placer mine near Ester, 12 km west of Fairbanks. Both of these newer samples are geochemically indistinguishable from P11 (Fig. 8A, B), have the same distinct glass morphology, and are found within inorganic loess ≤1 m below OCT. Given the regional distribution of this tephra bed, we formally name it the Boneyard tephra, based on the informal local name for the Palisades, where it was first discovered.

4.2.15. Palisades-12 and 13 (P12/P13)

We identified two unique tephra within one sample from a yellowish diffuse bed up to 0.5 cm thick, in a cryoturbated peaty bed ~1.2 m below OCT at Site IB4 (UA 2167; Fig. 2). These tephra were not found in association with P11, thus their stratigraphic order is not clear. Both P12 and P13 are rhyolitic, but they form two distinct, coherent geochemical populations that do not fall on trends that would be expected if they were two populations from a single eruption (Fig. 7C, D). Both have glass morphology typical of Type I tephra beds, dominated by platy glass, tricuspate shards and thick-walled pumice. Glass geochemistry of P12 supports this Type I classification. However, P13 is a high (~77) SiO$_2$ wt% tephra bed that is in a compositional range where Type I and Type II tephra tend to overlap, thus its classification would require further geochemical investigations (e.g. Westgate et al., 2009; Preece et al., 2011b). Neither of these two tephra correlates to any known bed from Yukon or Alaska.

4.2.16. Old Crow tephra

This tephra can be traced across both Palisades East and West, and is generally present in most measured sections; we identified 20 unique occurrences of OCT at Palisades. OCT is always located
stratigraphically below (≤6 m), or locally re-worked into, the MIS 5e peat/forest bed. Its tightly-constrained rhyolitic composition (Fig. 9A, B), glass morphology, and stratigraphic context are well-documented at the Palisades (Begét et al., 1991; Matheus et al., 2003; Reyes et al., 2010a, 2010b, 2011) and elsewhere in eastern Beringia (e.g. Preece et al., 2011a).

4.2.17. Palisades–14 (P14)

This unique tephra bed was found at Site B, within both the paleomagnetic transect (UA 1147, 1197) and at an adjacent gully (UA 1477, 1478), and at Site D2 (UA 1476). At all three sites it is found within the MIS 5e forest bed (∼28–30 m above river level; ∼45 m at Site D2), which contains large Picea logs that are locally upright and rooted (Reyes et al., 2010b). The tephra is white to pink, and is present as discontinuous pods up to 1 cm thick. Similar to P9, P14 has a Type I dacitic glass composition with a minor rhyolitic component (Fig. 7A, B). Glass shards are typically tri-cuspate or bubble-walled. Pumice is also present and commonly elongate, and brown glass is present. Mineralogy consists largely of orthopyroxene and plagioclase. It does not correlate to any known tephra from Yukon or Alaska.

4.2.18. Palisades–15 (P15)

Two samples in the eastern half of the Palisades correlate to the Halfway House tephra (HHt), known from the Fairbanks region. Sample UA 2134 was collected ∼25 m above river level on the west side of a major gully that forms Site E (Reyes et al., 2011). The white tephra bed was reworked into pods up to 2.5 cm thick and 30 cm long, 15 cm above a cryoturbated peaty soil with a distinct B-horizon. The tephra was not in direct stratigraphic association with any other tephra, though OCt was found on the eastern side of the gully ∼15 m above river level (Reyes et al., 2011). Further west, at Site D2, we collected sample UA 1462 ∼50 m above river level and stratigraphically above OCt and the inferred MIS 5e peat (Fig. 2). Both samples are rhyolitic Type I tephra beds, with glass morphology dominated by tri-cuspate and bubble-walled shards and thick-walled pumice. Glass shards are relatively blocky, and microlites were common. HHt is named after its reference section at Halfway House, ∼50 km west of Fairbanks on the George Parks Highway (Preece et al., 1999). At this site it is present above OCt and the MIS 5e soil, but ∼75 cm below a second paleosol that has been interpreted as representing a younger warm sub-stage of MIS 5 (Jensen et al., 2011a). Thus, HHt dates to the last interglaciation sensu lato, potentially MIS 5d (Preece et al., 1999; Jensen et al., 2011a). The stratigraphic context of UA 2134 and 1462 at Palisades, together with glass major-element geochemistry and glass morphology that are indistinguishable from reference material, indicate a robust correlation to Halfway House tephra (Fig. 8A, B; Tables 2 and 3).

4.3. Paleomagnetic measurements

Inclination and declination values for the two paleomagnetic transects at Sites B1 and D1 are shown in Fig. 10 (all data available in supplementary). These results show that, with the exception of a short event in Site B1, all samples are normally magnetized and suggest that most of the Palisades sediments were deposited during the Brunhes chron (i.e. < 780 ka). The single reversal between 26 and 27 m above river level at Site B1 is unambiguous in both declination and inclination measurements (Figs. 10 and 11), and likely represents a short excursion event during the Brunhes. The apparent noise in the declination data (Fig. 10) for the lower part of the record is due in part to the low intensity of the horizontal component of the geomagnetic field. This is a result of the steep inclinations for this part of the transect, which allow the field direction to pass through vertical and, thus, simulate declination reversals. This can be seen clearly in the stereographic projection of the data (Fig. 11).

5. Discussion

5.1. Stratigraphy

Matheus et al. (2003) presented a stratigraphic framework for Palisades East, which included five lithostratigraphic units, three prominent peat horizons (i.e. upper, middle and lower), and at least one major unconformity separating early Pleistocene and late-middle Pleistocene sediments (Fig. 3). Our new tephr stratigraphy is consistent with much of the Matheus et al. (2003) framework, with key adjustments in the lower third of the Palisades stratigraphic record (Fig. 3).

Starting at the base of the Palisades, below the “unconformity”, are their Units 1 and 2, separated by the lower peat (Fig. 3). The
Fig. 11. A,B – Z-plot orthogonal projections for samples 11 (reversed) and 73 (normal) showing typical behavior of samples during demagnetization. Axes for declination (diamonds) are NS, EW, North up. Axes for inclination (squares) are projected onto the plane containing the mean vector, thus showing the true inclination with respect to the horizontal (i.e. normal field down). C – Steroplot showing all samples analyzed in this study.
lower peat, as described by Matheus et al. (2003), generally lies above PAL, and ranges from river level to 14 m. We suggest that the river level peat is, instead, a separate unit that can be traced across most of the Palisades. This river level peat is likely only fully exposed at low river levels, and is rich in woody macrofossils. Several of the tephras samples collected at this level contained abundant Picea needle fragments, which suggests that like the upper, middle and lower peats at the Palisades, it represents an interval of interglacial climate (Matheus et al., 2003). Our separation of the lower and river level peats is supported by the tephrostratigraphy, where unique suites of tephra are associated stratigraphically with the river level peat and the lower peat. An additional line of evidence in support of unique river level and lower peats is the presence of a semi-continuous organic unit — comprising organic-silt, cryoturbated peat blebs, large wood fragments — between PAL and the river level peat. Unfortunately, sediments from river level to PAL are poorly exposed and frequently inaccessible, so the continuity and stratigraphic context of the organic unit directly below PAL is not yet firmly established.

Between the lower and middle peat, Matheus et al. (2003) argue that the presence of one, or possibly several, large unconformities is required to reconcile the relatively seamless stratigraphy of alternating peat/lake phases (interglacial) and massive silt/glacial units with their identification of the early Pleistocene PA (2.02 ± 0.14 Ma), EC and MC tephra beds, and interpretation of PAL tephra as similarly aged. The absence of PA, EC and MC tephra beds at our multiple measured sections, together with our paleomagnetic and tephrostratigraphic evidence, suggests early Pleistocene sediments are not present across much of the Palisades. Therefore, the invocation of one or more large unconformities spanning many 100,000s of years is not

The ‘unconformity’ defines the contact between Unit 2 and Unit 3 of Matheus et al. (2003): OCt. SC-F and the discontinuous peat underlying SC-F (i.e. middle peat, tentatively assigned to MIS 7) are within Unit 3, which is predominantly massive loess (Matheus et al., 2003; Fig. 3). The MIS 5e peat/forest-bed (i.e. upper peat) defines the contact between Unit 3 and Unit 4. Unit 4, above the MIS 5e peat/forest-bed, was assigned to MIS 2–4 by Matheus et al. (2003). However, the presence of HHT at Sites D2 and E suggests that sediments dating to younger sub-stages of MIS 5 are present locally. Unit 5 of Matheus et al. (2003) represents Holocene loess and peat accumulation and is not described here.

5.2. Paleomagnetism

The normal polarity of Palisades sediments at both transects that suggest they fall within the Brunhes chron (>780 ka). At Gold Hill in Fairbanks, the glass fission-track age of PA tephra (ca 2 Ma), and its presence in loess with reverse magnetic polarity, place PA firmly in the 2.58–0.78 Ma Matuyama reversed chron (Westgate et al., 1990). Thus, PAL cannot be co-magmatic with PA because sediment surrounding PAL at Sites B1 and D1 are magnetically normal.

The small reversal above OCt (124 ± 10 ka), and ~20 cm below the MIS 5e upper peat, probably represents the well-defined Blake event (e.g. Smith and Foster, 1969; Fig. 10). Various age determinations for the Blake event include an estimate of 123 ± 3 ka from North Atlantic and Arctic marine sediment cores (Lund et al., 2006), and a mean 40Ar/39Ar age of 120 ± 16 ka on globally distributed lava flows (Singer and Hoffman, 2005). There are a number of similar reversals between the Blake event and the Brunhes–Matuyama boundary, most of which are very short and could be difficult to find in loess deposits. However, some of these transient events, such as the Pringle Falls event (211 ± 13 ka) and a series of events ca 600–500 ka (e.g. Laj and Channell, 2007; Singer et al., 2008), may be present in Alaskan loess records. The paleomagnetic record of Westgate et al. (1990) from the Gold Hill Loess near Fairbanks, Alaska, shows a short reversal about 2 m below OCt, which would place it close to the expected location for the Pringle Falls reversal. Recent high resolution re-sampling of Gold Hill and Halfway House has identified additional events, including a likely candidate for the Skálalæmilfell event (ca 96 ka, Jicha et al., 2011), but shows no record of the Blake (Jensen et al., 2011b; Evans et al., 2011, 2012). Paleomagnetic records from Imuruk Lake on the Seward Peninsula, lacustrine deposits at Koyukuk bluff (KY11) in west-central Alaska, and loess at Halfway House, show an excursion just below OCt that was originally interpreted as the Blake (Westgate et al., 1983, 1985; Schweiger and Matthews, 1985). However, new age determinations and paleoecological constraints on OCt (Reyes et al., 2010b; Preece et al., 2011a), present above the event in all three locations, place OCt within late MIS 6, suggesting that the Blake event almost certainly must postdate deposition of OCt. Thus, our recognition of a brief magnetic reversal event at Palisades East may represent the first discovery of the Blake event in Yukon and Alaska.

5.3. Regional tephras correlations

Problematic at the time of analyses was the repeated occurrence of samples that contained multiple glass geochemical populations, raising the possibility that some samples could have been contaminated during collection and processing steps. However, systematic contamination seems unlikely because many of the samples were collected and analyzed over the course of five years. We further reject the possibility of systematic sample contamination because the mixed-population samples correlate to other similarly mixed samples from other sites in the region. Some of these other mixed samples, such as three samples collected from a single peat unit at Chester Bluff (UA 1070, 1071, 1072), were analyzed much earlier but not formally described because their glass geochemistry was initially considered inconclusive (e.g. Fig. 3 of Jensen et al., 2008, the “undescribed tephra”). Indeed, the existence of samples from multiple sites that contain the same mixed glass geochemical populations provides robust evidence for the correlations. The identification of these new tephra beds at previously studied sites now adds additional age constraints to sediments in the lower third of Palisades East.

5.3.1. Age control on ‘river level’ tephra beds

We correlate Palisades tephra bed P1 to Alyeska Pipeline tephra (APT), which we also recognize as a geochemical population present in five additional samples from two other sites elsewhere in eastern Beringia. The APT reference locale is a partially overgrown exposure of interbedded organic units and loess, ~13 m high, behind the Alyeska Pipeline viewing area on the Steele Highway near Fairbanks. The tephra is in cryoturbated organic-rich silt and peat with large wood fragments. Six meters of overlying silt separate APT from a ~10 cm thick bed of angular pebbles, granules and oxidized silt that is interpreted as an unconformity. The Sheep Creek-Fairbanks tephra is 3 m above this unconformity, providing a minimum age to the section (Fig. 6). Six paleomagnetic samples were collected through APT that are normally magnetized (see Supplementary data).

APT is also present in four samples from two measured sections at Chester Bluff, in eastern Alaska (Jensen et al., 2008). Three of the samples (population 3 of UA 1070, 1071, 1072) were collected from a dry compressed peat 9 m below C8t and 11 m above Gl tephra (500 ± 100 ka; Preece et al., 2011b). A fourth APT sample (UA 1542) was found at the second section within thin alternating beds of peat and inorganic silt that grade down into thick peat containing Preido
Hill tephra (PrH), a tephra that is also present at the first site, below UA 1070/71/72, but above GI (Jensen et al., 2008; Fig. 6).

APT is also present as the secondary population in a tephra (UA 1448) collected at the Tetlin Junction site within organic-rich sandy silt. The sample containing APT is 1.5 m below the Tetlin tephra, which is dated by $^{39}Ar/^{39}Ar$ on hornblende to 627.5 ± 47.7 ka (Schaefer, 2002; Fig. 6). The main population in UA 1448, named Taylor Highway tephra (THt), correlates to tephra P2a at Palisades and also forms a distinct population in Chester Bluff samples UA 1070, 1071, and 1072. This cross-correlation places APT and THt and also forms a distinct population in Chester Bluff samples UA 1070, 1071, and 1072. This cross-correlation places APT and THt, in the Tetlin tephra (627.5 ± 47.7 ka) and GI (500 ± 100 ka) tephra beds (Fig. 6). The apparent inverted ages for Tetlin and GI tephra are reconcilable given their large 1σ uncertainty terms. The age control provided by Tetlin and GI tephra suggests that APT was likely deposited between ca 400 and 700 ka.

Another ‘river level’ tephra, P3, correlates to Valley Creek tephra (VCt; Fig. 5), a tephra bed first identified in the lower reaches of the Stewart River basin in Yukon, within colluvium that unformanably overlies pre-Reid (a local term for undifferentiated pre-MIS 6 glaciations; e.g. Ward et al., 2008) outwash gravels (Morrison et al., 1998; Preece et al., 2011b). It has also recently been identified in a ~1 km long discontinuous placer mining cut on Dominion Creek, in the Klondike, 500 km south of Dawson City, Yukon (UA 13885; Fig. 5). There, VCt is cryoturbated within normally magnetized peaty organic-rich silts (see Supplementary data). This exposure also contains PrH at its upstream end, and the Gold Run (740 ± 60 ka), Hollis (700 ± 70 ka), and Hollis 2 (630 ± 80 ka) tephra beds at its furthest downstream end (Westgate et al., 2009, 2011). Although VCT is not in direct stratigraphic association with these beds, their normal magnetization and presence in the same exposure support a middle Pleistocene age estimate for VCt. It is important to note that LCCt, which is hard to differentiate from VCt by major-element glass geochemistry alone (Fig. 5), was originally collected at a placer mining exposure informally known as MIBEN2 (Preece et al., 2000). The reference sample for PrH was also collected at the MIBEN2 cut, at a different time, but in a similar stratigraphic context. Thus, both LCCt and VCt are stratigraphically linked to PrH in the Klondike region and at Chester Bluff, suggesting that LCCt and VCt are middle Pleistocene in age (Preece et al., 2000, 2011b; Jensen et al., 2008).

We correlate four shards of P4 tephra at Palisades to Noyes tephra, which is the main geochemical population in Chester Bluff samples UA 1070, 1071, and 1072. These Chester Bluff samples also contain populations of APT (P1), THt (P2a), and VCt (P3), lending further support to the tentative geochemical correlation of P4 to Noyes tephra.

To summarize, the ‘river level’ tephra beds correlate to external sites where they are deposited in sediments that are unequivocally middle Pleistocene in age. These tephra are younger than GI (500 ± 100 ka) but older than Tetlin (627.5 ± 47.7 ka), and occur in sediments with normal polarity. The presence of multiple tephra combined together in individual samples is likely the result of two factors: (1) several large eruptions occurring over a relatively short period of time, and (2) reworking and mixing due to a slower rate of loess deposition over interglacial periods (e.g. Muhs and Bettis, 2003).

5.3.2. The age of Chester Bluff tephra

Our new tephrostratigraphy at the Palisades is relevant to the age of Chester Bluff tephra (CBt). This tephra has now been recognized along a ~500 km long transect from the Palisades, through its reference locale at Chester Bluff in east-central Alaska (Jensen et al., 2008), to the south Klondike in the Yukon (S.J. Preece, pers. comm.) (Fig. 1). At its reference locale of Chester Bluff, CBt is above — and locally reworked into — a prominent interglacial peat bed (Bigelow, 2003; Jensen et al., 2011b; Fig. 6). The peat and tephra are within normally magnetized sediments, and Old Crow (124 ± 10 ka) and GI (500 ± 100 ka) tephra provide minimum and maximum ages, respectively (Froese et al., 2003; Jensen et al., 2008; Fig. 6). The Biederman tephra (BT) is present above CBt at Chester Bluff and Birch Creek (Jensen and Froese, 2009), a site in east-central Alaska (McDowell and Edwards, 2001). At both sites BT is in the same stratigraphic position; below OCl, and cryoturbated within the upper contact of a peaty organic-rich silt bed. The SC-F tephra is also present between OCl and BT at Birch Creek (Fig. 6). The peaty organic-rich silt associated with BT at Birch Creek is rich in Picea macrofossils, including well-preserved logs. Pollen samples from the equivalent unit at Chester Bluff contain up to 38% Picea pollen, suggesting this organic silt/peat unit represents an interglacial with a minimum age of MIS 7, based on the presence of SC-F above BT at Birch Creek. Thus, the corresponding minimum age for CBt is early MIS 8 or late MIS 9 (Jensen and Froese, 2009; Jensen et al., 2011c), with a loose maximum age provided by GI tephra at Chester Bluff, and the underlying APT/P1, THt/P2a, VCT/P3 and Noyes/P4 beds at the Palisades and Chester Bluff. As this paper went to press, Westgate et al. (2013) reported an occurrence of CBt, which they termed Surprise Creek tephra, in the Old Crow Flats, north-central Yukon. They report a glass fission-track age of 170 ± 70 ka for the tephra. This age is young, but not irreconcilable with the stratigraphy presented here considering the large 1σ error.

6. Conclusion

Palisades East is an ~8 km long exposure of perennially frozen sediments, predominantly loess, interbedded with multiple peat and forest beds, tephra, relic ice and vertebrate fossils. This site contains several tephra beds previously described in the literature, including Halfway House (MIS 5), Old Crow (124 ± 10 ka), Sheep Creek-F (190 ± 20 ka), and Chester Bluff (minimum age ca. MIS 9) (Berger et al., 1996; Jensen et al., 2008, 2011a, 2011c; Preece et al., 2011a).

We have identified four tephra beds at multiple Palisades sections near river-level that correlate to Chester Bluff in east-central Alaska (Jensen et al., 2008), the Alyeska Pipeline viewing area in Fairbanks, the Tetlin Junction site on the Alaska Highway near Tok (Schaefer, 2002), and the Klondike goldfields south of Dawson City, Yukon. The correlated tephra beds include three previously undescribed beds we here named the Alyeska Pipeline (APT), Taylor Highway (THt) and the Noyes tephra beds. The fourth is correlated to Valley Creek tephra (VCt), known from the Klondike region. All four of these tephra are present in magnetically normal sediments and are stratigraphically associated with other dated middle Pleistocene tephra beds. In particular, APT and THt are found stratigraphically below Tetlin tephra (627.5 ± 47.7 ka), and above GI (500 ± 100 ka). We also described and identified a new regionally distributed bed, the Boneyard tephra, within ~75 cm of OCl. This tephra is also present at two sites in the Fairbanks region. Finally, we described and identified an additional eight new tephra beds that have not yet been reported elsewhere, including a new tephra bed (P14) within the MIS 5e forest bed.

In our re-examination of Palisades East we were able to recollect PAL and PAU, but we did not locate the PA, EC or MC tephra described by Matheus et al. (2003). Rather than dating to the early Pleistocene, PAL must be older than ~200 ka but younger than ~500 ka, based on: the direct stratigraphic association between PAL and the underlying APT (P1), THt (P2a), and CBt (P7) beds; two palaeomagnetic transects through sediments containing PAL that yielded normal polarity; and the presence of SC-F above PAL. To account for the identification of PA by Matheus et al. (2003), it is possible that small pockets of older sediments were present at
Palisades East, but have been subsequently removed by the continual erosion of the exposure.

The small reversal event present in loess above OCT and directly below the MIS 5e forest bed likely represents the Blake geomagnetic event. This is the first reported occurrence of this excursion in Alaskan loess records, and joins a growing body of evidence that these subtle variations in the geomagnetic field may be more common in these loess records than previously thought (e.g. Westgate et al., 1990; Evans et al., 2011; Jensen et al., 2011b).

Multiple organic-rich silt/peat deposits interpreted as interglacial, placed in context of the inferred ages of CBT, APT and THT, suggest that Palisades East contains an extensive middle Pleistocene paleoenvironmental record that likely contains few, if any, major unconformities. This is a rarely preserved time in eastern Beringia and is usually only seen in fragments; Chester Bluff is the only other known site to contain a similar semi-continuous record. These interglacial records, the correlation of CBT, APT, THT, VCT, and Noyes tephra across hundreds of kilometers, and the addition of ten newly identified tephra beds within the context of these tephras and dated beds such as OCT and SC-F, make the Palisades a key reference site for the middle Pleistocene across the Yukon and Alaska.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2012.11.035.

References


