Available online at www.sciencedirect.com
SCIENCE @ DIRECT®
ACADEMIC PRESS
Quaternary Research 60 (2003) 50–62
QUATERNARY RESEARCH
www.elsevier.com/locate/yqres

Recurring middle Pleistocene outburst floods in east-central Alaska

Duane G. Froese,[a,]* Derald G. Smith,[b] John A. Westgate,[c] Thomas A. Ager,[d] Shari J. Preece,[c] Amanjit Sandhu,[c] Randolph J. Enkin,[e] and Florence Weber[f]

[a] *Department of Earth Sciences, Simon Fraser University Burnaby, British Columbia, V5A 1S6 Canada*
[b] *Department of Geography, University of Calgary, 2500 University Drive, Calgary, Alberta T2N 1N4 Canada*
[c] *Department of Geology, University of Toronto, Toronto, Ontario, M5S 3B1, Canada*
[d] *United States Geological Survey, Mail Stop 980, Box 25046 Federal Center, Denver, CO 80225, USA*
[e] *Geological Survey of Canada, 9860 West Saanich Road, Sidney, British Columbia, V8L 4B2, Canada*
[f] *United States Geological Survey, P.O. Box 80586, Fairbanks, AK 99708, USA*

Received 24 June 2002

Abstract

Recurring glacial outburst floods from the Yukon-Tanana Upland are inferred from sediments exposed along the Yukon River near the mouth of Charley River in east-central Alaska. Deposits range from imbricate gravel and granules indicating flow locally extending up the Yukon valley, to more distal sediments consisting of at least 10 couplets of planar sands, granules, and climbing ripples with up-valley paleocurrent indicators overlain by massive silt. An interglacial organic silt, occurring within the sequence, indicates at least two flood events are associated with an earlier glaciation, and at least three flood events are associated with a later glaciation which postdates the organic silt. A minimum age for the floods is provided by a glass fission track age of 560,000 ± 80,000 yr on the GI tephra, which occurs 8 m above the flood beds. A maximum age of 780,000 yr for the floods is based on normal magnetic polarity of the sediments. These age constraints allow us to correlate the flood events to the early-middle Pleistocene. And further, the outburst floods indicate extensive glaciation of the Yukon-Tanana Upland during the early-middle Pleistocene, likely representing the most extensive Pleistocene glaciation of the area.

Keywords: Glacial chronology; Tephra; Early-middle Pleistocene; Yukon River; Outburst floods

Introduction

The restricted extent of late-Wisconsinan glaciation in Yukon and Alaska, collectively eastern Beringia, has resulted in the preservation of sedimentary sequences potentially spanning much of the Quaternary (Westgate et al., 1990; Begét, 2001). The occurrence of widespread distal tephra beds within these sediments provide a means of directly dating sequences beyond the limit of the radiocarbon method and the potential to link records of differing origin regionally and to global changes (Begét, 2001). Studies in the interior of eastern Beringia have focused, mainly, on the extensive placer mining exposures of the Fairbanks area, Alaska (e.g. Péwé, 1975; Preece et al., 1999) and the Dawson area, Yukon Territory (Preece et al., 2000; Froese et al., 2000; 2001). While these two areas have provided some of the most complete and highest concentration of pre-late-Quaternary sites in the interior of Yukon and Alaska, comparable records should exist throughout this region.

This study focuses on a series of newly identified exposures along the Yukon River in east-central Alaska. The sites are located between the Fairbanks and Klondike areas and contain a sequence of interbedded eolian, fluvial, and organic deposits associated with multiple tephra. The sequence is overlain by up to 40 m of loess, containing multiple organic horizons, of presumed interglacial charac-

* Corresponding author. Department of Earth and Atmospheric Sciences, University of Alberta Edmonton, Alberta, T6G 2E3 Canada. Fax: +780-492-2030.

E-mail address: duane.froese@ualberta.ca (D.G. Froese).

0033-5894/03/$ – see front matter © 2003 University of Washington. Published by Elsevier Inc. All rights reserved.
doi:10.1016/S0033-5894(03)00090-5

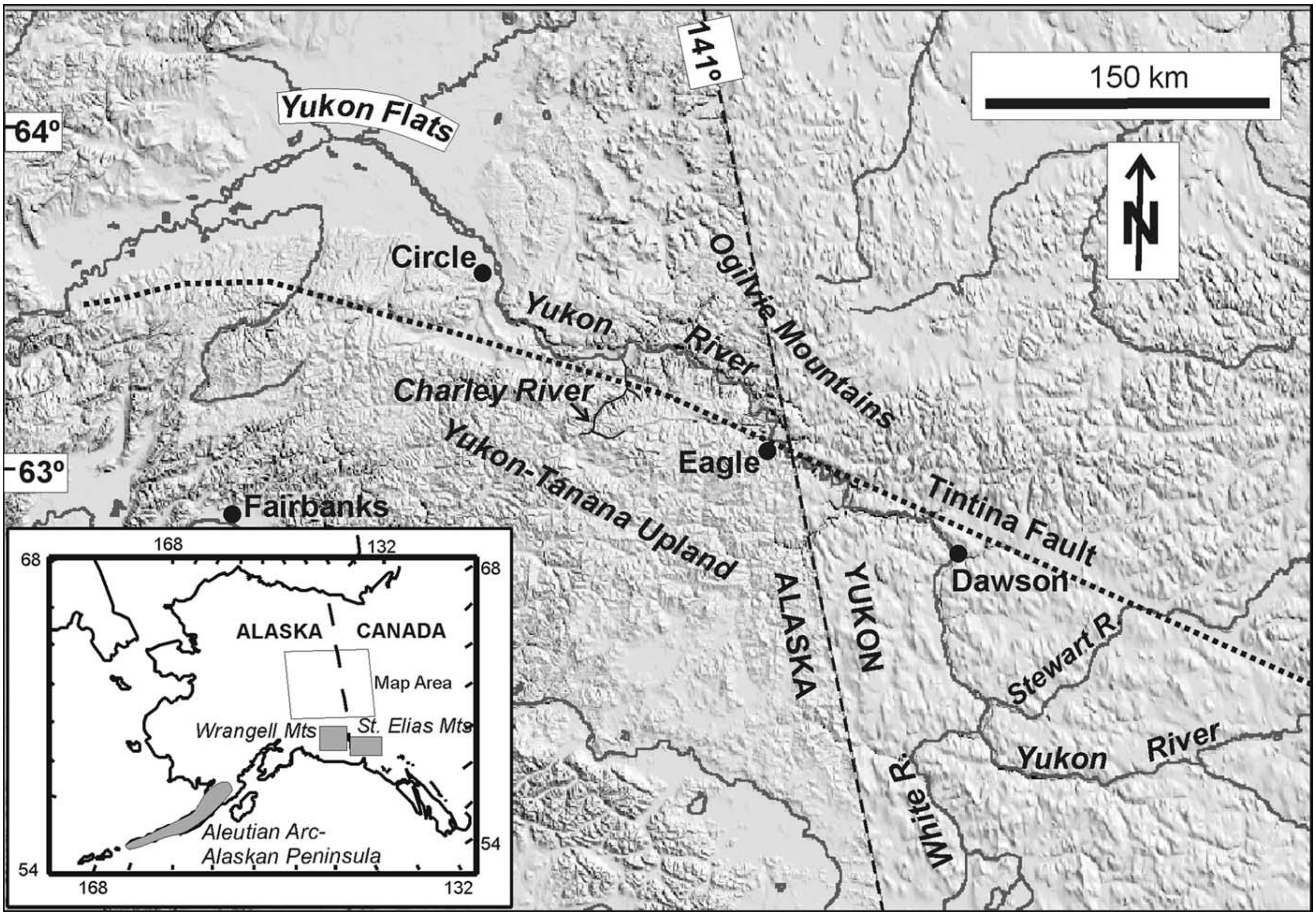

Fig. 1. Location of Charley River area and sites noted in the text. Yukon River flows northwest from central Yukon to east-central Alaska.

ter, suggesting that the exposure dates considerably beyond the last glaciation. In this study, we report on the lowest part of the sequence, which contains a succession of rhythmically bedded sands and silts with paleocurrent directions, locally, going up the Yukon River valley. We establish the origin of these rhythmites, the paleoecology of interbedded organic silts, chronology, and probable connection to glaciation of the Yukon-Tanana Upland.

Setting

The Yukon River in eastern Alaska trends northwest roughly parallel to the Tintina Fault (Fig. 1). Near the Alaska-Yukon border, the river crosses the fault, which separates Selwyn basin sedimentary rocks from accreted terranes to the south. North of the Tintina Fault is the western extension of the Ogilvie Mountains from the Canadian side, while to the south is the Yukon-Tanana Upland (Fig. 1). In Alaska, the mountains bordered by the Yukon Flats to the west and the Ogilvie Mountains to the east are generally low with few peaks exceeding 1300 m asl (Fig. 1). In contrast, the Yukon-Tanana Upland has peaks approaching 2000 m asl which, during the Pleistocene, supported local glaciers that flowed down the surrounding valleys (Weber, 1986).

Climate of the interior of east-central Alaska is subarctic continental. The St. Elias and Alaska ranges provide a strong rain shadow, limiting the incursion of moist Pacific air masses into the interior. Annual precipitation is about 300 mm, 20–30% of which falls as snow. Temperatures in the interior range from near 30°C in summer to −60°C in winter, with a July mean of 15.5°C (NCDC 1949-2000 for Eagle, Alaska, Western Regional Climate Center).

Vegetation at low elevations in interior Alaska is northern boreal forest. On well-drained upland sites, the forest is characterized by white spruce (*Picea glauca*), paper birch (*Betula papyrifera*), and aspen (*Populus tremuloides*). The understory vegetation consists of mosses and low shrubs such as currants (*Ribes*), Labrador tea (*Ledum groenlandicum*), blueberry (*Vaccinium uliginosum*), sedges (*Eriophorum, Carex*), grasses (*Gramineae*), willows (*Salix* spp.), alder (*Alnus*), dwarf birch (*Betula nana*), and resin birch (*Betula glandulosa*). Poorly drained sites, commonly associated with thick peaty soils and shallow permafrost, are dominated by black spruce (*Picea mariana*), with a ground

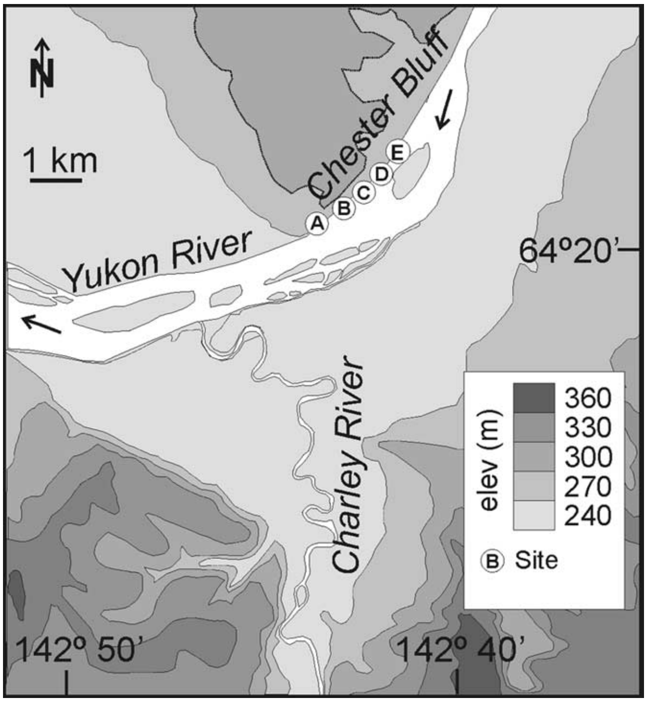

Fig. 2. Location of logged sections at Chester Bluff.

cover of mosses, heaths (e.g., *Vaccinium* spp. and *Ledum* spp.) and cottongrass (*Eriophorum*) tussocks.

The Yukon River study reach is located within the unglaciated region of central Alaska. The mountains north of the study reach were too low to support local glaciers during the Quaternary, but some glaciers extended into the region from higher valleys of the western Ogilvie Mountains in Canada (Duk-Rodkin, 1999). In contrast, the Yukon-Tanana Upland to the south was a center for local ice masses during the Quaternary. Weber and Hamilton (1984) and Weber (1986) detail a record of at least four glaciations during the Quaternary, including the early and middle Pleistocene Charley River and Mount Harper glaciations, a younger pre-Wisconsin Eagle Glaciation, and the late Wisconsin Salcha Glaciation (Hamilton, 1994). Manley et al. (2002) suggest, on the basis of cosmogenic dating of moraines, that the Eagle and Salcha moraines may be early and late Wisconsin, respectively, and the Mount Harper Glaciation is at least 150,000 yr old. They were unable to date the Charley River Glaciation, however, because the moraines have no boulders suitable for cosmogenic dating, but based on their greater extent they must predate the Mount Harper Glaciation.

We studied exposures at Chester Bluff on the north side of the Yukon River opposite the mouth of the Charley River during July 1999 and 2000 (Fig. 2; 64° 27.57′ N, 142° 42.60′ W). At these sites detailed vertical lithostratigraphic logs were compiled on a bed-by-bed basis. Where exposures allowed, horizontal facies changes were noted. Elevations at all sites were measured with a Lasertech 100XL laser range finder with reference to the Yukon River during July 1999 and 2000. Measured elevations are correct to within 1 m. Orientations of cross-beds and clast imbrication were measured with a Brunton compass. In addition, oriented paleomagnetic samples were collected from silty-fine sand, loess, tephra beds, and organic sediments.

Lithostratigraphy

The Chester Bluff sediments can be subdivided into four main units, from bottom to top: (1) black shale exposed to 10 m above river level (bedrock), (2) 8–10 m of stratified gravel (paleo-Yukon River gravel), (3) 5–12 m of stratified sand and silt rhythmites with minor gravel facies, and (4) 20–40 m of loess. At four sites we were able to describe in detail the stratified sand and silt rhythmites that are the focus of this paper (sites A, C, D, E; Figs. 2, 3, and 4). At a fifth site (site B, Figs. 2, 3, and 4), paleomagnetic samples were collected through the sequence.

The sedimentology of the rhythmite deposits varies considerably from west to east with generally coarser and thicker deposits present at the westerly exposures. The rhythmite deposits (Figs. 3 and 4) have four components: (1) a sharp basal contact; (2) normally graded, planar-bedded pebble-gravel to pebbly sand and cross-bedded coarse sand; (3) upvalley paleocurrent directions; and (4) an upper cap of massive fine sand and silt.

At site A (Figs. 2 and 3), 8 m of paleo-Yukon River gravel, imbricate to the west in the direction of the present Yukon River, is overlain by 1 m of crudely horizontally stratified sandy-silt and massive silt. Above these sediments, at 19 to 21 m above river level, are two rhythmites separated by a sharp erosional contact. The upper of the two rhythmites is overlain at 21 m by a consolidated organic silt (0.2 m thick), a colluvial pebble diamicton (0.15 m thick), and massive mottled silt (1.35 m thick). These sediments, in turn, are overlain by three rhythmite beds ranging from 0.8 to 1.5 m thick. A small sand-wedge occurs at the top of the second of these three rhythmites (Fig. 4D). The uppermost couplet (25 m) is crosscut by a composite epigenetic ice-wedge cast with a depth of 1.7 m and maximum width of 1 m. The ice-wedge cast is capped by a pebble-diamict unit with clasts up to 4 cm in diameter which is overlain by a 30-cm-thick organic silt. The organic silt and diamict are continuous across the 5-m width of the exposure. This organic silt horizon is covered by 3 m of planar-bedded sands and a 1-m-thick organic silt horizon containing pods of the Charley River tephra (Fig. 4F).

Site C is located approximately 150 m east of site A (Figs. 2 and 3). Sediments directly overlying the Yukon River gravel, at 18–19.5 m, consist of planar-tabular cross-bedded gravel (paleocurrent at 50°), grading to massive sand and silt. These sediments are overlain by three rhythmites consisting of normal-graded gravel and sand ranging from 0.7 to 2 m thick. All three rhythmites were deposited by flows to the north (10°). Above this, at 24 to 25.2 m, is

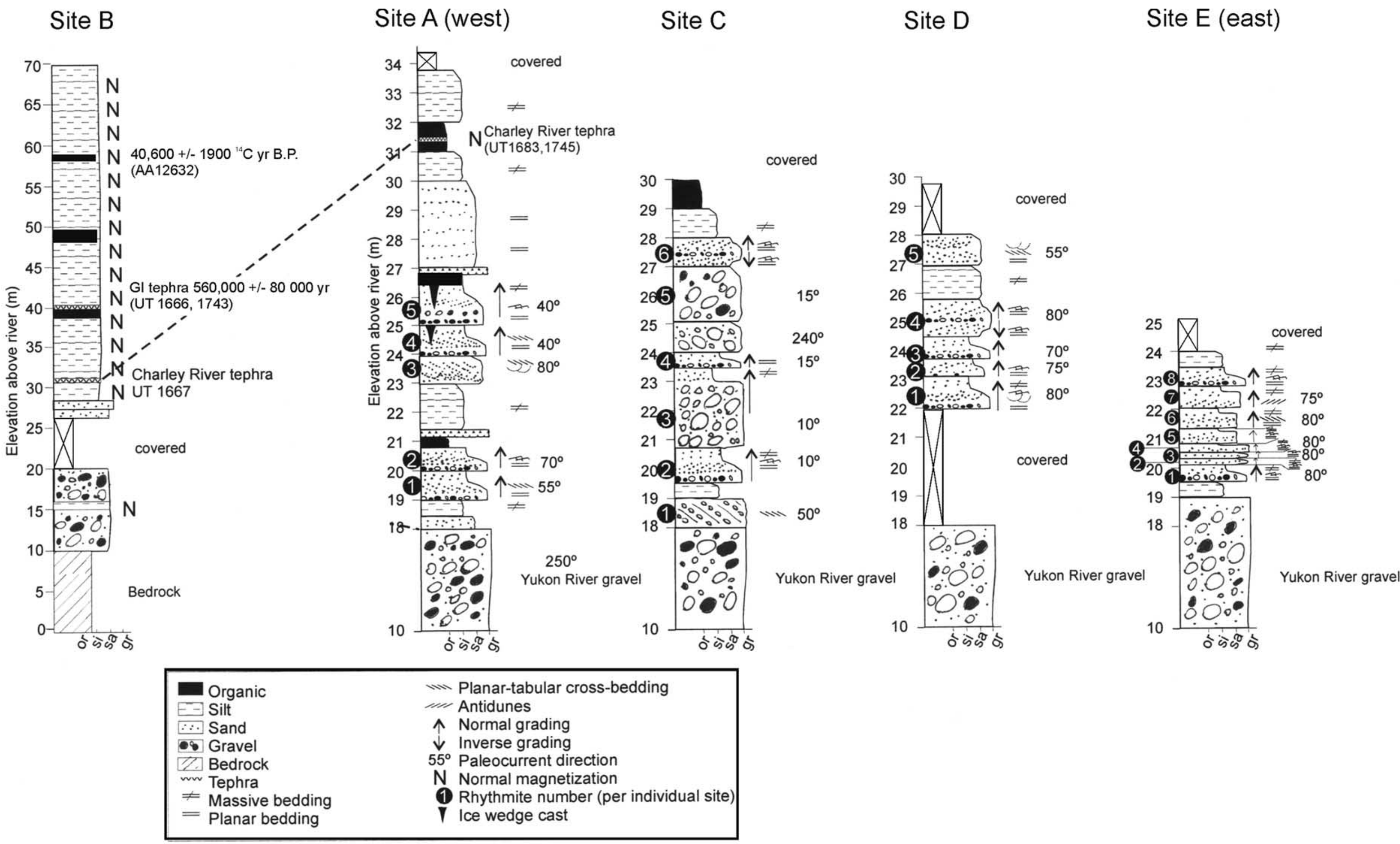

Fig. 3. Lithostratigraphic logs of sections at Chester Bluff located on Figure 2. The sites span a lateral distance of approximately 3 km. The base of all sections is the river surface measured in July 2000.

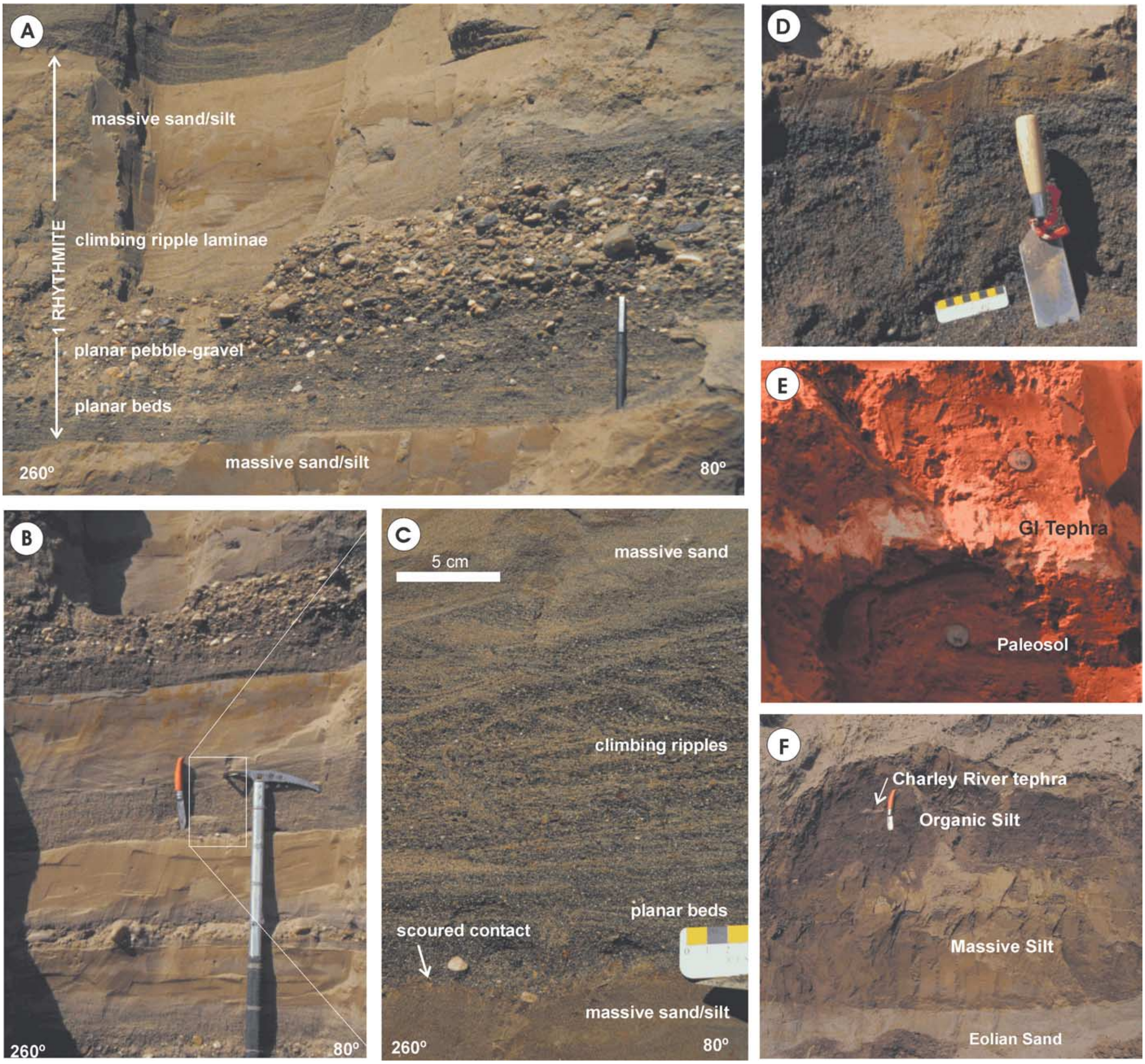

Fig. 4. (A, B, C) Rhythmites at Chester Bluff. Each rhythmite has an erosional basal contact and consists of planar-bedded sands and pebble gravel grading into cross-bedded sands and massive sandy silt with paleocurrent indicators oriented toward the northeast or east, up the Yukon River valley. (D) Sand wedge developed on rhythmite surface (bed 4) at site A. (E) GI tephra overlying a paleosol developed in loess at site B (Figs. 2 and 3). (F) Charley River tephra within organic silt above rhythmites at site A (Figs. 2 and 3).

a massive gravel with a paleoflow direction to the west (240°). At 25 to 28.5 m are three normally graded pebble gravel to sand rhythmites with flow directions to the north. These sediments are overlain by 0.5 m of massive silt and an organic silt bed that is correlated to the upper organic silt at site A. Sites D and E are the most easterly studied exposures at Chester Bluff, approximately 500 m east of Site B, and contain five and eight rhythmites, respectively, deposited by flows to the northeast and east (Figs. 3 and 4).

The rhythmite deposits are interpreted as resulting from the repeated drainage of a glacial lake (or lakes) in the headwaters of the Charley River. We associate a glacial signature with these deposits for the following reasons. First, the paleocurrent directions (north and northeasterly up the Yukon River valley) indicate a water source derived from the Charley River (Fig. 2). Second, the upvalley paleocurrents in the main Yukon River valley require a large volume of water, sufficient to reverse local flow on the Yukon River for several kilometers upvalley. Given a valley width at Chester Bluff of more than 3 km (Fig. 2), the water volume would exceed historic peak discharge on the upper Yukon recorded at Eagle (Froese, 2001; Brabetts et al., 2000). For the much smaller Charley River to produce a flood of this magnitude requires the storage and sudden release of water. One possibility suggested by a reviewer is for these to be flood surges produced by large ice jams along the Charley River. As a point of comparison, the largest historic ice-jam flood event along the Yukon River at Dawson City in 1979 reached a maximum stage behind the ice dam greater than the 100-yr-recurrence open-water stage (Gerard, 1984). However, the estimated discharge was comparable only to the 1–2 yr recurrence open water flow due to the minimal velocity resulting in negligible downstream effects from the release of this water (Gerard, 1984; Gerard et al., 1992). Third, mapping of glacial limits in the Yukon-Tanana Upland has shown that large glacial lakes formed and periodically released during the Quaternary (Weber, 1986), providing a ready source for flood events at the mouth of Charley River. While a landslide dam could also provide a flood source, the cyclic nature of the rhythmites suggests a recurring mechanism making a landslide source unlikely. And fourth, these rhythmites are analogous to the slackwater sediments described from the Channel Scablands of Washington State in which repeated outburst floods flowed, locally, up tributary valleys to the main flood route (Waitt, 1980, 1985).

Geochronology

Paleomagnetic samples and tephra were collected at site B and tephra at site A. In addition a sample of wood from the uppermost organic horizon at site B yielded an AMS radiocarbon age of 40,600 ± 1900 ^{14}C yr B.P. (AA12632). We interpret this as a minimum age for the deposits, but note they are probably considerably older given the presence of multiple organic horizons, of presumed interglacial character, between the dated sample and rhythmites below.

Paleomagnetism

Oriented samples were collected by inserting plastic cylinders (2.5 cm diameter) horizontally into a cleaned vertical face. Samples were taken from fine-grained overbank sediments within Yukon River gravels and from loess and fine sand deposits at a vertical interval of no more than 20 cm, and directly above and below all tephra beds. Remanence measurements were made on an AGICO JR-5A spinner magnetometer. Stepwise alternating field demagnetizations were carried out using a Schonstedt GSD-5 with tumbler in peak fields up to 100 mT. Samples were demagnetized using 5–10 steps and directions determined by principal component analysis (Kirschvink, 1980).

All of the site B paleomagnetic samples have a single component of magnetization (Fig. 5). The orthogonal plot in Figure 5 shows that the primary normal magnetization has not been affected by secondary reverse overprints that are commonly present in pre-Bruhnes normally magnetized sediments (e.g., Froese et al., 2000). The normal magnetization suggests that sediments at site B, including the fine-grained overbank sediments within the Yukon River gravel, are of Brunhes age and therefore less than 780,000 yr old. This provides a maximum age for the Charley River outburst flood events.

Tephrochronology

Several tephra beds are present within the loess and organic silts overlying the flood deposits in the Chester Bluff exposures. Only the two lowermost tephra beds are reported here because they constrain more precisely the age of the Charley River outburst flood events. One of these beds, the GI tephra, was previously recognized in the Fairbanks area (Preece et al., 1999). GI tephra occurs at site B approximately 8 m above the newly identified Charley River tephra that is also present at site A (Figs. 3 and 4E).

GI tephra consists mostly of colorless, bubble-wall glass shards with some brown glass and pumice fragments. Mineral grains, which are sparse, include feldspar, apatite, and orthopyroxene. This tephra bed belongs to the Type I group of Preece et al. (1999) and is derived from a vent in the Aleutian arc—Alaska Peninsula region (Fig. 1). Charley River tephra consists mostly of fine-grained pumiceous glass with a small amount of blocky, poorly vesicular glass. It is heavily contaminated with detrital minerals, but a few primary grains of feldspar, FeTi oxides, biotite, hornblende, orthopyroxene, and apatite were identified. These minerals suggest a Type II bed with a provenance in the Wrangell volcanic field of southeastern Alaska (Preece et al., 1999).

The glass composition of each of these two tephra beds is shown in Table 1 and Figure 6. Glass shards of GI tephra range from a rhyolitic to andesitic composition. Charley River tephra has a rhyolitic composition (Le Bas et al., 1986) and a very small intershard compositional range.

GI tephra was first identified in the Gold Hill Loess at Fairbanks, Alaska (Preece et al., 1999) and its presence at Chester Bluff is based on petrographic features and the composition of the glass and magnetite. Glass shards in the GI tephra at Fairbanks have the same composition as the dominant glass population (Fig. 6A, Pop. 2, Table 1) in the tephra (UT1666 and UT1743) at Chester Bluff. The less abundant, more Fe-rich glass shards in UT1666 and UT1743 at Chester Bluff have not been observed as yet in the GI tephra at Fairbanks (UT788), but equivalence of these two tephra beds is confirmed by their magnetite compositional data. GI tephra at Fairbanks contains two distinct titanomagnetite populations (Fig. 6C, Table 2)—exactly the same as those in the tephra bed (UT1666 and UT1743) at Chester Bluff.

The age of GI tephra (UT802) at Fairbanks was determined by the diameter-corrected fission-track (DCFT) method, using the rhyolitic glass shards (Sandhu and Westgate, 1995). The results are given in Table 3. The weighted mean age of two separate age determinations is 560,000 ±

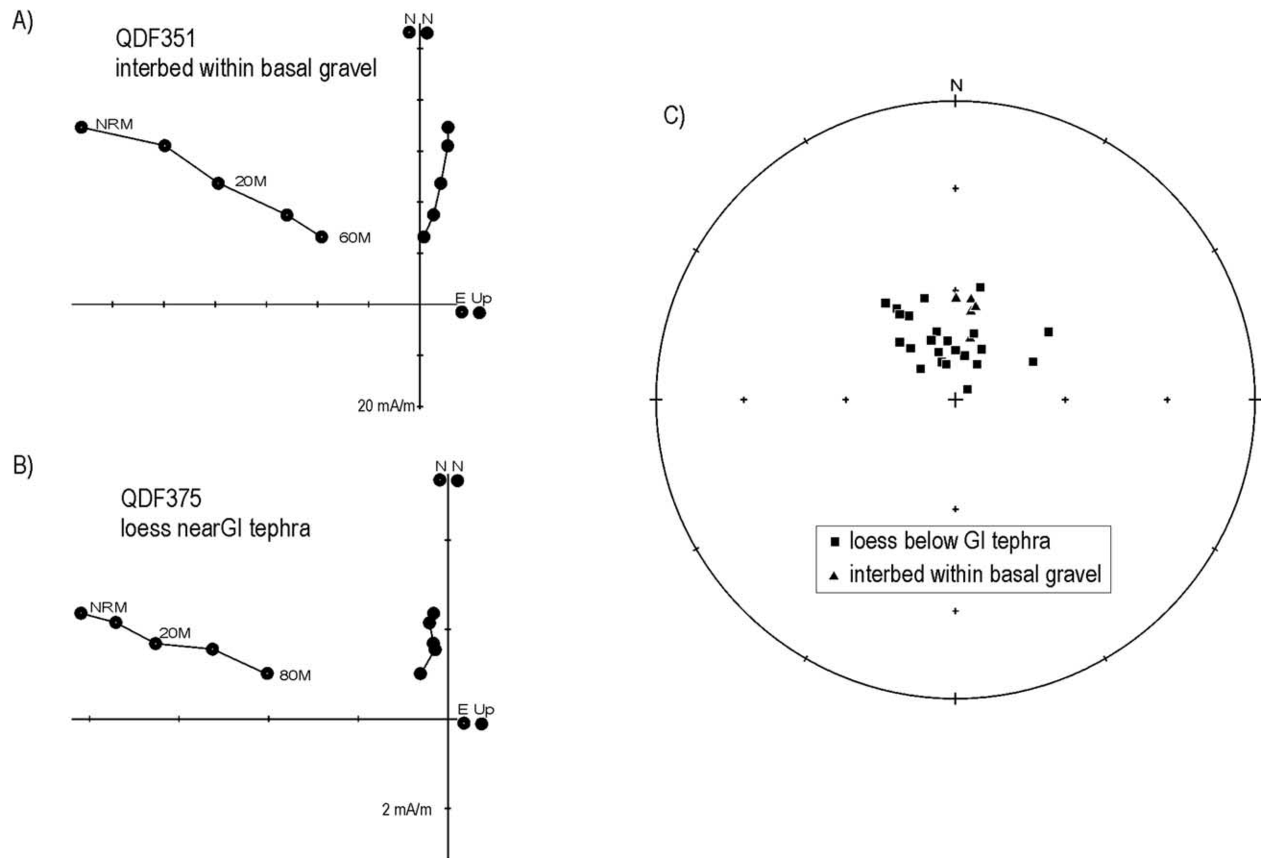

Fig. 5. Representative demagnetization characteristics of paleomagnetic samples. Orthogonal plots (A, B) show simple monocomponent demagnetization with normal polarity. The stereograph (C) plots magnetization directions for the samples below GI tephra and the lower interbed within the basal Yukon River gravel.

80,000 yr (1σ), which is consistent with the normal magnetic polarity of the enclosing sediment (Fig. 3). Further, the age obtained on the internal glass standard (Huckleberry Ridge tephra) points to an acceptable level of accuracy.

Paleoecology

Samples were analyzed for pollen and spore content in order to characterize the local and regional vegetation and

Table 1
Average major-element composition of glass shards of Tephra beds

Tephra location	GI Fairbanks	GI Chester Bluff			Charley River Chester Bluff
			Pop. 1	Pop. 2	
SiO_2	70.48 (0.28)	60.98	66.04 (0.58)	70.30 (0.58)	72.58 (0.26)
TiO_2	0.54 (0.12)	1.11	0.81 (0.11)	0.62 (0.12)	0.23 (0.09)
Al_2O_3	14.47 (0.11)	16.23	15.38 (0.14)	14.48 (0.18)	15.75 (0.13)
MgO	0.51 (0.05)	2.04	1.22 (0.08)	0.53 (0.09)	0.56 (0.03)
FeO_t	3.33 (0.14)	7.62	5.07 (0.25)	3.47 (0.23)	1.71 (0.11)
MnO	0.10 (0.03)	0.16	0.11 (0.06)	0.10 (0.06)	0.08 (0.04)
CaO	1.96 (0.08)	5.04	3.61 (0.12)	1.99 (0.22)	2.04 (0.09)
Na_2O	4.57 (0.13)	4.56	4.50 (0.14)	4.45 (0.14)	4.54 (0.14)
K_2O	3.84 (0.12)	2.18	3.11 (0.15)	3.85 (0.13)	2.44 (0.08)
Cl	0.21 (0.05)	0.10	0.15 (0.05)	0.20 (0.04)	0.07 (0.04)
$H2O_d$	3.39 (1.71)	2.00	2.00 (0.49)	4.46 (1.31)	5.67 (1.58)
n	14	1	8	28	48

All analyses done on a Cameca SX-50 wavelength-dispersive microprobe operating at 15-keV accelerating voltage, 10-μm beam diameter, and 6-nA beam current. Standardization achieved by use of mineral and glass standards. Analyses recast to 100% on a water-free basis. (#), standard deviation; *n,* number of analyses; FeO_t, total iron oxide as FeO; $H2O_d$, water by difference; Pop., glass shard population. Average composition in wt% based on the following samples: GI Fairbanks (UT788), GI Chester Bluff (UT1666, UT1743); Charley River tephra (UT1667, UT1677, UT1683, and UT1745).

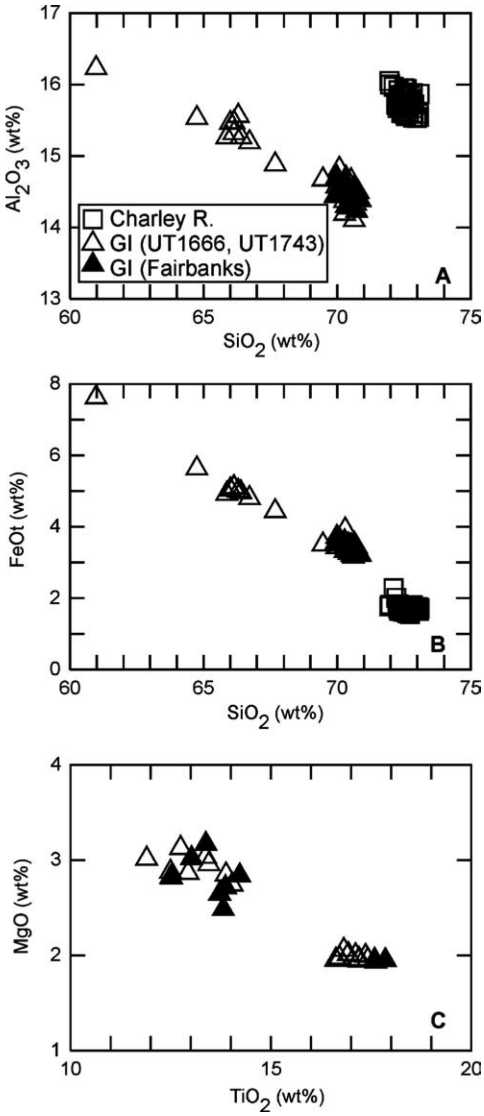

Fig. 6. Oxide variation diagrams showing compositions of glass and magnetite in GI and Charley River tephra beds, east-central Alaska. (A) Al_2O_3–SiO_2 plot for glass shards; Charley River tephra only known from Chester Bluff (see Fig. 3 and Table 1). (B) FeO_t–SiO_2 plot for glass shards. (C) MgO–TiO_2 plot for magnetites in GI tephra bed at Fairbanks and Chester Bluff.

climate at times when the organic-rich sediments were deposited. Eleven samples were collected from three organic-rich silt units at site A (Fig. 7). Samples 13a and 13b are from the lowermost organic-rich silt unit in the section (ca. 20.8–22.2 m above the base of the section). Sample 13a, the lower of the two samples, yielded a pollen and spore assemblage dominated by *Picea* pollen, with less abundant but significant amounts of *Betula, Alnus,* and Ericaceae pollen. Herbaceous plants such as Gramineae and Cyperaceae are represented by only a few percent of the pollen in the sample. The sample also contained a few fern (Polypodiaceae type) and moss spores (*Sphagnum*). Sample 13b has much the same assemblage as sample 13a, but *Picea* percentages are considerably lower, and *Betula* and Ericaceae percentages are higher. Both samples 13a and 13b appear to record an interglacial climate when boreal forest grew in the Charley River area, perhaps similar to that found in the region today. A change toward lower percentages of *Picea* pollen near the top of this silt unit suggests a shift, at least locally, to a more open forest, with a decline in spruce populations while deciduous trees and shrubs and Ericaceae increased in abundance. This may reflect climatic cooling near the end of an interglacial, or increased fire frequency.

A second group of productive samples was collected from an organic silt unit 26.8–27 m above the base of the section. All of the samples (samples 15–20, Fig. 7) contain pollen of *Picea, Betula, Alnus, Salix,* Ericaceae, Cyperaceae, Gramineae, and various herb types (e.g., Caryophyllaceae, Ranunculaceae, Saxifragaceae). *Picea* and *Betula* percentages decline, and percentages of *Salix*, Gramineae, Cyperaceae, and miscellaneous herbs increase, upward through the silt unit. The pollen assemblages suggest that boreal forest vegetation grew in the Charley River area during an interglacial or warm interstade. Declining percentages of *Picea* and *Betula* suggest that climate cooled as the silt accumulated. Cooling would explain the shift toward more open forest or forest tundra at the time the upper samples in this unit were deposited.

A third group of samples was collected from the uppermost organic silt unit in this section, from 31.1 to 32 m, associated with the Charley River tephra. The two lowermost samples (22 and 23) contain abundant Gramineae, *Betula, Alnus,* and Ericaceae pollen, *Picea* pollen is uncommon. These assemblages may record a predominantly deciduous forest-shrubland with few spruce trees. The sediments may have been deposited during an interstade, or during the early phase of an interglaciation, before spruce populations had become established locally. Sample 24, from near the top of the silt unit, contains a higher percentage of *Picea* pollen and slightly lower percentages of *Betula* and *Alnus* pollen in comparison to samples 22 and 23. Cyperaceae pollen percentages are also higher, and spore-producing plants (*Lycopodium*, Polypodiaceae, *Sphagnum*) are more abundant than in samples 22 and 23. The pollen assemblage suggests an open boreal forest composed of *Picea, Betula,* and *Alnus,* with Ericaceae and Cyperaceae forming much of the understorey. It suggests that interglacial or warm interstadial conditions had become established by the time sample 24 was deposited.

The three organic silt units at site A record three separate warm intervals during the middle Pleistocene. Interglacial or interstadial floras of this age have not previously been documented from interior Alaska. The composition of the pollen assemblages suggests that interglacial and interstadial floras of interior Alaska have changed little from the middle Pleistocene to the Holocene. This inference is supported by fossil evidence from 10 presumed interglaciations spanning the past two million years in adjacent Yukon Territory (Schweger et al., 1999).

Table 2
Average composition of magnetites in GI tephra

Tephra bed location	GI tephra (UT788) Fairbanks		GI tephra (UT1666, UT1743) Chester Bluff	
	Pop. 1	Pop. 2	Pop. 1	Pop. 2
SiO_2	0.24 (0.12)	0.13 (0.01)	0.16 (0.10)	0.20 (0.16)
TiO_2	13.51 (0.58)	17.72 (0.19)	13.04 (0.70)	17.10 (0.32)
Al_2O_3	3.00 (0.31)	2.12 (0.02)	3.14 (0.17)	2.13 (0.04)
Cr_2O_3	0.05 (0.03)	0.02 (0.00)	0.06 (0.03)	0.02 (0.02)
V_2O_3	0.58 (0.06)	0.34 (0.04)	0.59 (0.08)	0.32 (0.04)
Fe_2O_3	38.10 (1.51)	31.55 (0.19)	39.27 (1.36)	32.47 (0.57)
FeO	38.72 (0.49)	43.74 (0.25)	38.19 (0.83)	42.92 (0.93)
MgO	2.81 (0.23)	1.95 (0.00)	2.92 (0.12)	1.98 (0.04)
MnO	0.55 (0.04)	0.75 (0.03)	0.51 (0.05)	0.71 (0.05)
CaO	0.04 (0.02)	0.03 (0.02)	0.03 (0.02)	0.05 (0.05)
NiO	0.04 (0.01)	0.01 (0.02)	0.05 (0.02)	0.02 (0.03)
Total	97.60 (1.21)	98.37 (0.31)	97.93 (1.28)	97.92 (0.42)
FeO_t	73.01 (1.12)	72.13 (0.08)	73.53 (1.24)	72.13 (0.64)
n	7	2	9	10

All analyses (wt%) done on a Cameca SX-50 wavelength-dispersive microprobe operating at 15-keV accelerating voltage, 1-μm beam diameter, and 25-nA beam current. Standardization achieved by use of mineral and synthetic oxide standards. FeO and Fe_2O_3 calculated using Carmichael (1967). (#), standard deviation; *n*, number of analyses; FeO_t, total iron as FeO; Pop., magnetite population.

Sequence, age, and source of flood events

The presence of an interglacial sediment unit at 21 m, separating the rhythmites at Site A, indicates that the outburst floods occurred over two glacial cycles. By comparison with sedimentologically similar rhythmites (slackwater deposits) associated with outburst floods in Washington State (Waitt, 1980, 1985), we interpret each rhythmite as an individual flood event, representing the drainage of a glacial lake in the headwaters of the Charley River. This interpretation is supported by the presence of a small sand wedge on the surface of a rhythmite at Site A, indicating successive thermal contraction cracking, requiring several years of exposure (e.g., Murton et al., 2000) between at least two of the flood events.

Table 3
Glass-fission-track age of GI tephra

Sample number Analyst	Date irradiated	Spontaneous track density, 10^2 t/cm^2	Corrected spontaneous track density, 10^2 t/cm^2	Induced track density, 10^5 t/cm^2	Track density on muscovite detector over dosimeter glass, 10^5 t/cm^2	Etching conditions, HF:temp:time (%:°C:s)	D_s, μm	D_i, μm	D_s/D_i or D_i/D_s#	Age, 10^6 yr
GI tephra										
UT802 AS	31/01/00	5.00 ± 0.78 (41)		1.56 ± 0.02 (4850)	4.91 ± 0.04 (12744)	24:21.5:75	5.19 ± 0.12	6.29 ± 0.09	0.83 ± 0.02	0.50 ± 0.10
UT802*			6.05 ± 0.94 (41)	1.55 ± 0.02 (4850)	4.91 ± 0.04 (12744)	24:21.5:75	5.19 ± 0.12	6.29 ± 0.09	1.21 ± 0.03#	0.61 ± 0.13*
UT802 JAW	31/01/00	5.41 ± 0.76 (50)		1.94 ± 0.02 (8519)	4.91 ± 0.04 (12744)	24:21.5:75	5.19 ± 0.12	6.29 ± 0.09	0.83 ± 0.02	0.43 ± 0.08
UT802*			6.54 ± 0.93 (50)	1.94 ± 0.02 (8519)	4.91 ± 0.04 (12744)	24:21.5:75	5.19±0.12	6.29 ± 0.09	1.21±0.03#	0.53 ± 0.10*
								Weighted mean age		0.56 ± 0.08
Huckleberry Ridge tephra; internal standard										
UT1094 JAW	31/01/00	43.23 ± 1.42 (931)		4.21 ± 0.03 (25152)	4.87 ± 0.04 (12744)	24:21:120	6.09 ± 0.07	7.54 ± 0.09	0.81 ± 0.01	1.59 ± 0.17
UT1094*			53.57 ± 1.76 (931)	4.20 ± 0.03 (25152)	4.87 ± 0.04 (12744)	24:21:120	6.09 ± 0.07	7.54 ± 0.09	1.24 ± 0.02#	1.97 ± 0.21*

The population-subtraction method was used. Samples with asterisk symbol corrected for partial track fading by the track-size (DCFT) method (Sandhu and Westgate, 1995); the uncorrected age is simply noted by the sample number. Ages calculated using the zeta approach and $\lambda_D = 1.551 \times 10^{-10}$ yr^{-1} Zeta value is 318 ± 3 based on 6 irradiations at the McMaster Nuclear Reactor, Hamilton, Ontario, using the NIST SRM 612 glass dosimeter and the Moldavite tektite glass (Lhenice locality) with an $^{40}Ar/^{39}$ Ar plateau age of 15.21 ± 0.15 × 10^6 yr (Staudacher et al., 1982). Standard error ($\pm 1\sigma$) on age estimate is calculated according to Bigazzi and Galbraith (1999). Area estimated using the point-counting method (Sandhu et al., 1993). D_s, mean spontaneous track diameter; D_i, mean induced track diameter; AS, Amanjit Sandhu; JAW, John Westgate. Number of tracks counted is given in parentheses. The single-crystal (sanidine) laser-fusion $^{40}Ar/^{39}$ Ar age of Huckleberry Ridge tephra is 2.003 ± 0.014 × 10^6 yr (2σ) (Gansecki et al., 1998).

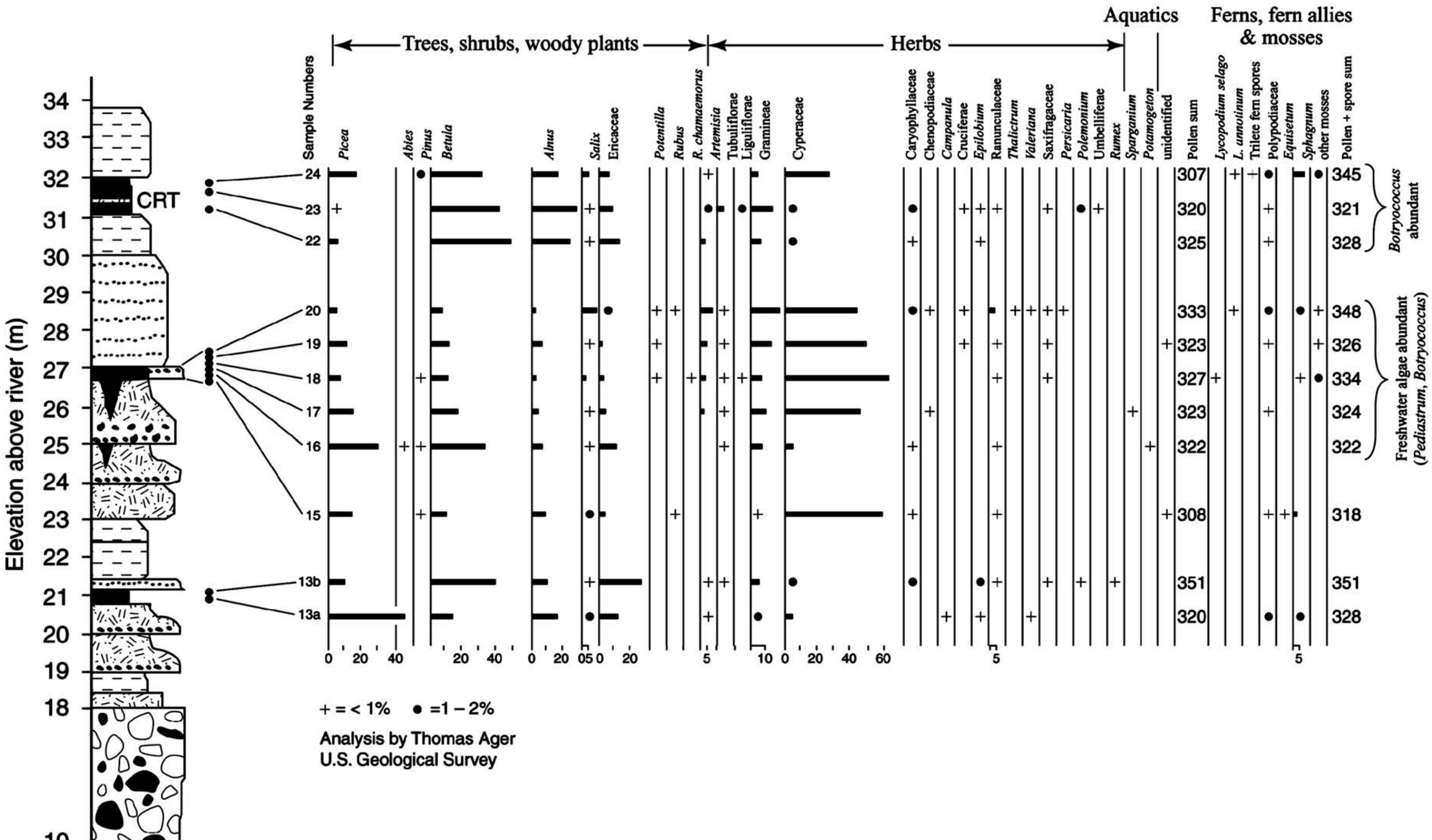

Fig. 7. Pollen and spores recovered from organic silt units at site A.

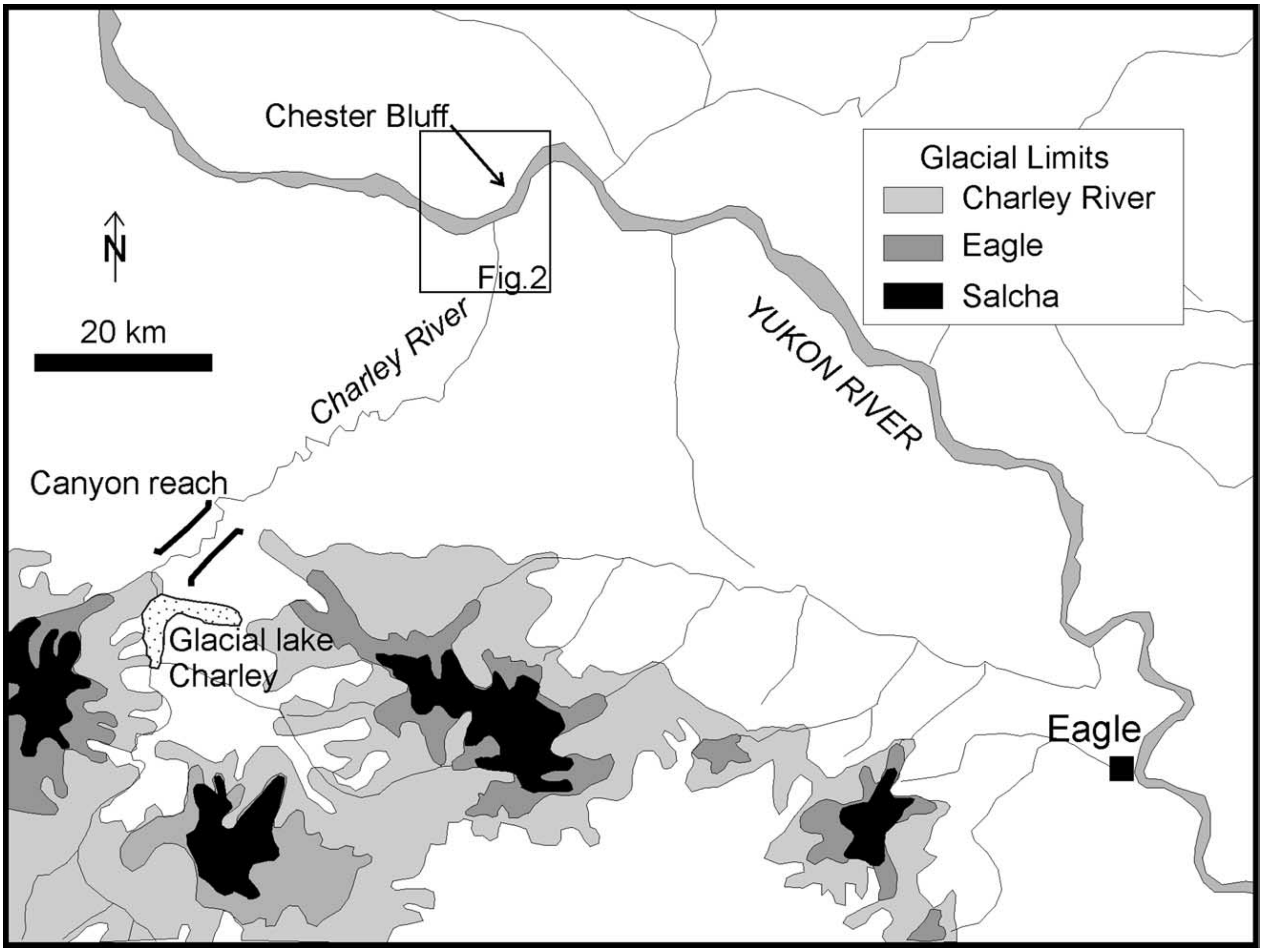

Fig. 8. Glacial limits in the Yukon Tanana Upland after Duk-Rodkin et al. (in press) and location of glacial lake Charley that likely produced the recurring outburst floods recorded at Chester Bluff.

The most complete sequence of flood events is recorded at site E, which is the furthest upvalley. The section at site E contains at least eight rhythmites, each of which is interpreted as a separate flood. The two rhythmites above 24 m at site D are not exposed at site E, indicating that there were at least 10 events. The lack of an interglacial unit at site E makes it unclear whether the site E rhythmites are associated with the earlier glaciation or the later glaciation recorded at Site A. In sum, it can be established that there are at least 10 events, at least two of which are associated with an earlier glaciation, and at least three during a subsequent glaciation.

The Yukon-Tanana Upland was repeatedly glaciated during the Quaternary (Weber, 1986). Small lakes formed along ice margins during the Mt. Harper, and to a lesser extent Eagle and Salcha glaciations (Weber, 1986). However, during the Charley River Glaciation, large proglacial lakes formed as valley glaciers blocked local drainage (Weber, 1986). One prominent lake, located above the lower canyon of the Charley River, formed when ice advanced from the upland to the west blocking the main stem of the river (Fig. 8). We refer to this lake as glacial lake Charley (Fig. 8). On the basis of regional mapping by one of us (Weber) we infer that repeated drainage of this lake is the most probable source of the floods that deposited the rhythmites at Chester Bluff.

The presence of GI tephra 15 m above the rhythmites at site B provides a minimum age of 560,000 ± 80,000 yr for the floods. A maximum age of 780,000 yr is provided by the normal polarity of the sediments. This constrains the flood deposits between 560,000 ± 80,000 and 780,000 yr ago, and therefore makes them of early-middle Pleistocene age.

The Charley River glaciation was the most extensive Pleistocene advance in the Yukon-Tanana Upland (Weber, 1986), and on the basis of cosmogenic ages, the advance is older than 150,000 yr, the minimum age for the more restricted Mount Harper Glaciation (Manley et al., 2002). Weber (1986) estimated the age of the Charley River Glaciation as early Pleistocene, and a stratigraphically lower till as possibly being of Pliocene age. Duk-Rodkin et al. (in press), however, suggest that both of these advances are of Brunhes age (<780,000 yr) based on normal magnetic polarity of the two tills, and moderate soil development relative to late Pliocene and early Pleistocene paleosols in adjacent central Yukon. This suggests that the Charley River Glaciation moraine is a composite moraine of at least two glacial advances of about the same extent during the early Brunhes (Duk-Rodkin et al., in press). The present study is consistent with these observations and Weber's (1986) suggestion that the Charley River Glaciation included at least two advances. Following that work, we suggest that the outburst floods inferred from the rhythmites at Chester Bluff are a record of extensive glaciation of the Yukon-Tanana Upland during the early-middle Pleistocene, probably represented by these two advances.

Conclusions

Rhythmite deposits exposed along Chester Bluff record the abrupt drainage of glacial lakes in the headwaters of the Charley River. Evidence for subaerial exposure between rhythmites indicates that multiple flood events occurred during a single glacial cycle; and interglacial sediment between rhythmites extends the flood events over at least two glacial cycles. The age of the flooding is constrained by paleomagnetism and a new fission-track age on the GI tephra, previously only known from the Fairbanks area. The tephra age indicates that flooding occurred prior to 560,000 +/− 80,000 yr ago and, on the basis of normal magnetism of the associated sediments, is assigned to the Brunhes Chron (<780,000 yr ago). The newly identified Charley River tephra, derived from a vent in the Wrangell Mountains of southeastern Alaska, predates GI tephra and also occurred during the Brunhes Chron (<780,000 yr ago). A probable source for the flood events is glacial lake Charley that formed when ice reached the extent of the Charley River Glaciation of Weber (1986). Together, these observations suggest that the early-middle Pleistocene was a time of extensive, and probably the most extensive, glaciation of the Yukon-Tanana Upland.

Acknowledgments

Financial support was provided by the Natural Science and Engineering Research Council of Canada to D.S. and J.W. This research would not have been possible without a research permit from the U.S. National Park Service for work in Yukon Charley Rivers National Preserve. In particular, we acknowledge the help of Cyd Martin and Patty Rost of the National Park Service. Field assistance was provided by John Laughton, Gary Parkstrom, Nadine Raynolds, and Richard Norman. An earlier version of this manuscript benefited from the constructive comments of John Clague, Dan Muhs, and Robert Thompson, and official journal reviews by Jim Begét and Robert Thorson.

References

Begét, J.E., 2001. Continuous late Quaternary proxy climate records from loess in Beringia. Quaternary Science Reviews 20, 499–507.

Bigazzi, G., Galbraith, R.F., 1999. Point-counting technique for fission track dating of glass shards, and its relative standard error. Quaternary Research 51, 67–73.

Brabetts, T.B., Wang, B., Meade, R.H., 2000. Environmental and hydrologic overview of the Yukon River basin, Alaska and Canada, Investigations Report 99–247. United States Geological Survey. Water Resources.

Carmichael, I.S.E., 1967. The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates. Contributions to Mineralogy and Petrology 14, 36–64.

Duk-Rodkin, A., 1999. Glacial limits map of Yukon Territory, Geological Survey of Canada Open File 3694.

Duk-Rodkin, A., Barendregt, R.W., Froese, D.G., Weber, F., Enkin, R., Smith, R., Zazula, G.D., Waters, P., Klassen, R., 2003. Timing and extent of Plio-Pleistocene glaciations in northwestern Canada and east-central Alaska. Quaternary Science Reviews.

Froese, D.G., 2001. Eastern Beringia paleoclimate from eolian and fluvial deposits, Plio-Pleistocene middle Yukon River, central Yukon and Alaska. Unpublished Ph.D. thesis, University of Calgary.

Froese, D.G., Barendregt, R.W., Enkin, R.J., Baker, J., 2000. Paleomagnetic evidence for multiple late Pliocene-early Pleistocene glaciations in the Klondike area, Yukon Territory. Canadian Journal of Earth Sciences 37, 863–877.

Gansecki, C.A., Mahood, G.A., McWilliams, M., 1998. New ages for the climactic eruptions at Yellowstone: single-crystal $^{40}Ar/^{39}Ar$ dating identifies contamination. Geology 26, 343–346.

Gerard, R., 1984. Yukon River Freeze-up and Break-up Study. Yukon River Basin Study Hydrology Report No. 4, unpublished report Inland Waters Directorate, Environment Canada.

Gerard, R., Jasek, M., Hicks, F., 1992. Ice-jam Flood Assessment, Yukon River at Dawson. Unpublished Report Indian and Northern Affairs Canada, Whitehorse, Yukon.

Hamilton, T.D., 1994. Late Cenozoic glaciation of Alaska, in: Plafker, G., Berg, H.C. (Eds.), The Geology of Alaska, Geological Society of America, Boulder, CO, pp. 813–844.

Kirschvink, J., 1980. The least-squares line and plane and the analysis of paleomagnetic data. Geophysical Journal of the Royal Astronomical Society 62, 699–718.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanellin, B., 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology 27, 745–750.

Manley, W.F., Briner, J.P., Lubinski, D.J., Caffee, M.W., 2002. Glacial history, surface exposure ages, and paleo-ELA's of the Yukon-Tanana Upland: preliminary Results. 32nd Annual Arctic Workshop Abstracts, Boulder, CO.

Murton, J.B., Worsley, P., Gozdzik, J., 2000. Sand veins and wedges in cold aeolian environments. Quaternary Science Reviews 19, 899–922.

Péwé, T.L., 1975. Quaternary Geology of Alaska. United States Geological Survey Professional Paper 835.

Preece, S.J., Westgate, J.A., Stemper, B.A., Pewe, T.L., 1999. Tephrochronology of late Cenozoic loess at Fairbanks, central Alaska. Geological Society of America Bulletin 111, 71–90.

Preece, S.J., Westgate, J.A., Alloway, B.V., Milner, M.W., 2000. Characterization, identity, distribution, and source of late Cenozoic tephra beds in the Klondike District of the Yukon, Canada. Canadian Journal of Earth Sciences 37, 983–996.

Sandhu, A.S., Westgate, J.A., Alloway, B.V., 1993. Optimizing the isothermal plateau fission track dating method for volcanic glass shards. Nuclear Tracks 21, 479–488.

Sandhu, A.S., Westgate, J.A., 1995. The correlation between reduction in fission-track diameter and areal track density in volcanic glass shards and its application in dating tephra beds. Earth and Planetary Science Letters 131, 3–4.

Schweger, C.E., White, J.M., Froese, D.G., 1999. Preglacial and interglacial pollen records from central and northern Yukon: 3 Ma of forest history. Canadian Quaternary Association Biannual Meeting, Program and Abstracts, Calgary, Alberta, p.34.

Staudacher, T.H., Jessberger, E.K., Dominik, B., Kirsten, T., Schaeffer, O.A., 1982. ^{40}Ar-^{39} Ar ages of rocks and glasses from the Nördlinger Ries Crater and the temperature history of impact breccias. Journal Geophysics 51, 1–11.

Waitt, R.B., 1980. About forty last-glacial Lake Missoula jokuhlhaups through southern Washington. Journal of Geology 88, 653–679.

Waitt, R.B., 1985. Case for periodic, colossal jokulhlaups from Pleistocene glacial Lake Missoula. Geological Society of America Bulletin 96, 1271–1286.

Weber, F.R., 1986. Glaciation of the Yukon-Tanana Upland, in: Hamilton, T.D., Reed, K.M., Thorson, R.M. (Editors), Glaciation in Alaska-The Geologic Record, Alaska Geological Society, pp. 79–98.

Weber, F.R. Hamilton T.D., 1984. Glacial geology of the Mt. Prindle area, Yukon-Tanana Upland, Alaska, Short Notes on Alaskan Geology 1982: Alaska Division of Geological and Geophysical Surveys Professional Report 86, pp. 42–48.

Westgate, J.A., Stemper, B.A., Péwé, T.L., 1990. A 3 m.y. record of Pliocene-Pleistocene loess in interior Alaska. Geology 18, 858–861.

Westgate, J.A., Preece, S.J., Froese, D.G., Walter, R.C., Schweger, C.A., 2001. Tephrochronology dates two extensive glaciations in Yukon Territory. Quaternary Research 56, 288–306.