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Full-glacial paleosols in perennially frozen loess sequences, Klondike goldfields, Yukon Territory, Canada

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Abstract

Perennially frozen loess deposits in the Klondike goldfields include paleosols formed in full-glacial environments, correlated by Alaskan distal tephra with Marine Isotope Stages (MIS) 2 and 4. Patterns of organic and inorganic carbon and clay distribution, microstructures, and profile morphologies indicate that soil formation occurred in a base-rich environment in which organic matter accreted predominantly as root detritus. At sites approximately 20 km apart, the expression of cryoturbation and ice wedge development decreases in strength upward in loess–paleosol sequences correlated with MIS 4, suggesting increasing aridity. Configurations of cryoturbation features and ice-wedge thaw unconformities, the presence of numerous ground squirrel burrows, and an absence of peat accumulation suggest that these substrates were predominantly well-drained, with active layers of equal or greater thickness than in modern soils on similar sites in the west-central Yukon. Some characteristics of these paleosols are similar to those of modern steppe and tundra soils, consistent with plant macrofossil evidence for local ecological diversity during full-glacial conditions in eastern Beringia.

Keywords: Beringia; Cryoturbation; Loess; Paleosols; Permafrost; Soil micromorphology; Steppe; Tephra; Tundra

Introduction

Paleoenvironmental reconstructions of Beringia during the last and earlier glaciations are based primarily on fossil biological evidence, including pollen, plant macro-remains, insects and megafauna, and have been used to support inferences about other ecosystem components such as soils (Cwynar and Ritchie, 1980; Ritchie and Cwynar, 1982; Guthrie, 1990; Zazula et al., 2005). The central importance of soils has been recognized in conceptual models of Beringian full-glacial ecosystems (Guthrie, 1990; Schweger, 1997), but there have been only limited direct paleopedological data to support these paleoenvironmental reconstructions. Full-glacial paleosols preserved under ca. 21,500 cal yr BP tephra on the northern Seward Peninsula in Alaska were interpreted as having formed in a climate that was cooler and drier than at present, with active loess deposition (Höfle and Ping, 1996; Höfle et al., 2000). Loess–paleosol sequences in central Alaska record several glacial–interglacial cycles, and research has emphasized loess provenance and accumulation rates, criteria for recognizing and classifying paleosols, and the interglacial record of paleosols, but it has not yet addressed the pedological characteristics of full-glacial environments (e.g., Muhs et al., 2000, 2003).

In the Klondike goldfields of west-central Yukon Territory, perennially frozen deposits contain a rich record of Pleistocene flora and fauna preserved in primary and redeposited loess, with chronological control provided by numerous distal tephra beds derived from vents in southern Alaska (Preece et al., 2000; Froese et al., 2001, 2002). The occurrence of full-glacial paleosols in these sediments has been reported (Fraser and

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Burn, 1997), but their characteristics, origins and paleoenvironmental significance have not been addressed previously. This paper presents data on the morphological, physical, and chemical properties of these full-glacial paleosols, interprets their genesis in relation to modern analogues, and demonstrates their regional nature.

Regional setting and study site locations

Perennially frozen organic matter-rich silty sediments, known as "muck" deposits, are preserved in valley bottoms and on north or north-east slope aspects in the Klondike goldfields of unglaciated west-central Yukon Territory (Fraser and Burn, 1997; Kotler and Burn, 2000) and central Alaska (Péwé, 1975). In central Yukon, radiocarbon ages indicate that muck aggradation was pronounced near the onset of the last glaciation, ca. 25,000 yr BP, associated with deteriorating climates that were conducive to loess entrainment and redistribution (Froese et al., 2002; Zazula et al., 2005). The occurrence of older tephra beds within muck deposits indicates several intervals of loess accumulation associated with previous glacial intervals (Westgate et al., 2001).

Paleosols and associated sediments were examined in muck deposits at two placer gold mines approximately 20 km apart: Tatlow Camp (63°49′19”N 139°1′41′′W) on Quartz Creek and the Christie Mine (63°39′59′′N 138°38′42′′W) on lower Dominion Creek (Fig. 1). On the basis of major element chemistry of glass shards, tephras at the Christie Mine and in deeper strata at Tatlow Camp are correlated with the Sheep Creek K (SCt-K) and Dominion Creek tephras (DCt) (Westgate and Preece, 2005). Dominion Creek tephra has a glass fission track age of 82,000 ± 9000 yr and occurs in close association with the SCt-K tephra, indicating that it is a much younger eruption than the better known Sheep Creek Fairbanks occurrence (Westgate et al., 2001; Westgate and Preece, 2005). Based on this chronology, paleosols associated with SCt-K and DCt are correlated to early marine isotope stage (MIS) 4, while the Dawson tephra, dated to 24,000 ^{14}C yr BP is associated with early MIS 2 (Froese et al., 2002).

Methods

Paleosol horizons and associated sediments were described and sampled in 2003 and 2004 at exposures created by recent placer mining. Morphological descriptions (Appendix A) used soil horizon designations and descriptive terminology according to the Canadian System of Soil Classification (Soil Classification Working Group, 1998) and the Expert Committee on Soil Survey (1983). Bulk soil samples for physical and chemical characterization were collected from freshly cleaned sections in a partially or completely thawed condition and dried at room temperature prior to analysis. Laboratory analyses consisted of particle-size analysis by the pipette method (Gee and Bauder, 1986) following removal of organic matter and carbonates, total carbon and nitrogen (Fisons NA1500 NC analyzer), and inorganic carbon (Bundy and Bremner, 1972). Organic C was

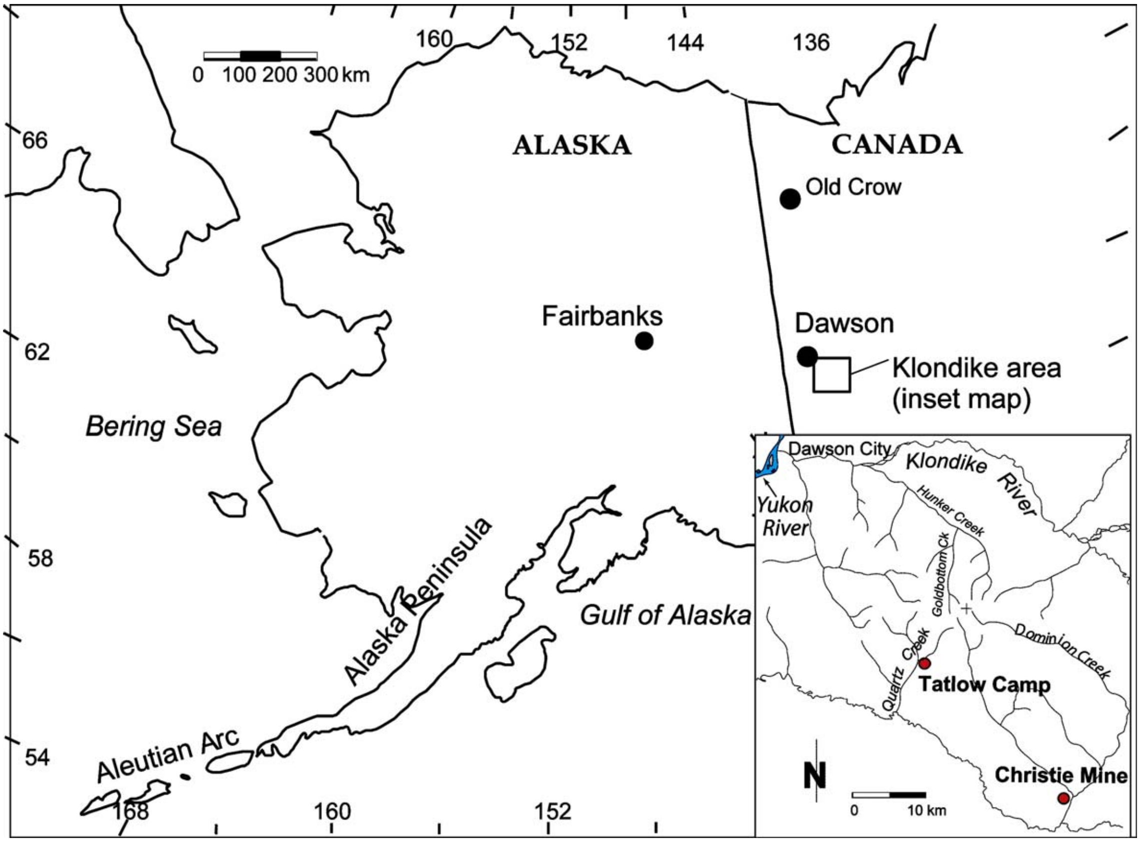

Figure 1. Study site locations.

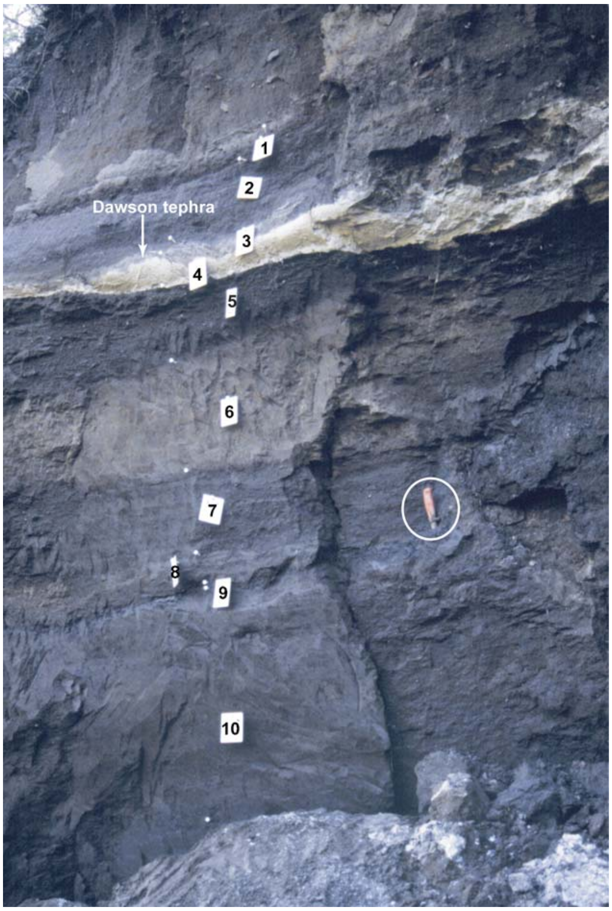

Figure 2. Overview of section at site 1, Tatlow Camp, Quartz Creek, with horizon numbering as in Table 1. Knife handle (circled) is 10 cm long.

calculated as the difference between total and inorganic C. Total elemental concentrations were determined on whole samples by X-ray fluorescence. Intact samples of representative portions of eight paleosol horizons were freeze-dried, impregnated with epoxy resin, and thin sectioned (30 μm) for micromorphological study with a petrographic microscope.

Results

At Tatlow Camp on Quartz Creek, two distinct loess–paleosol sequences were studied at sites approximately 100 m apart. At each site, the tephra could be traced about 25 m laterally while detailed soil descriptions and sampling were completed at exposures cleaned laterally for at least 2 m. At site 1, a 2.5-m-thick section includes several dark brown to black buried A horizons (5–30 cm thick) both above and below the Dawson tephra (Fig. 2; Appendix A). The generally smooth or planar horizon boundaries range from gradual to abrupt, and the multiple buried A horizons are approximately parallel, without apparent cross-cutting erosional contacts. Herbaceous roots occur as turf-like concentrations within these horizons, as well as disseminated at lower densities throughout the intervening grayish silty materials, but there are no horizons with sufficiently high concentrations of organic matter to be designated as peat (17% organic C) in the Canadian System of Soil Classification (Soil Classification Working Group, 1998). Numerous incipient A horizons (<1 cm thick) occur within the grayish Ck horizons, with slightly darker colors suggesting localized organic matter enrichment. Mottles are absent from all horizons. Except for the Dawson tephra layer, all horizons are moderately effervescent when tested in the field with dilute HCl.

At the second site at Tatlow Camp, three major paleosols occur in a sequence 2.5–3.0 m thick, and although horizons with darker colors suggest higher organic matter concentrations, no peat layers are present (Appendix A). The uppermost paleosol (soil 1) consists of a 20-cm-thick, weakly effervescent black A horizon similar in morphology to the multiple buried A horizons at site 1. Approximately 1.5–2.0 m of grayish silty sediments, containing thin (~1 cm thick) incipient A horizons, separate soils 1 and 2. Soil 2 averages 40 cm in thickness and

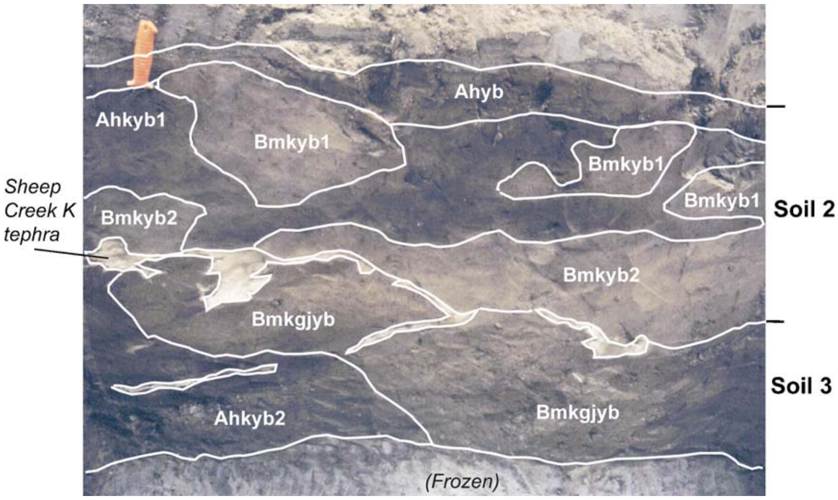

Figure 3. Soils 2 and 3 as exposed in July 2004 at site 2, Tatlow Camp, Quartz Creek, corresponding to 7 lowest horizons for this site listed in Table 1. Knife handle is 10 cm long. Both soils 2 and 3 are strongly cryoturbated, producing discontinuous horizonation typical of Turbic Cryosols. Cryoturbation has reworked the layer of Sheep Creek K tephra, that separates soil 3 from soil 2, into discontinuous streaks and pods. In soil 2, all horizons are buried (b), calcareous (k) and cryoturbated (y). Additionally in soil 3, evidence of weak mottling (gj) exists in the lower Bmk horizons.

directly overlies soil 3, which was exposed more completely in 2004 (Fig. 3; Appendix A). Mottling is present only in portions of the B horizon of soil 3. Both paleosols are morphologically complex, with irregular and occasionally broken boundaries. Dominion Creek tephra is partially incorporated in the Ahkyb of soil 2, and more distinct multiple layers of Sheep Creek K tephra directly overlie and are incorporated within both A and B horizons of soil 3 (Fig. 3). Ice wedges up to 3 m wide and approximately 10 m apart are truncated below soil 3, while much smaller (up to 1 m width) secondary and tertiary wedges cross-cut soils 1 and 2.

At the Christie Mine, 20 km to the southeast, lateral variability was examined along approximately 50 m of exposures that display a sequence of paleosols and tephra that is strikingly similar to the second Tatlow Camp site (Fig. 4; Appendix A). The uppermost paleosol (soil 1) consists of a strongly effervescent black to dark gray A horizon, 1.5 to 2.0 m above two more morphologically complex paleosols containing Dominion Creek and Sheep Creek K tephras, respectively (Fig. 4). As at Tatlow Camp, soils 2 and 3 displayed considerable irregularity in their horizon boundaries. Fine and very fine roots are abundant throughout this sequence of loess and paleosols. Within soil 2, Dominion Creek tephra occurs as discontinuous lenses approximately 1 cm thick in an A horizon with a complex pattern of involuted zones of varying organic matter content (Fig. 4). The upper boundary of soil 3 is highlighted by the Sheep Creek K tephra and displays a crudely undulating pattern with a lateral separation of 30–50 cm between the elevated points in the microtopography with 10–20 cm of relief (Fig. 4). Where soils 2 and 3 are exposed together, they are of approximately equal thickness, totalling approximately 1 m. Ice wedges 1–2 m wide have disrupted the two lower paleosols along the ice wedge margins but do not extend as far up section as soil 1. The complex ice wedges were partially truncated by the paleo-active layers of soils 2 and 3, containing prominent thaw unconformities 40–70 cm below the upper surfaces of these paleosols.

At all three sites, particle size distributions for all horizons are dominated by silt (mean = 76%, standard deviation = 6.2%). Virtually all of the sand is finer than 0.25 mm, and mean clay concentrations are 10.8% (standard deviation = 3.4%) (Table 1). Total C concentrations averaged 3.2%, of which inorganic C comprised 0.28%, equivalent to 2.4% $CaCO_3$. Organic C concentrations are strongly correlated with loss on ignition ($r^2 = 0.82$, $P < 0.001$; data not shown). Paleosol A horizons have

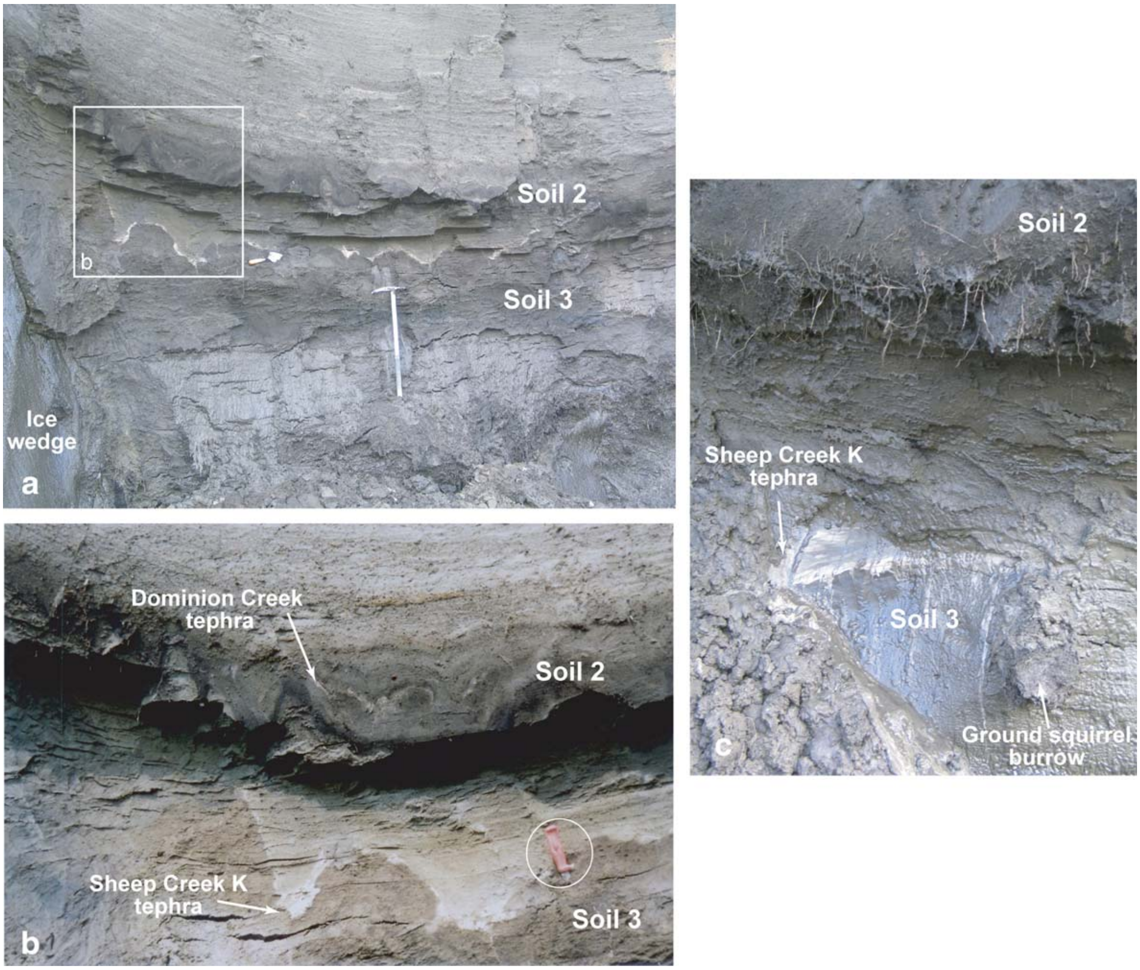

Figure 4. Soils 2 and 3 as exposed in July 2004 at Christie Mine, Dominion Creek: (a) overview, and (b) detail view, with knife handle (circled; 10 cm long) for scale. August 2003 view (c) of soils 2 and 3, indicating Sheep Creek K tephra and ground squirrel burrow. Horizons listed in Table 1 were sampled from a different portion of the exposure available in 2003.

Table 1
Selected analytical data for loess–paleosol sequences, Tatlow Camp (Quartz Creek) and Christie Mine (Dominion Creek)

Sample No.	Horizon/Unit	Depth	%											C_o/N	CaO/TiO_2	Na_2O/TiO_2	K_2O/TiO_2	Ti/Zr
			Sand	Silt	Clay	C_o	C_i	N	CaO	Na_2O	K_2O	P_2O_5	TiO_2					
Tatlow Camp, Quartz Creek, site 1																		
1	Ahkb1	0–7	19.6	66.1	14.3	5.3	0.59	0.47	6.97	2.08	2.13	0.33	0.91	11.3	7.69	2.29	2.35	19.9
2	Ck1	7–33	8.5	80.7	10.8	2.7	0.38	0.28	4.75	2.29	2.13	0.26	0.90	9.7	5.27	2.54	2.36	18.0
3	Ck2	33–41	18.2	74.9	6.9	1.0	0.33	0.11	3.85	3.14	2.68	0.16	0.65	8.8	5.92	4.82	4.11	12.3
4	Dawson tephra	41–50	24.0	73.4	2.6	0.2	0.02	0.02	1.66	4.48	3.68	0.04	0.29	8.9	5.68	15.32	12.57	5.1
5	Ahkb2	50–65	15.4	72.4	12.2	2.2	0.49	0.24	5.39	2.12	1.98	0.24	0.93	9.2	5.81	2.29	2.13	18.0
6	Ck3	65–107	15.0	74.7	10.3	1.8	0.37	0.17	5.23	2.18	1.89	0.24	0.92	10.8	5.66	2.36	2.05	17.2
7	Ahkb3	107–135	13.6	76.5	9.9	2.1	0.40	0.22	5.26	2.27	1.92	0.24	0.93	9.5	5.63	2.43	2.06	17.1
8	Ck4	135–147	16.4	73.4	10.2	1.6	0.44	0.17	5.39	2.25	1.88	0.24	0.89	9.2	6.04	2.52	2.11	17.6
9	Ahkb4	147–149	12.5	78.8	8.7	1.7	0.40	0.17	5.25	2.18	1.82	0.23	0.85	10.0	6.14	2.54	2.13	17.1
10	Ck5	149–231	14.6	73.4	12.0	2.1	0.39	0.22	5.18	2.16	1.96	0.23	0.92	9.6	5.65	2.36	2.14	19.2
Tatlow Camp, Quartz Creek, site 2																		
1	Ahkb1 (S1)	0–20	5.7	83.6	10.7	3.7	0.16	0.36	3.98	1.91	2.00	0.26	0.83	10.4	4.81	2.30	2.41	16.5
2	Ck	20–150	7.7	84.6	7.8	2.2	0.39	0.20	4.69	2.08	1.95	0.24	0.84	11.0	5.60	2.48	2.32	17.3
3	Ahkb2	*	5.5	86.6	7.9	2.2	0.51	0.21	5.26	2.13	1.92	0.24	0.83	10.4	6.32	2.55	2.30	18.4
4	Ahkyb (S2)	150–180	5.9	80.7	13.4	5.9	0.19	0.52	5.07	2.22	1.96	0.27	0.91	11.4	5.58	2.44	2.16	21.2
1	Ahyb (S2)	0–9	5.0	81.1	13.9	5.8	0.10	0.58	4.25	2.14	2.17	0.29	0.89	10.1	4.77	2.41	2.43	19.4
2	Ahkyb1 (S2)	9–33	4.6	81.2	14.3	6.3	0.12	0.58	4.90	2.06	1.92	0.29	0.91	10.8	5.39	2.27	2.11	21.3
3	Bmkyb1 (S2)	5–25	5.6	84.6	9.8	2.9	0.18	0.32	4.59	2.27	1.81	0.21	0.88	9.2	5.22	2.58	2.06	22.1
4	Bmkyb2 (S2)	33–44	6.5	83.6	9.9	2.5	0.20	0.28	4.87	2.54	1.78	0.23	0.89	9.1	5.45	2.84	1.99	24.2
5	SCt-K	44–46	28.9	67.4	3.7	1.2	0.15	0.11	5.57	3.62	1.76	0.20	0.56	10.4	9.89	6.43	3.13	24.4
6	Ahkyb2 (S3)	46–60+	14.2	74.2	11.7	3.2	0.14	0.28	3.87	2.14	1.66	0.24	0.95	11.4	4.06	2.25	1.74	17.7
7	Bmkgjyb (S3)	46–60+	23.6	63.9	12.5	1.5	0.07	0.12	3.21	2.22	1.48	0.14	0.96	12.5	3.36	2.32	1.54	15.0
Christie Mine, Dominion Creek																		
1	Ahkb (S1)	0–20	6.3	86.6	7.1	2.5	0.44	0.26	4.23	2.14	2.17	0.29	0.89	9.5	4.74	2.41	2.43	15.6
2	Ck1	20–90	16.0	78.6	5.4	1.1	0.52	0.12	4.65	2.00	1.86	0.21	0.80	9.0	5.81	2.51	2.33	16.2
3	Ck2	90–200	14.0	79.5	6.5	1.8	0.43	0.17	4.59	2.09	1.90	0.23	0.82	10.4	5.57	2.54	2.30	16.9
4	Ahkyb (S2)	200–220	11.8	76.8	11.4	3.5	0.11	0.33	3.72	2.16	2.06	0.28	0.86	10.6	4.34	2.51	2.41	18.4
5	Ck3	220–260	16.5	76.4	7.1	2.2	0.23	0.22	4.20	2.31	1.81	0.23	0.83	9.9	5.08	2.79	2.18	19.4
6a	Ahkyb2-1 (S3)	10–27	14.2	70.4	15.4	5.6	0.06	0.47	3.99	2.04	1.90	0.31	0.88	12.0	4.51	2.31	2.15	19.0
6b	Ahkyb2-2 (S3)	27–45	13.0	70.6	16.4	7.0	0.17	0.57	4.43	2.06	1.99	0.36	0.90	12.3	4.90	2.27	2.21	19.3
7	Ck4	45–70+	20.3	67.5	12.2	2.7	0.08	0.28	2.89	2.01	1.98	0.22	0.83	9.7	3.46	2.41	2.37	17.2

Abbreviations: S1–S3 = MIS 4 paleosols; C_o = organic carbon; C_i = inorganic carbon; SCt-K = Sheep Creek K tephra. Elemental analyses (CaO, Na_2O, K_2O, P_2O_5, TiO_2) expressed on volatile-free basis.

* Multiple discontinuous dark bands 10–30 cm thick dispersed through Ck.

organic C concentrations ranging up to 7%, usually accompanied by lower concentrations of inorganic C than in the intervening gray silty layers. Both organic C and clay concentrations are highest in paleosol A horizons, and these properties are strongly correlated across all samples not consisting primarily of tephra (r^2 = 0.63, $P < 0.001$; Fig. 5). The ratio of organic C : N varied within a narrow range (8.8–12.5) with no clear pattern in relation to soil horizon type.

Except for horizons influenced by tephra, abundances of mobile major elements (Ca, Na, K) show little variation, whether expressed as concentration or as ratios with immobile elements such as Ti (Table 1) or Zr (not shown). Total phosphorus concentrations show a similar pattern of variation as organic C concentrations (r^2 = 0.47, $P < 0.001$). Ti/Zr ratios of all horizons average 18 and vary in a narrow range (17–24), except for horizons containing the Dawson tephra (Table 1).

Although soil structure was not readily apparent in the field, thin sections of paleosol A horizons at all three sites reveal predominantly granular and/or platy microstructural units, either well-defined or coalesced in varying degrees to form a spongy fabric composed of intermixed silt-sized mineral grains and dark humified organic particles (10–50 μm diameter) (Figs.

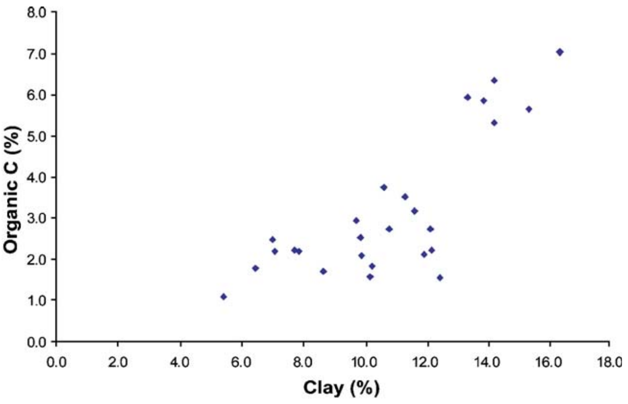

Figure 5. Clay and organic carbon concentrations in loess–paleosol sequences, Tatlow Camp and Christie Mine.

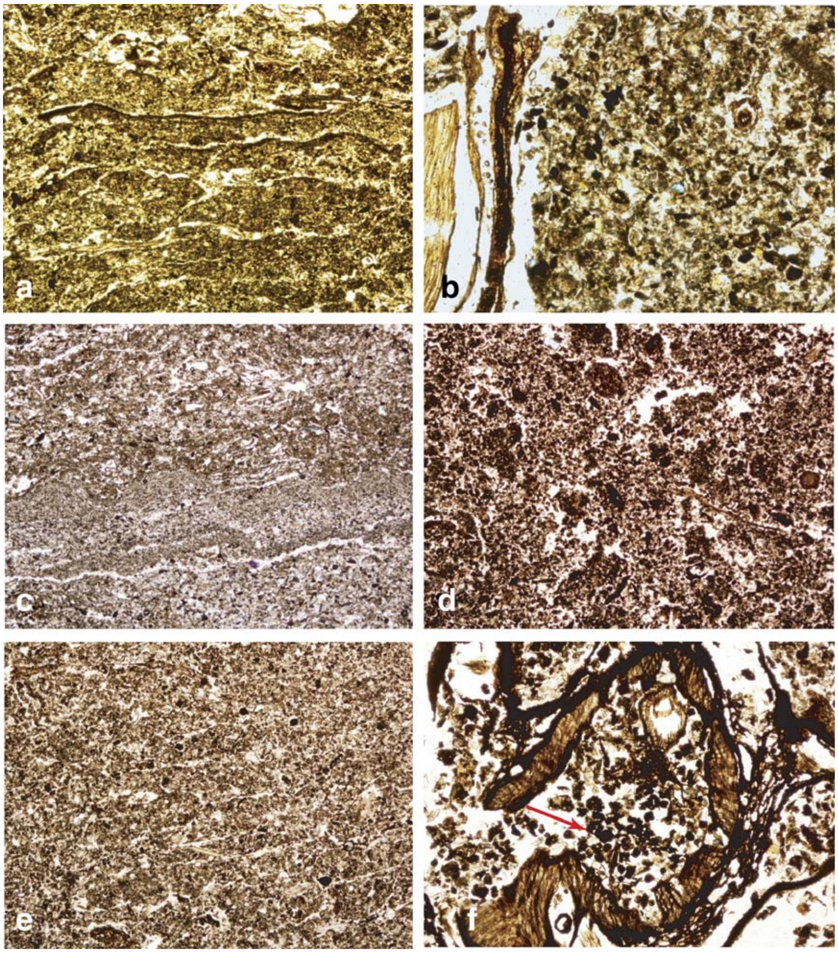

Figure 6. Micrographs (plane polarized light) of thin sections from selected paleosol horizons. MIS 2 sequence (site 1) at Tatlow Camp, Quartz Creek: (a) banded microstructure in Ahkb2 horizon; (b) spongy microstructure, with partially decomposed root residues, in Ahkb2 horizon; (c) laminations with particle-size sorting in Ck3 horizon; MIS 4 sequence (site 2) at Tatlow Camp, Quartz Creek: (d) Ahkyb horizon (soil 2) with abundant organic matter, weak granular microstructure. MIS 4 sequence, Christie Mine, Dominion Creek: (e) Ahkyb1 horizon (soil 2) with weak granular microstructure, coalesced to platy units separated by planar voids; (f) partially decomposed root residue, infilled with fecal pellets (arrow), in Ahkyb2 horizon (soil 3). Frame widths: 1.7 mm for a, c, f; 4.3 mm for b, d, e.

6a–d). Consistent with field observations of ubiquitous root detritus in and between paleosol A horizons, virtually all fields of view contain abundant partially humified herbaceous plant residues, occasionally with associated fecal pellets of soil fauna (Fig. 6f). Although expressed with varying strength in most of the paleosol A horizons (Figs. 6a, c, e), planar voids are most clearly evident in the three horizons immediately below the Dawson tephra at Tatlow Camp. In these cases, planar voids are associated with banded fabrics, separating platy structural units capped with finer silt particles (Fig. 6a), or with texturally-differentiated laminations 0.5–1.0 mm thick (Fig. 6c). C horizons with a more massive matrix may contain vestiges of circular arrangements of microstructural units (orbiculic fabric; Fox and Protz, 1981).

Discussion

Soil characteristics

The predominance of silt in these sequences is similar to the particle size data reported by Fraser and Burn (1997) for other Klondike muck deposits, and is consistent with the inferred loessal origin of these deposits. Although the earlier study reported a lower mean clay concentration for Klondike muck deposits (5.4%) than we obtained at our sites (10.8%), this may reflect differing methods since our particle size analyses included pretreatments for organic matter and carbonate removal that would increase the measured clay content.

The elemental analyses indicate that only weak chemical weathering has occurred, as shown by the limited variation in concentrations of major elements and in their ratios with immobile elements. Although pH was not measured, the presence of measurable inorganic carbon concentrations suggests that alkaline conditions and a mild weathering environment prevailed. Pronounced alkalinity is supported by the presence of caliciphilous plant taxa, including seeds of *Sueda* cf. *calceoliformis* within fossil squirrel nests at these sites. The similarities in major element concentrations and ratios (e.g., Ti/Zr) among the loess-derived horizons suggest that these deposits originated from similar sources, despite the spatial separation and age range of these sequences. Fraser and Burn (1997) suggested that the loess incorporated in the Klondike muck deposits originated from the Yukon River floodplain and outwash deposits of the McConnell (MIS 2) glaciation.

The range of organic C concentrations in these loess–paleosol sequences is consistent with data reported by Fraser and Burn (1997) for Klondike muck deposits, allowing for differing methods in these studies (loss on ignition at 400°C vs. determination of organic C as the difference between total and inorganic C). Similar organic C concentrations (mean = 3.0%, standard deviation = 1.0%) were also found in full-glacial tundra paleosols preserved under tephra on the Seward Peninsula, Alaska (Höfle et al., 2000). Near Kluane Lake, Yukon, modern well-drained loessal grassland soils, lacking permafrost, display similar organic carbon concentrations in surface horizons (Laxton et al., 1996).

The significant direct correlation between clay and organic C concentrations may have more than one explanation. Both properties have maximum values in buried A horizons, suggesting that these horizons formed during periods of land surface stability that allowed a longer time for organic matter accumulation and clay formation. However, given the mild weathering environment in these calcareous materials, it is more likely that differences in clay content reflect depositional processes rather than secondary mineral formation. In Alaskan loess sequences, Muhs et al. (2003) also reported higher clay concentrations in paleosols relative to the underlying loess and attributed this to weaker winds that would transport and deposit only finer particles, and at a lower accretion rate, during periods of soil formation. This mechanism, combined with an extended duration of organic matter accumulation, could account for the association between clay and organic C concentrations. Alternatively, this relationship may be analogous to that found in modern surface A horizons in the Great Plains (Nichols, 1984) where higher clay concentrations are thought to increase soil organic matter reserves by physical protection, as well as promoting organic matter inputs by increasing primary productivity in semi-arid environments through the higher water-holding capacity of finer-textured soils.

The complex involutions of soil organic matter apparent in soils 2 and 3 at both the Tatlow and Christie sites are typical of modern permafrost-influenced soils affected by cryoturbation within the active layer (Bockheim et al., 1997). These paleosols appear to be buried equivalents of Eutric Turbic Cryosols in the Canadian System of Soil Classification (Soil Classification Working Group, 1998) and Haploturbels in the U.S. Soil Taxonomy (Soil Survey Staff, 1999). The maximum depths (approximately 50 cm) to which such involutions have penetrated also provide an indication of minimum active layer thickness, and for soils 2 and 3, these depths were consistent with the configurations of underlying thaw unconformities in ice wedges associated with these paleosols. Similarly, the undulating surface expression of soils 2 and 3 at both sites is also a cryoturbation feature and is consistent with a tussock tundra plant community.

In contrast, the much simpler morphology of soil 1, and of the multiple buried A horizons in the MIS 2 loess–paleosol sequence at Tatlow Camp, make it more difficult to infer active layer thicknesses but do suggest that cryoturbation was less active. These paleosols have their modern equivalents in the Eutric Static Cryosols (Soil Classification Working Group, 1998) and the Haplorthels (or Mollorthels, if Ahb horizons exceed 18 cm in thickness) (Soil Survey Staff, 1999). Numerous fossil rodent middens were found throughout these sequences, suggesting that full-glacial active layers would have been thicker than in the modern environment in this area (Zazula et al., 2005). The relatively subtle color differences that were used to demarcate horizon boundaries in the MIS 2 sequence at Tatlow Camp are consistent with the more limited variation in organic C concentrations through this sequence. This may indicate that loess accretion during the MIS 2 was more rapid than during the older sequences that contained more strongly differentiated paleosols, with higher maximum concentrations of organic C in their A horizons.

The prevailing soil-moisture regimes during formation of these paleosols likely tended towards mesic in the older part of the sequences at Tatlow Camp and Christie Mine, with sufficient moisture availability to allow ice wedge formation and cryoturbation but with enough aeration to restrict hydromorphic features (mottling) to some lower horizons and prevent formation of peat layers at the surface. Adequate drainage of these soils is also suggested by the presence of fossil ground-squirrel nests between soils 1 and 2, and soils 2 and 3. Above soil 2, and in the MIS 2 sequence at Tatlow Camp, somewhat more xeric conditions are suggested by the more restricted ice wedge development and more limited cryoturbation.

Inferences from soil micromorphology

Microstructures in these selected paleosol horizons are similar to those in modern soils containing ice lenses formed under perennially or seasonally frozen conditions. Ice lens formation leads to strong expression of planar voids and banded fabrics, as documented for modern Cryosols and as verified by experimental studies (Van Vliet-Lanöe, 1985; Pawluk, 1988; Smith et al., 1991; Kemp, 1999). Cryoturbation can be expressed at the microscopic level by orbiculic fabrics containing granular units that have coalesced and undergone rotational movements attributed to vertically and laterally advancing freezing fronts (Fox and Protz, 1981).

The presence of banded fabrics and platy microstructures, including those with internal particle-size segregation, is not sufficient evidence alone for past periglacial conditions, as similar structures can occur in silty soils of mid-latitude forest and steppe environments with seasonal freeze–thaw activity (Mermut and St. Arnaud, 1981; Sanborn and Pawluk, 1989). Weak to moderately-developed granular microstructures are also present in these paleosols, and both field and experimental evidence demonstrate that such features form in periglacial or seasonally frozen climates (Pawluk, 1988; Smith et al., 1991). But, as with banded fabrics, granular microstructures are not unique to periglacial environments. For example, in organic matter-rich A horizons of soils of mid-latitude steppes and steppe–forest transitions, soil fauna also have an important role in creating granular microstructures (Pawluk, 1987).

Thus, although a range of evidence points to a strong periglacial influence on the genesis and properties of these paleosols, their A horizons also display micromorphological characteristics that occur in soils with similar textures in modern temperate and boreal grassland environments in western Canada. These analogues include mid-elevation Chernozems and morphologically similar alpine soils in the interior of British Columbia (Green et al., 1978; Sanborn and Pawluk, 1989) and calcareous Regosols and Brunisols formed on accreting loess in the Kluane Lake area of the southwestern Yukon (Marsh et al., in press). In the Siberian loess region, similar microfabrics occur in Chernozemic paleosols, although these formed during interglacial conditions (MIS 5) (Chlachula et al., 2004).

The considerable thickness of the Klondike "muck" deposits has been attributed to redeposition of loess by slope processes such as sheetwash and rill erosion (Fraser and Burn, 1997). Therefore, the laminations with particle size sorting that were evident in some horizons in the MIS 2 sequence at Tatlow Camp (Fig. 6c) likely represent sedimentary bedding. Similar features indicative of reworking have been documented in numerous loess successions in Europe, Asia, and South America (Mücher et al., 1981; Mücher and Vreeken, 1981; Vreeken, 1984; Kemp et al., 1999, 2004).

Modern analogues

Sufficient moisture availability existed to allow varying degrees of cryoturbation and ice wedge development, and for organic matter to accumulate in mineral A horizons to concentration levels typical of upland, mesic environments where surficial moss peat layers are thin or absent. Micromorphological evidence demonstrates that organic matter inputs occurred primarily by in situ decomposition of root detritus, with both physical and perhaps faunal processes producing aggregates of silt-sized mineral particles and humified organic constituents. Soil profile morphology, ice wedge configurations, and ground squirrel burrow distribution suggest that, at a minimum, active layers were thicker than exist at this latitude today on comparable aspects and parent materials. Collectively, these paleosols display properties found in modern soils formed on calcareous loess across a range of tundra and steppe environments in northwestern Canada. Other analogous soils with a similar assemblage of properties can be found on the cold, arid coast of the East Siberian Sea, where Smith et al. (1995) described grassy upland tundra with Brunisolic Static Cryosols (Pergelic Cryoborolls) displaying both A horizon development and little or no cryoturbation.

A paleopedological perspective on the steppe–tundra debate

Are these paleosol sequences and sites sufficiently representative that meaningful inferences can be made about the full-glacial landscape in eastern Beringia? These paleosols exhibit a range of morphological and chemical characteristics of modern soils found in both steppe and tundra settings, consistent with plant macrofossil evidence for a diversity of local habitats in Klondike full-glacial environments (Zazula et al., 2005). Hence, based on the greater variety of soil morphologies than was preserved in the MIS 2 sites on the Seward Peninsula, these paleosols appear to represent a wider portion of the Beringian soil–vegetation continuum hypothesized by Höfle et al. (2000). Because of the long duration represented by these Klondike sequences, some of this variety may reflect both temporal changes in the climatic controls on cryogenic processes and differences in rates of loess accretion. Nevertheless, the striking accordance in soil morphology and other properties through the MIS 4 sequences at the Tatlow Camp and Christie Mine sites—20 km apart—suggest that these reflect regional environmental trends and not merely localized conditions.

Conclusions

Multiple paleosols preserved in perennially frozen loess and exposed at two placer mines in the Klondike goldfields provide an important record of full-glacial environments in eastern Beringia. Based on the presence of the Dawson, Dominion Creek, and Sheep Creek K tephras, these loess sequences are correlated with MIS 2 and 4. Major element concentrations indicate that these paleosols experienced only limited chemical weathering in an alkaline environment prior to burial and preservation in permafrost, and further suggest that loess composition, and perhaps provenance, changed little through MIS 2 and 4 in the south Klondike area.

At both sites, the older loess deposits display a similar vertical sequence of three paleosols, with an upward trend to reduced expression of cryoturbation and more limited ice wedge development, suggesting a regional pattern of progressively more arid conditions during MIS 4. Throughout these sequences, soil moisture regimes were apparently dry enough to have prevented peat accumulation, and active layers were sufficiently thick to allow extensive colonization by ground squirrels. Paleosol A horizons are distinguished by increased organic carbon and clay concentrations, a pattern that may reflect both variations in sedimentation rates as well as the physical protection of organic matter by clay inferred for soils of modern steppes. Micromorphological characteristics resemble those of modern soils of temperate and boreal grasslands, in which organic matter accretes primarily by below ground inputs of root detritus. These paleosols also display microstructures associated with climates having seasonally or perennially frozen conditions. Taken together, this array of paleosol characteristics indicates affinities with modern soils of both steppe and tundra environments, suggesting a diversity of localized environments in full-glacial landscapes in eastern Beringia.

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Appendix A

Morphological descriptions of MIS 2 and 4 sequences at Quartz Creek and Dominion Creek, Yukon Territory, Canada. Soil horizon designations and descriptive terminology are according to Soil Classification Working Group (1998) and Expert Committee on Soil Survey (1983).

Table A1. Loess–paleosol sequence at site 1, Tatlow Camp, Quartz Creek. Bracketed horizon numbers correspond to horizon labels in Figure 2 and sample numbers in Table 1.

Horizon	Depth (cm)	Description
Ahkb1 (1)	0–7	Very dark brown (10 YR 2/2 m); silt loam; friable; massive; abundant, very fine and fine, vertical and oblique roots; moderate effervescence; abrupt, wavy boundary; 5–10 cm thick.
Ck1 (2)	7–33	Very dark grayish brown (10 YR 3/2 m); silt; friable; massive; plentiful, very fine and fine, vertical and oblique roots; moderate effervescence; clear, broken boundary; 20–30 cm thick.
Ck2 (3)	33–41	Very dark grayish brown (2.5 Y 3/2 m); silt loam; friable; massive; plentiful, very fine and fine, vertical and oblique roots; moderate effervescence; abrupt, broken boundary; 5–10 cm thick. (Mixing zone composed of loess and tephra.)
Dawson tephra (4)	41–50	Light brownish gray (10 YR 6/2 m); silt loam; friable; massive; abrupt, smooth boundary; 6–15 cm thick.
Ahkb2 (5)	50–65	Black (10 YR 2/1 m); silt loam; friable; weak, fine platy; moderate effervescence; plentiful, very fine and fine, vertical and oblique roots; clear, wavy boundary; 10–20 cm thick.
Ck3 (6)	65–107	Very dark grayish brown (2.5 Y 3.5/2 m) and dark grayish brown (2.5 Y 4/2 m); silt loam; friable; massive; plentiful, very fine and fine, vertical and oblique roots; moderate effervescence; abrupt, wavy boundary; 25–40 cm thick.
Ahkb3 (7)	107–135	Very dark grayish brown (2.5 Y 3/2 m) and black (10 YR 2/1 m); silt loam; friable; massive; plentiful, very fine and fine, vertical and oblique roots; moderate effervescence; abrupt, wavy boundary; 25–30 cm thick.
Ck4 (8)	135–147	Very dark grayish brown (10 YR 3/2 m); silt loam; friable; massive; plentiful, very fine and fine, vertical and oblique roots; moderate effervescence; abrupt, wavy boundary; 7–12 cm thick.
Ahkb4 (9)	147–149	Dark gray (5 Y 4/1 m); silt loam; plentiful, very fine and fine, vertical and oblique roots; moderate effervescence; abrupt wavy boundary; 2–3 cm thick.
Ck5 (10)	149–231+	Very dark grayish brown (2.5 Y 3/2 m) and black (10 YR 2/1 m); silt loam; friable; massive; plentiful, very fine and fine, vertical and oblique roots; moderate effervescence.

Table A2. Loess–paleosol sequence at site 2, Tatlow Camp, Quartz Creek. Broken line separates descriptions of different exposures examined in 2003 (Soils 1 and 2) and 2004 (Soils 2 and 3—as shown in Fig. 3). Bracketed horizon numbers correspond to sample numbers in Table 1.

Horizon	Depth (cm)	Description
Ahkb1 *Soil 1* (1)	0–20	Black (7.5 YR 2.5/1 m); silt; massive; friable; abundant, very fine and fine roots; very weak effervescence; clear, wavy boundary; 15–25 cm thick.
Ck (2)	20–150	Very dark grayish brown (2.5 Y 3/2 m); silt; massive; friable; abundant, very fine and fine roots; moderate effervescence; abrupt, wavy boundary; 100–150 cm thick.
Ahkb2 (3)	(discontinuous dark bands dispersed in Ck)	Black (N 2.5/1 m); silt; massive; friable; abundant, very fine and fine roots; moderate effervescence; abrupt, broken boundary; 10–30 cm thick.
Ahkyb *Soil 2* (4)	150–180	Black (7.5 YR 2.5/1 m); silt loam; massive; friable; abundant very fine and fine roots; very weak effervescence; abrupt, wavy boundary (frozen at lower boundary). Contains Dominion Creek tephra.
- - - - - -	- - - - - -	- - - - - -
Ahyb *Soil 2* (1)	0–9	Dark brown (7.5 YR 3/2 m); silt loam; weak, fine and medium subangular blocky; friable; abundant, fine roots; abrupt, wavy boundary; 4–10 cm thick.

(continued on next page)

Table A2 (*continued*)

Horizon	Depth (cm)	Description
Ahkyb1 *Soil 2* (2)	9–33	Very dark brown (10 YR 2/2 m); silt loam; weak, fine and medium subangular blocky; friable; abundant, very fine and fine roots; very weak effervescence; abrupt, irregular boundary; 6–25 cm thick.
Bmkyb1 *Soil 2* (3)	5–25	Brown (10 YR 4/3 m); silt; weak, fine and medium subangular blocky; friable; common, very fine roots; weak effervesence; abrupt, broken boundary; 0–16 cm thick.
Bmkyb2 *Soil 2* (4)	33–44	Dark grayish brown (10 YR 4/2 m); silt; weak, fine and medium subangular blocky; friable; common, very fine roots; weak effervesence; abrupt, broken boundary; 2–25 cm thick.
Sheep Creek K tephra (5)	44–46	Grayish brown (10 YR 5/2 m); silt loam; massive; friable; abrupt, broken boundary; 0–9 cm thick, with discontinuous 1–2 cm thick inclusions in Bmgjy and Ahy3.
Ahkyb2 *Soil 3* (6)	46–60+	Dark brown (7.5 YR 3/2 m); silt loam; friable; weak, fine and medium subangular blocky; few, very fine roots; weak effervesence.
Bmkgjyb *Soil 3* (7)	46–60+	Very dark grayish brown (2.5 Y 3/2 m); silt loam; friable; common, fine and medium, prominent, dark yellowish brown (10 YR 3/6 m) mottles; moderate, medium subangular blocky and moderate fine granular; few very fine roots; very weak effervescence.

Table A3. Loess–paleosol sequence as exposed in 2003, at the Christie Mine, Dominion Creek. Broken line separates description of Soil 3, examined at an exposure 100 m west of site at which soils 1 and 2 were described. Bracketed horizon numbers correspond to sample numbers in Table 1. This exposure differed in some morphological details from the 2004 exposure shown in Figure 4 but not in the sequence of paleosols and tephra layers and their relative thicknesses.

Horizon	Depth (cm)	Description
Ahkb *Soil 1* (1)	0–20	Black (N 2.5/1 m) and very dark gray (2.5 Y 3/1 m) silt; massive; friable; abundant, very fine and fine roots; strong effervescence; clear, broken boundary; 20–25 cm thick.
Ck1 (2)	20–90	Dark gray (2.5 Y 3.5/1 m); silt loam; massive; friable; abundant, very fine and fine roots; strong effervescence; gradual, wavy boundary; 70–90 cm thick.
Ck2 (3)	90–200	Dark gray (2.5 Y 3.5/1 m) and black (10 YR 2/1 m); silt loam; massive; friable; abundant, very fine and fine roots; moderate effervescence; clear, irregular boundary; 100–120 cm thick.
Ahkyb1 *Soil 2* (4)	200–220	Black (10 YR 2/1 m); silt loam; massive; friable; abundant, very fine and fine roots; weak effervescence; clear, wavy boundary; 15–25 cm thick.
Ck3 (5)	220–260	Very dark gray (2.5 Y 3/1 m); silt loam; massive; friable; abundant, very fine and fine roots; weak effervescence; clear, broken boundary; 30–50 cm thick.
- - - - - -	- - - - - -	- -
Sheep Creek K tephra	0–10	5–15 cm thick.
Ahkyb2 *Soil 3* (6a,b)	10–45	Black (10 YR 2/1 m) and very dark gray (2.5 Y 3/1 m); silt loam; massive and moderate fine granular; abundant very fine and fine roots; weak effervescence; clear, irregular boundary; 30–40 cm thick.
Ck4(7)	45–70+	Very dark gray (2.5 Y 3/1 m); silt loam; massive; friable; abundant, very fine and fine roots; weak effervescence.

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