Topographically controlled grassland soils in the Boreal Cordillera ecozone, northwestern Canada

Paul Sanborn

Ecosystem Science and Management Program, University of Northern British Columbia, 3333 University Way, Prince George, British Columbia, Canada V2N 4Z9 (e-mail: sanborn@unbc.ca).

Received 29 May 2009, accepted 16 October 2009.

Sanborn, P. 2010. **Topographically controlled grassland soils in the Boreal Cordillera ecozone, northwestern Canada**. Can. J. Soil Sci. **90**: 89–101. Properties and ecological relationships of grassland soils were examined at three widely separated sites (Stikine River Valley, British Columbia, and Carmacks and Kluane Lake, Yukon) in the Boreal Cordillera ecozone of northwestern Canada. At these latitudes (58 to 62°N), grasslands are largely restricted to south-facing aspects, and usually occur as islands within the boreal forest. The grayish and yellowish brown, base-rich, Ah horizons had a thickness-weighted mean organic carbon concentration of 19.5 g kg^{-1}. Ah horizons exhibited a range of microstructures similar to that documented in grassland soils in the southern Cordillera and Great Plains, ranging from spongy to massive in the young loess-derived Kluane Lake pedon to well-developed crumb microstructure in the finer-textured Stikine pedon. These pedons met the morphological and chemical criteria, and likely the soil climate requirements, for the Dark Brown and Brown great groups of the Chernozemic order of the Canadian System of Soil Classification (3rd ed.).

Key words: Grassland, Boreal Cordillera, Chernozem, soil micromorphology, soil genesis, soil classification

Sanborn, P. 2010. **Étude topographique du sol des prairies dans l'écozone de la cordillère boréale du nord-ouest du Canada**. Can. J. Soil Sci. **90**: 89–101. L'auteur s'est penché sur les propriétés et les liens écologiques du sol des prairies à trois endroits très éloignés les uns des autres (vallée de la rivière Stikine, en Colombie-Britannique, et lacs Carmacks et Kluane, au Yukon) de l'écozone de la cordillère boréale, dans le nord-ouest du Canada. À ces latitudes (58 à 62°N), les prairies se cantonnent largement aux endroits orientés au sud et forment habituellement des îlots dans la forêt boréale. Les riches horizons Ah grisâtres ou brun jaune, riches en bases, renferment en moyenne 19,5 g de carbone organique par kg de sol, après pondération pour l'épaisseur. Les horizons Ah présentent une gamme de microstructures semblables à celles rapportées pour les prairies du sud de la cordillère et des grandes plaines, et vont de spongieux à massifs dans le jeune pédon du lac Kluane, issu du loess, à une microstructure granuleuse bien développée dans le pédon à texture plus fine de la rivière Stikine. Ces pédons respectent les critères morphologiques et chimiques, et sans doutes les contraintes sol-climat, des grands groupes de tchernozioms brun foncé et bruns dans le système canadien de classification des sols (3e édition).

Mots clés: Prairies, cordillère boréale, tchernoziom, micromorphologie du sol, pédogenèse, classification des sols

North of the extensive grasslands in the major valleys of central and southern British Columbia, the Boreal Cordillera Ecozone (Ecological Stratification Working Group 1995) of British Columbia and Yukon has more widely scattered and individually smaller occurrences of low elevation grasslands (Pojar 1982; Smith et al. 2004). Grasslands within the western portion of this ecozone between approximately 58 and 62°N occur in the rainshadow of the Coast and St. Elias Mountains. Within individual valleys, the distribution of grasslands is strongly controlled by aspect-related differences in microclimate. Grasslands are largely restricted to south-facing slopes, with local vegetation boundaries also influenced by fire history, substrate characteristics, and patterns of cold air drainage. Although these grasslands may be viewed as ecological outliers in the boreal landscape, they provide locally significant range resources and wildlife habitat, as well as refugia for species that would otherwise be absent in boreal settings. These grasslands also have paleoenvironmental significance as potential analogues for the plant communities of cold, dry steppe environments that occupied unglaciated areas of northwestern North America during the Pleistocene ice ages (Zazula et al. 2003).

Soils associated with these boreal grasslands have received cursory attention, mostly through ecological inventories rather than conventional soil surveys. In northwestern British Columbia, a reconnaissance biophysical inventory reported that soils in grasslands on south to southwest-facing slopes in the Tahltan Highlands–Coast to Interior transition contain organic matter-enriched surface mineral horizons, and were classified as Melanic Brunisols (Fenger and Kowall 1992). For grasslands across a broad area of northern and central British Columbia, Pojar (1982) referred to the characteristic soils variously as "marginal Chernozems", "melanized Brunisols" and Black Chernozems. In southern Yukon, grasslands are best expressed on south-facing slopes in the Yukon Plateau–Central Ecoregion (Smith et al. 2004). Their characteristic soils are mildly weathered, alkaline, and have dark A horizons and are classified as Melanic Brunisols. A distinctive component of soil parent materials in southern Yukon is the widespread occurrence of a surface veneer of the late Holocene White River tephra (1147 calibrated years BP; Clague et al. 1995). In steeply sloping grasslands, much of the tephra veneer has been modified by organic matter accumulation to form Ah horizons that are generally less than 10 cm thick and overlie buried profiles classified as Melanic Brunisols (Strickland et al. 2005). In grasslands at Kluane Lake, southwestern Yukon, A horizons of Melanic and Eutric Brunisols exhibit effervescence and alkaline soil reactions, reflecting their calcareous loess parent material (Laxton et al. 1996).

Although this study concerns grassland soils at mid-elevations (< 1000 m) in northwestern British Columbia and southern Yukon, resource inventories elsewhere in British Columbia have also reported alpine grassland soils that appear to satisfy the morphological and chemical requirements of Chernozemic soils. In both the northern Rocky Mountain foothills (~57°N) and the southern interior plateau (~49°N), alpine grassland soils on south-facing aspects exhibited dark A horizons with granular structures, near-neutral pH, low C:N ratios and high base saturation (Lord and Luckhurst 1974; Green et al. 1978). Whether these soils could be classified as Chernozemic depended primarily on meeting a requirement for mean annual soil temperatures (MAST) exceeding 0°C in then-current Canadian soil classifications (Agriculture Canada 1974; Canada Soil Survey Committee 1978). Climatic criteria have been retained in subsequent revisions, and currently the Chernozemic A horizon must have a "mean annual soil temperature of 0°C or higher and a soil moisture regime subclass drier than humid" (Soil Classification Working Group 1998).

High-latitude ecosystems are expected to experience substantial climatic change within this century, with implications for vegetation zonation and soil processes such as carbon storage (Arctic Climate Impact Assessment 2005). Soil types in or near ecotones at the margins of their current distribution are of particular interest, because the extent of such soils may expand or contract substantially as ecological thresholds are crossed, or natural disturbance regimes are altered. It is therefore timely to examine the characteristics, genesis, and environmental relationships of grassland soils near the limits of their distribution in the Boreal Cordillera ecozone of northwestern Canada. This initial study addresses two questions: (1) How do the properties of these grassland soils compare with those of their counterparts elsewhere in western Canada, and particularly in the Cordillera? (2) Given the properties, ecological relationships and inferred genesis of these soils, is their taxonomic treatment in the Canadian System of Soil Classification appropriate?

MATERIALS AND METHODS

Study Sites

Pedons were described and sampled in uncultivated grasslands at three widely separated locations in northwestern Canada on slopes with southeast to southwest aspects (Fig. 1, Table 1). For this initial reconnaissance study, these criteria were intended to capture a wide geographical representation of sites with continuous grassland cover in diverse geomorphic settings. Land use at all sites was unmanaged rangeland and/or wildlife habitat.

All sites were glaciated during the latest advance of the Cordilleran ice sheet, but subsequent events have created a range of parent materials and landforms. (1) Near Telegraph Creek, BC, grasslands occur in the valleys of the Stikine River and its major tributaries, the Tuya and Tahltan Rivers. Although these rivers have cut their canyons in Tertiary and Quaternary basaltic lavas, grassland soils on the valley walls have formed on fine-textured sediments deposited in advance-phase glacial lakes (Spooner and Osborn 2000). (2) Approximately 3 km southwest of Carmacks, Yukon, grasslands occupy the steep south-facing slopes in an extensive area of hummocky topography created by a massive landslide in the local Cretaceous basaltic bedrock (Jackson 2000). Soil parent materials on this landform contain varying proportions of basaltic colluvium and glacial deposits of more diverse lithology. Surface horizons are silty, likely from incorporation of aeolian materials, and can include White River tephra as either a distinct surface veneer or as a discontinuous inclusion in surface horizons. (3) Along the southeastern shore of Kluane Lake, calcareous loess derived from the delta of the glacier-fed Slims River occurs as a silty veneer draped over a hummocky landscape of coarse glaciofluvial deposits. Loess deposition accelerated during the late Holocene in response to glacier expansion and increased sediment delivery by the Slims River (Laxton et al. 1996). Dust storms occur frequently in the lower Slims River valley during low water conditions and can be observed blowing across Kluane Lake.

Long-term data from the stations closest to the study sites give only a general indication of climatic conditions (Table 2), but the low precipitation and cold air temperatures in this region are apparent. Climate records from a few scattered stations cannot capture the complexity of topography-related microclimates that influence fine-scale vegetation and soil patterns. For example, at latitude 60°N, the yearly direct solar radiation calculated for a 15° south-facing slope is 24% higher than for flat ground and 75% higher than for a north-facing 15° slope (Buffo et al. 1972). Of the stations closest to the three study areas, only Haines Junction had soil temperature data available (Clayton et al. 1977): MAST ranged between 2.4 and 2.5°C for depths between 20 and 100 cm. Soil moisture regime subclass was designated as subhumid (Clayton et al. 1977). Permafrost was observed at

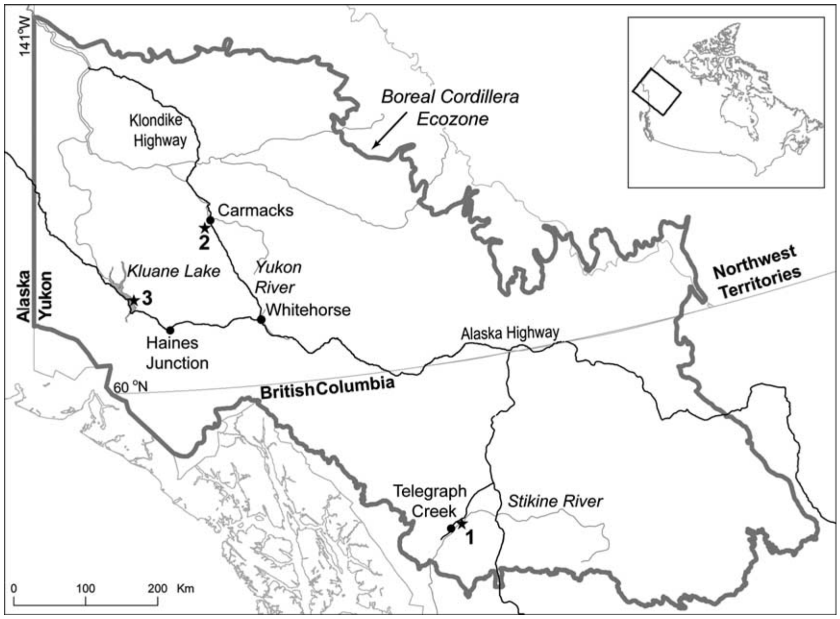

Fig. 1. Study site locations (indicated by stars) within the Boreal Cordillera Ecozone: 1 – Stikine River, 2 – Carmacks, 3 – Kluane Lake.

similar elevations on north aspects in the same landscapes as the Carmacks and Kluane Lake sites, and these areas lie within the sporadic discontinuous and extensive discontinuous permafrost zones, respectively (Heginbottom et al. 1995).

Sampling and Analytical Methods

Soils were described according to the standard methods and terminology of the Canadian System of Soil Classification (Soil Classification Working Group 1998) and the Expert Committee on Soil Survey (1983). Bulk samples of each soil horizon were collected for physical and chemical characterization, along with undisturbed samples of A horizons for thin section preparation.

Standard characterization analyses of the air-dry <2 mm fractions are reported on an oven-dry basis. Particle size analysis was performed by the pipette method (Gee and Bauder 1986) after removal of organic matter and secondary carbonates as needed. Soil chemical analyses included total carbon (C) and nitrogen (N) (LECO CHN-600 Elemental Analyzer), $CaCO_3$ equivalent by the empirical standard curve method (Carter et al. 1993), and pH, using a Fisher Accumet pH Meter (model 915) and a soil:water ratio of 1:1 and soil:0.01 M $CaCl_2$ ratio of 1:2. Organic C was measured by determination of total C (elemental analyzer) after destruction of carbonates with 1 M HCl. Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+}) were determined by the $BaCl_2$ method (Carter et al. 1993) with

Table 1. Location and site information for selected grassland pedons, northwestern British Columbia and southern Yukon Territory

	Site location (pedon number)		
	Stikine River, BC (BC08-06)	Carmacks, YT (Y08-39)	Kluane Lake, YT (Y08-41)
Latitude/Longitude	57°58’43.6”N/131°4’49.3”	62°4′51.5′′N/136°20′1.6′′W	61°9′18.5′′N/138°24′37.3′′W
Elevation (m)	411	712	827
Aspect (°)	140	130	225
Slope (%)	35	30	30
Parent material	Colluviated glaciolacustrine sediments	Colluviated loess, tephra and till over weathered basalt (Carmacks Group)	Loess veneer over glaciofluvial sand and gravel
Vegetation: dominant grasses and associated woody species	*Poa arctica, Bromus purpurescens, Rosa sp., Amelanchier alnifolia, Populus tremuloides*	*Calamagrostis purpurescens*	*Elymus sp., Carex sp.*

Table 2. Climate data for selected stations in northwestern British Columbia and southern Yukon Territory (Environment Canada 2007)

Station	Elevation (m)	Latitude/Longitude	Mean air temperature (°C)			Mean precipitation (mm)	Record period
			Annual	Maximum	Minimum	Annual	
Telegraph Creek, BC	250	57°54'N/131°20'W	2.7	8.0	−3.2	329	1979–2000
Carmacks, YT	525	62°6'N/136°18'W	−4.3	1.9	−10.5	270	1963–2004
Haines Junction, YT	599	60°46'N/137°35'W	−2.9	4.1	−9.7	306	1944–2007

determination of cation concentrations by inductively coupled argon plasma-atomic emission spectroscopy (ICP-AES). Extractable Fe, Al, and Si were determined by the sodium pyrophosphate, acid ammonium oxalate, and citrate-bicarbonate-dithionite methods (Carter et al. 1993) with elemental concentrations in the extracts determined by ICP-AES. Thin sections (30 µm thick) were prepared from intact samples after impregnation with Spurr Resin (System Three Resin, Auburn, WA) and described using terminology after Stoops (2003).

RESULTS

Morphology and Texture

The thickness of the Ah horizon exceeded 10 cm in all three pedons and increased toward lower slopes (Table 3). Soil surfaces were covered by a near-continuous biological soil crust, with only a limited accumulation of herbaceous detritus. At the Carmacks (Y08-39) site, the pedon was sampled in the upper portion of a ~100-m-long slope segment, with thicker Ah horizons in the lower 1/3 of the slope. Along the same gradient, the distinctness and thickness of the presumed White River tephra layer increased from discontinuous pockets in the Ah horizon, to a distinct layer ~20 cm thick containing an incipient Ah horizon and overlying a buried profile with a 15–25 cm thick Ah horizon.

Although root abundance is usually highest in the A horizons (Table 3, Fig. 2), localized concentrations of abundant herbaceous roots occurred in both B and C horizons. This was particularly evident in the Carmacks pedon, with numerous herbaceous roots penetrating the highly fractured basalt comprising the IIIBC and IIICca horizons. Larger woody roots from adjacent shrubs and trees were encountered in the Stikine pedon (Fig. 2), and this is likely common in small grassland patches.

Structures of the A horizons varied with texture, but all were friable or very friable. Ah horizons in the Stikine pedon were the finest-textured, with clay contents exceeding 200 g kg^{-1} (Table 4) and exhibited strong, fine granular structures, in combination with weak, medium subangular blocky structure in the Ah2 horizon (Table 3). Ah horizons in the sandier (Carmacks) and siltier (Kluane) pedons had much weaker expression of granular structures.

A horizon Munsell colour values in all pedons were darker than 5.5 dry, and 3.5 moist, and chromas were less than 3.5 moist (Table 2). A horizon colour values were at least one unit darker than those of IC horizons in the Stikine and Carmacks pedons. Although no IC horizon was present in the Carmacks pedon, the colour value contrast between the Ah and IIICca horizons was one unit. Dry colour chromas exceeded 1.5 in all A horizons, and dry colour values ranged between 4 and 5.

Chemical Properties

Soil reaction was near-neutral to moderately alkaline in all horizons. The highest pH values (≥8, determined in water) occurred throughout the Kluane pedon, coinciding with the presence of carbonates in all horizons except the Ah (Table 4). Exchangeable cations were dominated by Ca^{2+} and Mg^{2+}, with the highest values occurring in the lower basalt-derived horizons of the Carmacks pedon. Exchangeable Al^{3+} values (not shown) were negligible in all horizons. Exchangeable Na^{+} concentrations were highest in calcareous C horizons of the Kluane pedon, and in the Ck horizon, the exchangeable Ca^{2+}:Na^{+} ratio was below 10.

Organic carbon concentrations in the Ah horizons were modest, ranging between 13.0 and 29.8 g kg^{-1}, with a thickness-weighted mean of 19.5 g kg^{-1}, and up to 50% higher in the upper vs. lower Ah horizons (Table 4). Organic C:N ratios (not shown) were between 7 and 12 in all A and B horizons.

Sesquioxide concentrations showed little variation within A and B horizons, and values for both pyrophosphate- and oxalate-extractable Fe and Al were usually below 2.5 g kg^{-1} (Table 4). Dithionite-extractable Fe concentrations averaged 9.9 g kg^{-1} in A and B horizons, suggesting that most of the extractable Fe was in crystalline form.

Micromorphology

Within the Ah1 horizon, the Stikine pedon displays the most strongly defined crumb microstructure of the three pedons (Fig. 3). Within 1 cm of the soil surface, the largest rounded aggregates (~0.5 mm diameter) of intimately combined mineral and organic components are loosely intermingled with plant detritus, roots, and finer organomineral aggregates with more irregular shapes (Fig. 3a, b). Deeper in this horizon, the organomineral aggregrates are larger (>1 mm diameter), more elongated, and partially coalesced. The Ah2 horizon contains larger aggregates, many with morphology resembling the subangular blocky units evident on a larger scale in the field.

Table 3. Morphological descriptions of selected pedons from northwestern British Columbia and southern Yukon grasslands

Horizon	Depth (cm)	Description
Stikine River, BC (Site BC08-06): Orthic Brown Chernozem		
Ah1	0–5	Very dark grayish brown (10YR 3/2 m), dark grayish brown (10YR 4/2 d); loam; strong, fine, granular; friable; abundant, very fine and fine, random and oblique roots; 10–15% gravel; clear, wavy boundary; 4–8 cm thick; slightly acid.
Ah2	5–19	Dark brown (7.5YR 3/2 m), brown (7.5YR 5/2 d); loam; weak, medium, subangular blocky and strong, fine, granular; friable; plentiful, very fine and fine, and few, medium and coarse, oblique roots; 15–20% gravel; clear, wavy boundary; 12–20 cm thick; neutral.
Bm1	19–50	Very dark grayish brown (2.5 Y 3/2 m); clay loam; strong, fine and medium, subangular blocky; firm; plentiful, very fine and fine, and few, medium and coarse, horizontal and oblique roots; 5% gravel; gradual, wavy boundary; 25–35 cm thick; neutral.
Bm2	50–80	Very dark grayish brown (2.5 Y 3/2 m); clay loam; strong, medium, subangular blocky; firm; few, very fine and fine, random roots; clear, wavy boundary; 25–35 cm thick; neutral.
Cca	80–95+	Gray (2.5Y 5/2 m); loam; moderate, medium subangular blocky; friable; few, fine, random roots; 10% gravel; strongly effervescent; streaked, common, medium, random, friable, very pale brown (10YR 8/2 d) secondary carbonates; mildly alkaline.
Carmacks, YT (Site Y08-39): Orthic Dark Brown Chernozem		
Ah1	0–8	Very dark grayish brown (10YR 3/2 m), dark grayish brown (10YR 4/2 d); sandy loam; weak, medium, subangular blocky and moderate, fine, granular; very friable; plentiful, very fine and fine, oblique and random roots; 20% gravel; clear, wavy boundary; 6–9 cm thick; neutral.
Ah2	8–18	Dark brown (10YR 3/3 m) and brown (10YR 5/3 m), dark grayish brown (10YR 4/2 d); loam; moderate medium granular; very friable; plentiful very fine and fine, oblique and random roots; 20% gravel; clear, wavy boundary; 7–11 cm thick; neutral.
IIBm	18–41	Dark yellowish brown (10YR 3/4 m); loam; moderate, fine and medium granular; very friable; plentiful, very fine and fine, oblique and random roots; 50–60% basalt and mixed gravel (including rounded erratics); clear, wavy boundary; 17–25 cm thick; neutral.
IIIBC	41–63	Olive brown (2.5Y 4/4 m); sandy loam; single grain; loose; plentiful, very fine and fine, oblique and random roots; 70–80% weathered basalt fragments; clear, wavy boundary; 20–24 cm thick; neutral.
IIICca	63–90+	Olive brown (2.5Y 4/4 m) and light olive brown (2.5Y 5/6 m); sandy loam; single grain; loose; few, very fine and fine, random roots; moderately effervescent; streaked, common, fine and medium, random, friable, light gray (10YR 7/2 d) secondary carbonates (including coatings <1 mm thick on undersides of coarse fragments); 90% weathered basalt fragments; neutral.
Kluane Lake, YT (Site Y08-41): Calcareous Dark Brown Chernozem		
Ah	0–10	Dark yellowish brown (10YR 3/4 m), dark grayish brown (10YR 4/2 d); silt loam; weak, fine and medium, subangular blocky and weak, fine, granular; friable; abundant, very fine and fine, oblique and random roots; clear, wavy boundary; 8–12 cm thick; mildly alkaline.
Ahk	10–15	Dark yellowish brown (10YR 3/4 m), brown (10YR 5/3 d); silt loam; moderate, fine and medium subangular blocky; friable; abundant, very fine and fine, oblique and random roots; moderately effervescent; clear, smooth boundary; 2–7 cm thick; mildly alkaline.
Bmjk	15–35	Light olive brown (2.5Y 5/3 m); silt loam; moderate, fine and medium, subangular blocky; friable; abundant, very fine and fine, oblique and random roots; moderately effervescent; clear, wavy boundary; 15–25 cm thick; mildly alkaline.
Ck	35–55	Light yellowish brown (2.5Y 6/3 m); loam; massive; friable; plentiful, very fine and fine, oblique roots; strongly effervescent; abrupt, smooth boundary; 15–25 cm thick; moderately alkaline.
IICca	55–80+	Light olive brown (2.5Y 5/3 m); sand; single grain; loose; few, fine, random roots; 60% gravel and cobbles; strongly effervescent; <1 mm thick, very pale brown (10YR 8/2 d) secondary carbonate coatings on undersides of most coarse fragments; moderately alkaline.

The Carmacks pedon has a greater range of primary particle sizes and compositions in the Ah1 and Ah2 horizons, including sand- and fine gravel-sized basalt fragments and medium- and fine-sand-sized tephra particles (Fig. 4). Organomineral aggregates are usually less than 0.5 mm in diameter, and are loosely coalesced between the larger primary mineral particles to form a combination of crumb and spongy microstructure (Fig. 4d). Within the Ah1 horizon, there is a localized zone containing a high proportion of opaque, angular particles (0.1–0.5 mm diameter) that are likely charcoal fragments (Fig. 4c).

The Ah horizon of the Kluane pedon has only weakly expressed aggregation at the microscopic scale, with a microstructure ranging between spongy and massive. The matrix consists of densely coalesced primary silt and sand particles, roots and plant detritus (Fig. 5a, b). Brownish (organic?) coatings partially cover most mineral particles (Fig. 5d). There is little difference in microstructure between the Ah and Ck horizons, apart from a slightly lower degree of porosity in the latter (Fig. 5c).

DISCUSSION

Although there is some uncertainty regarding the climatic criteria, all three pedons appear to have Chernozemic A horizons based on their morphological and chemical properties: thickness $\geq$10 cm, dark colour, organic C content $\geq$1%, C:N ratio $<$17, high base saturation dominated by exchangeable Ca^{2+}, friable consistence, and aggregation. Based on the predominant A horizon colours, the Carmacks and Kluane pedons are Dark Brown Chernozems, and the Stikine pedon is a Brown Chernozem. Ah horizon organic C concentrations are within the range reported for Brown and Dark Brown Chernozems in the central (Valentine et al. 1987) and southern interior (Van Ryswyk et al. 1966; Fenger 1982) of British Columbia. For the Carmacks pedon, the Ah1 horizon organic C concentration is comparable with those of grassland A horizons elsewhere in the Carmacks area (Strickland et al. 2005). The presence of localized concentrations of charcoal particles within the Carmacks Ah1 horizon is consistent with reports that charcoal can comprise a significant proportion of soil C in forest-grassland ecotones (Ponomarenko and Anderson 2001).

The mild weathering intensity typical of grassland soils (Anderson 1987) is indicated by the low concentrations of pedogenic forms of Fe and Al as determined by the oxalate extraction (Parfitt and Childs 1988). The observed low values for oxalate- relative to dithionite-extractable Fe are typical of well-drained soils, as demonstrated for similar Chernozemic soils in Saskatchewan (Stonehouse and St. Arnaud 1971). Pyrophosphate is a more selective extractant for organic complexes of Al than those of Fe (Parfitt and Childs 1988). The low concentrations of pyrophosphate-extractable Fe and Al in both A and B horizons is further evidence of the limited formation and mobility of pedogenic Fe and Al forms in these pedons.

The climatic criteria for the Chernozemic A horizon, particularly for soil temperature, can be problematic for remote locations with little or no climate data for relevant site conditions. Data collected for permafrost research provide insights into the topographic controls of soil temperature regimes in northern landscapes. For example, near Keno Hill, Yukon (64°N), Côté et al. (2008) found that permafrost was absent, and MAST values at 50 cm were positive and up to 2.1°C on south- and southeast-facing sites between ~1000 and 1400 m elevation. In contrast, sites on north- to north-northwest-facing aspects in the same elevation range had negative MAST values, and permafrost was present. Although Côté et al. examined forest, upper subalpine, and alpine sites, these patterns suggest that for aspect-controlled grasslands at lower elevations ($<$1000 m) and farther south, MAST values should exceed 0°C.

As was found by a study of Chernozemic A horizon microstructures in Alberta and southern British Columbia (Sanborn and Pawluk 1989), texture appears to be a major influence on the distinctness and morphology of microaggregates, with the strongest crumb microstructure apparent in the pedon with the highest Ah horizon clay content (Stikine). The spongy appearance of both A and C horizons in the Kluane pedon is typical of other Quaternary soils formed in aggrading loess in grassland environments (Jacobs and Mason 2007). Although no soil faunal studies have been conducted in Boreal Cordilleran grasslands, some of the microaggregates (e.g., Fig. 3) resemble those interpreted to be fecal pellets produced by soil invertebrates in other Chernozemic soils (Pawluk and Bal 1985). Physical processes may also be involved in modifying soil microstructure, as in the case of elongated aggregates transitional to platy microstructures similar to those attributed to frost action in southern British Columbia Chernozemic A horizons (Sanborn and Pawluk 1989).

Where these soils differ most strikingly from their counterparts in the southern Cordillera and Great Plains is in their typical landscape setting and spatial pattern. Grasslands in northwestern Canada are ecological and pedological islands, with patch sizes usually measured in hectares, often with limited connectivity and displaying sharp boundaries to highly contrasting ecosystems and soil types. For example, at Kluane Lake, aspect-controlled boundaries between grasslands and boreal spruce forest occur on slope breaks on terrace edges and at the crests of ridges, and are accompanied by transitions between Chernozemic and Brunisolic soils over distances of less than 5 m. In sheltered depressions and at the foot of north-facing slopes, Cryosols can be found within 20 m of open grasslands and Chernozems on adjacent south-facing slopes (Sanborn and Jull 2009) – a juxtaposition that is unlikely to exist at middle latitudes. Such patterns are dramatically different from those on

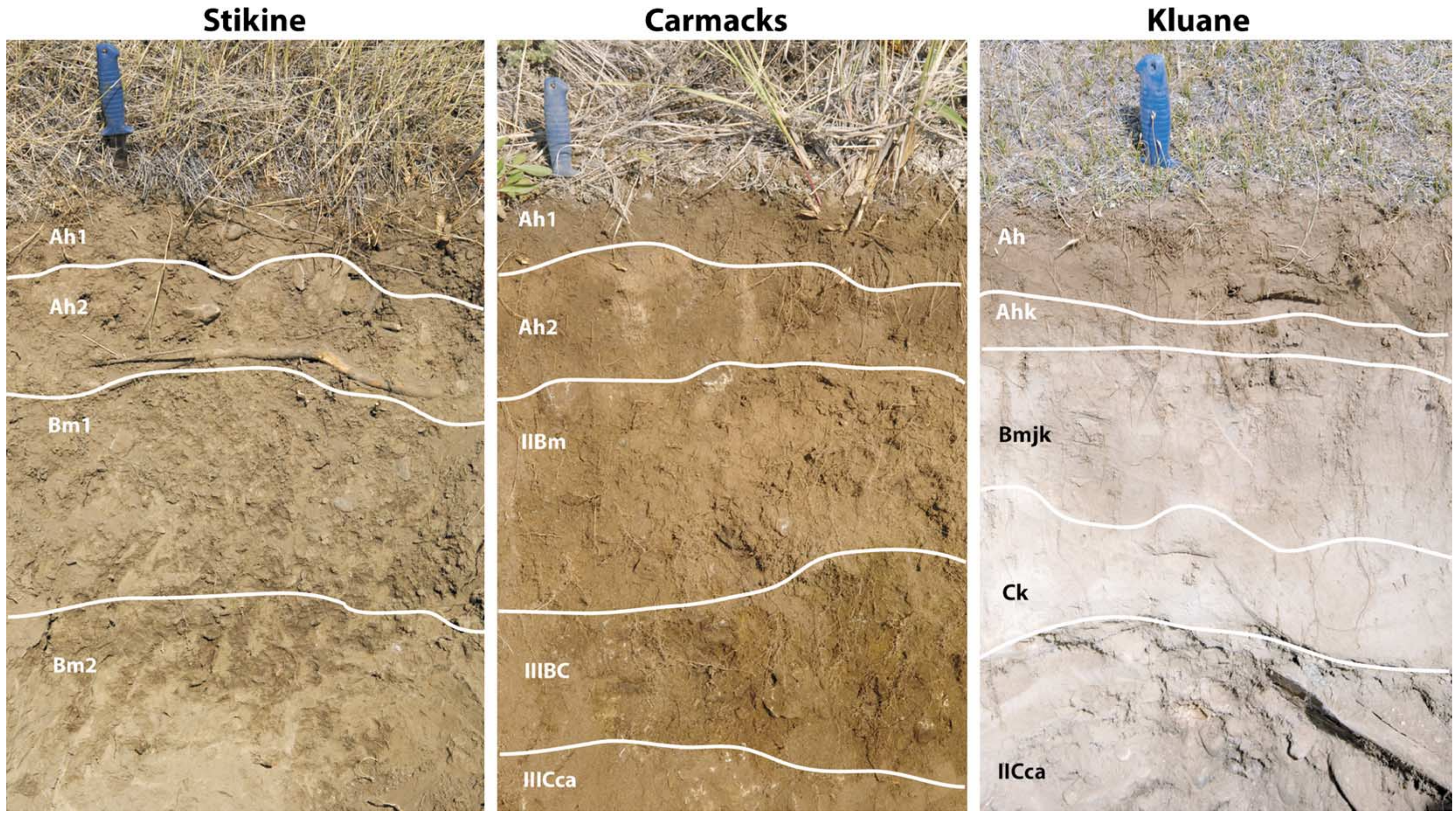

Fig. 2. Profiles of selected grassland soils, northwestern British Columbia and southern Yukon (knife handle is 10.5 cm long.)

Table 4. Physical and chemical properties of selected pedons from northwestern British Columbia and southern Yukon grasslands

Site/(pedon no.) Horizon/depth (cm)	Sand	Silt	Clay	Corg[z]	$CaCO_3$ equiv.	Total N	Al_p[y]	Fe_p	Al_o	Fe_o	Fe_d	pH (H_2O)	pH ($CaCl_2$)	Ca^{2+}	Mg^{2+}	K^+	Na^+	Sum
	g kg^{-1}													Exchangeable $cmol_c$ kg^{-1}				
Stikine River, BC (BC08-06)																		
Ah1 (0–5)	346	427	227	20.2	ND[x]	2.2	0.4	0.8	1.6	2.7	10.8	7.00	6.46	13.1	3.3	1.1	0.1	17.6
Ah2 (5–19	330	409	261	16.4	ND	1.8	0.4	0.9	1.7	2.6	11.0	7.18	6.63	14.2	3.7	0.8	0.1	18.9
Bm1 (19–50)	296	394	310	11.1	ND	1.1	0.4	0.9	2.2	2.5	11.6	7.34	6.74	11.9	5.0	0.5	0.2	17.7
Bm2 (50–80)	284	438	278	7.2	ND	0.7	0.3	0.7	1.7	2.3	10.0	7.63	6.88	11.6	4.7	0.3	0.2	16.8
Cca (80–95+)	432	416	152	5.0	52.8	0.4	0.1	0.3	0.8	1.6	5.2	8.34	7.49	8.1	2.0	0.2	0.1	10.4
Carmacks, YT (Y08-39)																		
Ah1 (0–8)	496	443	61	29.8	ND	3.0	0.3	0.8	1.6	1.8	7.8	7.55	7.04	23.3	5.6	1.2	0.1	30.2
Ah2 (8–18)	389	432	179	18.0	ND	1.6	0.1	0.1	1.7	2.0	11.5	7.67	7.21	24.1	8.7	0.9	0.1	33.9
IIBm (18–41)	591	265	144	7.3	ND	0.7	0.6	1.3	1.4	1.7	9.5	7.85	7.21	18.2	7.8	0.6	0.2	26.8
IIIBC (41–63)	686	197	117	8.1	10.2	0.8	1.3	4.2	1.2	1.7	11.7	7.72	7.16	26.3	12.1	0.7	0.2	39.3
IIICca (63–90+)	772	138	90	6.5	29.9	0.6	1.2	4.0	1.3	2.4	11.0	7.97	7.28	30.7	14.2	0.9	0.2	46.0
Kluane Lake, YT (Y08-41)																		
Ah (0–10)	329	602	69	19.9	ND	2.3	0.3	0.4	1.0	1.9	9.9	8.00	7.44	16.0	1.5	0.5	0.0	18.1
Ahk (10–15)	347	559	94	13.0	63.0	1.8	0.4	0.3	1.2	2.1	8.7	8.05	7.67	16.0	1.9	0.3	0.1	18.3
Bmjk (15–35)	292	624	84	8.3	104.8	1.0	0.2	0.2	0.9	2.0	8.3	8.49	7.84	10.9	3.7	0.2	0.2	15.1
Ck (35–55)	431	491	78	4.7	142.9	0.6	0.1	0.2	0.7	1.9	5.7	8.55	8.18	6.7	4.8	0.2	0.9	12.6
IICca (55–80+)	902	86	12	3.2	52.5	0.2	0.1	0.3	0.4	3.2	4.7	8.76	8.18	6.4	2.8	0.3	0.5	9.9

[z]Corg = organic carbon.
[y]Subscripts for Al and Fe extractions: p = pyrophosphate, o = oxalate, d = dithionite.
[x]ND, not determined.

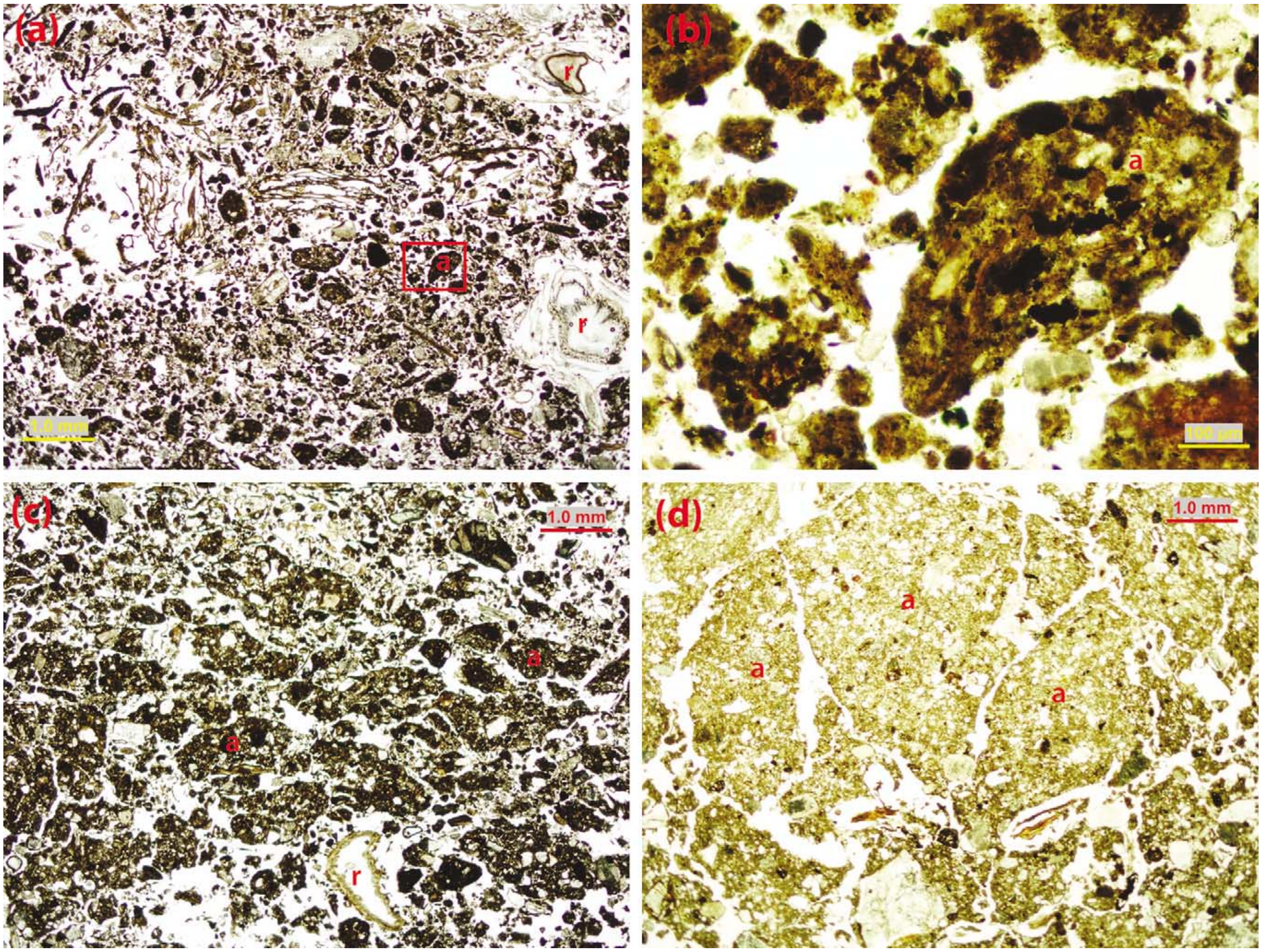

Fig. 3. Micrographs (plane light) of thin sections from Stikine pedon: (a) Ah1 horizon, ~0.5–1.0 cm depth, with rectangle outlining detail of crumb microstructure shown in (b); (c) Ah1 horizon, with aggregates ~1–2 mm long; (d) Ah2 horizon, with subangular blocky microstructure. Abbreviations: a, aggregate; r, root. Scale bars: 1 mm (a, c, d), 0.1 mm (b).

the Great Plains, where lower relief has produced catenary assemblages of soils that can belong to a single Chernozemic Great Group, and forest-grassland ecotones that occur on scales of kilometres (Anderson 1987; Pennock and Acton 1989). In central and southern British Columbia, the landscape has much more relief and topographic complexity than in the Great Plains, but grasslands and Chernozemic soils occur in contiguous patches on scales that are orders of magnitude larger (10^0 to 10^2 km^2) than those in the Boreal Cordillera (Valentine et al. 1987; Young et al. 1992). These contrasting soil landscape patterns across the range of grassland ecosystems in western Canada – small, poorly connected patches surrounded by forest vs. large, contiguous areas – may have consequences for soil biological diversity.

The grassland patches observed in this study usually had sharp edges coinciding with abrupt changes in aspect created by breaks of slope and geomorphic boundaries. This relationship between grassland distribution and permanent topographic features might suggest that such vegetation (and soil) patterns will persist in the face of climatic change. However, responses of boreal ecosystems to climatic change could create unexpected, nonlinear changes in soil landscape patterns. Recent observations of post-fire succession in southern Yukon indicate limited white spruce regeneration success on dry, southwest-facing aspects, creating a transition to open aspen parkland vegetation (J. Johnstone, Univ. Saskatchewan, personal communication). Combined with potential climate-related changes to fire regimes (McCoy and Burn 2005), such trends could trigger shifts from forest to grassland to an unexpectedly large degree. The major changes in ecological functions and soil processes that accompany forest-grassland transitions – organic matter dynamics, nutrient cycling, chemical

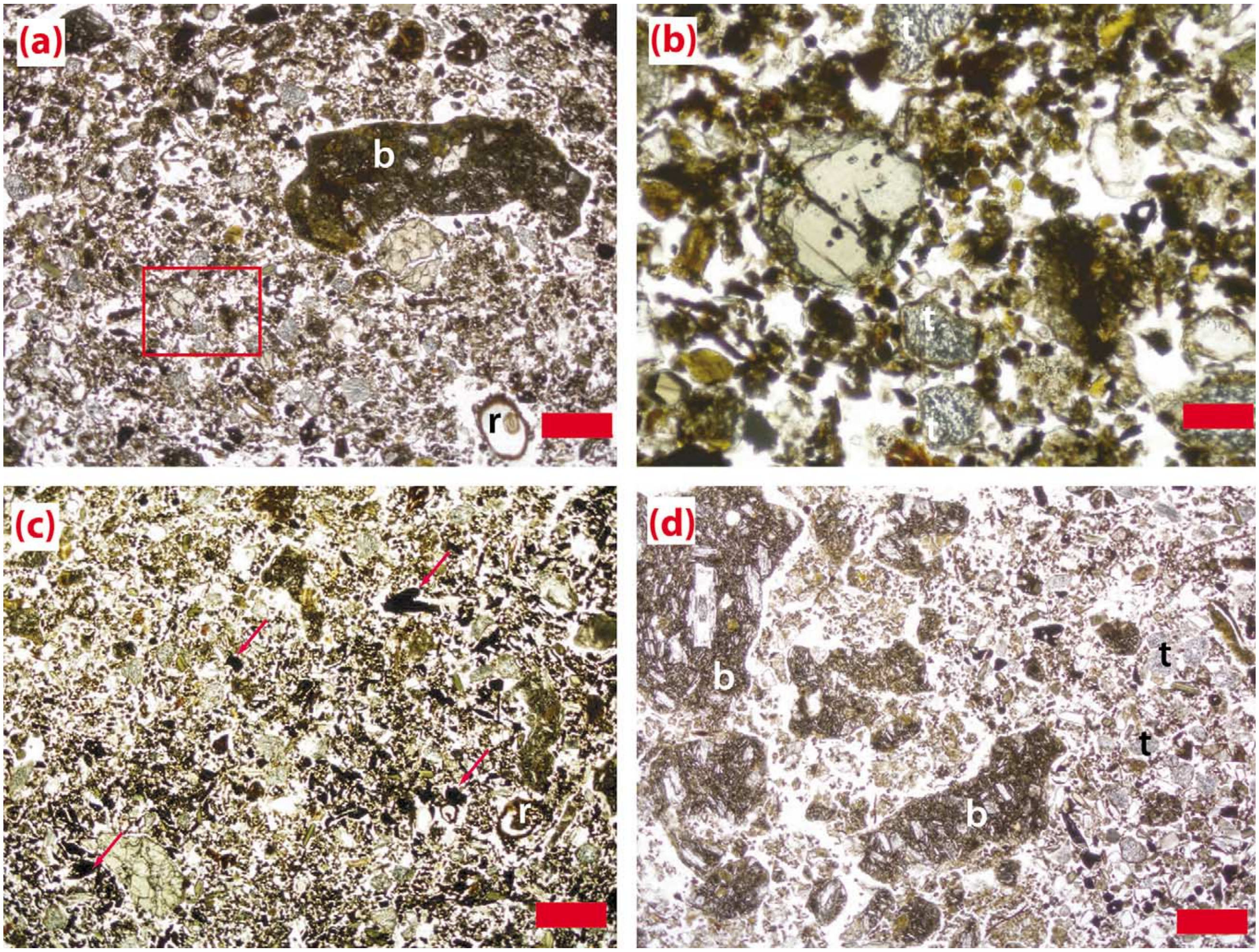

Fig. 4. Micrographs (plane light) of thin sections from Carmacks pedon: (a) Ah1 horizon, ~0.5–1.0 cm depth, with rectangle outlining detail of crumb and spongy microstructures, and tephra particles shown in (b); (c) Ah1 horizon, ~3.0–3.5 cm depth, with numerous charcoal particles (arrows); (d) Ah2 horizon, ~9.0–9.5 cm depth, with basalt fragments and tephra particles. Abbreviations: a, aggregate; b, basalt; c, charcoal; r, root; t, tephra. Scale bars: 1 mm (a, c, d), 0.2 mm (b).

weathering (Anderson 1987) – mean that such scenarios need to be considered by models of soil ecosystem response to climatic change.

The occurrence of these northwestern grassland soils on moisture-shedding, sloping sites also means that lateral movements of materials may be relatively more significant in their genesis than for their counterparts in more gentle topography elsewhere in western Canada. Processes involving downward fluxes, such as carbonate leaching or clay translocation, should be correspondingly less influential. Follow-up studies should examine catenary patterns in these soil landscapes in more detail to assess the degree to which lateral fluxes control the direction of pedogenesis. The parent material complexity exhibited by these pedons, most notably at the Carmacks site, would actually facilitate such research. Dated marker beds with distinctive compositions, such as the White River tephra, can be useful tracers in studies of soil mixing and transport on slopes (Roering et al. 2004). In addition, the late Holocene resumption of loess deposition at Kluane Lake provides an unusual opportunity to examine the responses of soils in a grassland-forest mosaic to aeolian processes (Sanborn and Jull 2009).

CONCLUSIONS

Pedons at three widely separated grassland sites within the Boreal Cordilleran ecozone of northwestern Canada satisfy the current morphological and chemical requirements of the Chernozemic order in the Canadian System of Soil Classification. Ah horizons in these pedons encompass the same range of texture-related variations in microstructure previously reported for Chernozemic soils in southern British Columbia and the Great Plains. Evidence such as landscape patterns of permafrost distribution suggest that low elevation

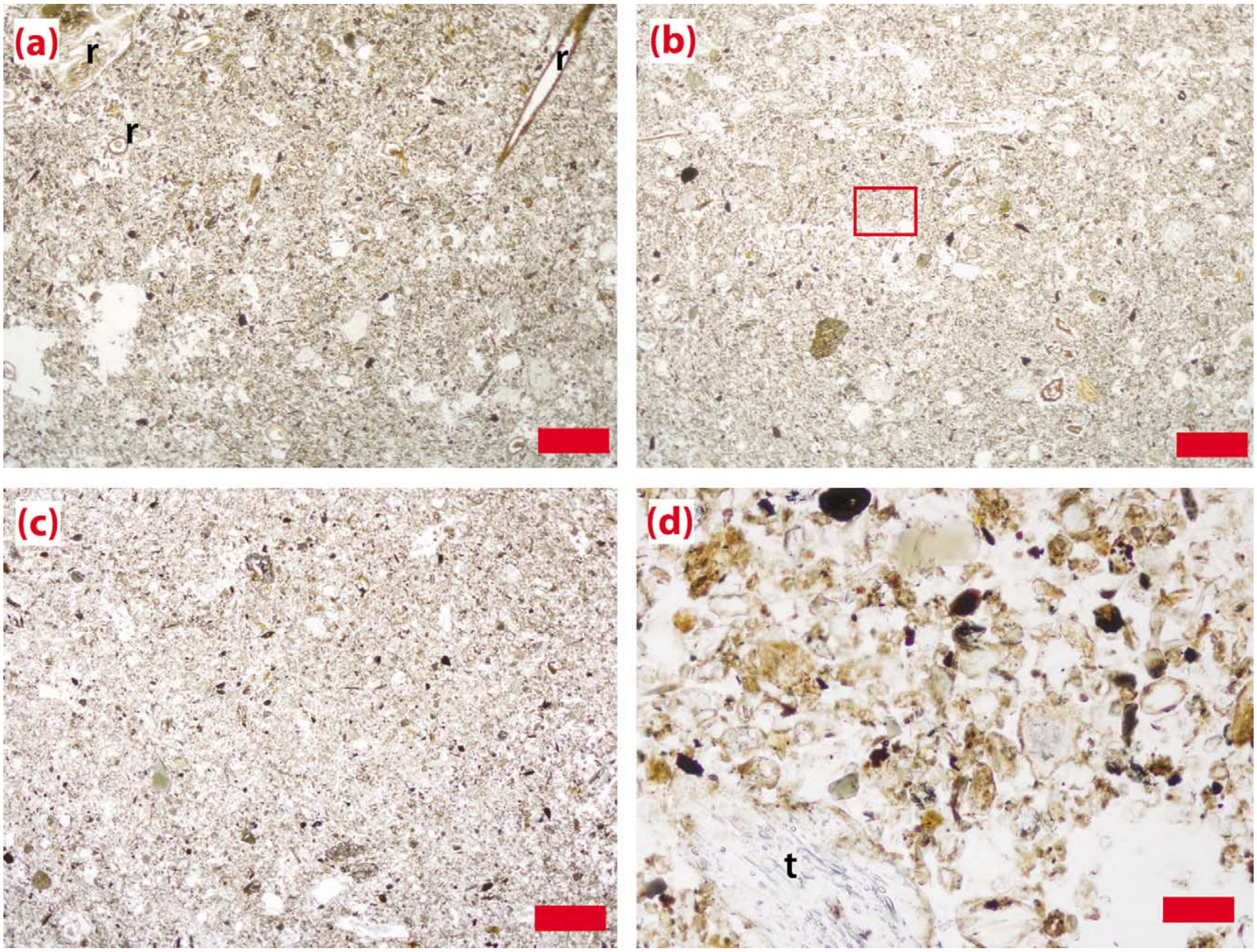

Fig. 5. Micrographs (plane light) of thin sections from Kluane pedon: (a) Ah horizon, ~1.0–1.5 cm depth; (b) Ah horizon, ~5.0–5.5 cm depth, with rectangle outlining detail of coated sand, silt, and tephra particles shown in (d); (c) Ck horizon, ~43.5–44.0 cm depth. Abbreviations: r, root; t, tephra. Scale bars: 1.0 mm (a, b, c), 0.1 mm (d).

(<1000) grassland pedons on south-facing aspects will meet the Chernozemic A horizon criterion for mean annual soil temperatures over 0°C. Although these soils occur well beyond the previously recognized distribution of Chernozems in Canada, this designation recognizes the ecological and pedological identity of these soils as the products of grassland environments.

These soils differ from other Chernozemic soils in western Canada primarily in their landscape patterns and restricted topographic distribution, occurring as aspect-controlled islands in the boreal forest and juxtaposed with strongly contrasting soil types such as Cryosols. The typical occurrence of these soils on steep slopes may accentuate downslope mixing and colluviation during pedogenesis, and contribute to parent material complexity.

ACKNOWLEDGEMENTS

This article is dedicated to Dr. Steve Pawluk, who provided my first opportunity to study Chernozemic soils. Laura Blonski (BC Ministry of Forests and Range) and Dr. Jim Pojar organized the field trip that stimulated this study, and assisted with plant identifications. UNBC students Ekaterina Daviel, Lesley Dampier, and Victoria Prigmore assisted in the field. Vanessa Egginton (BC Ministry of Forests and Range) helped with obtaining climatic data. Scott Smith (Agriculture and Agri-Food Canada) reviewed a draft of this manuscript, and began the field collaboration that eventually led to this study. Nancy Alexander prepared Figure 1. Financial support was provided by a NSERC Discovery Grant, the Canada Foundation for Innovation, the BC Knowledge Development Fund, and UNBC.

Agriculture Canada. 1974. A system of soil classification for Canada. Agriculture Canada, Revised. Information Canada, Ottawa, ON. Publ. 1455, 255 p.

Anderson, D. W. 1987. Pedogenesis in the grassland and adjacent forests of the Great Plains. Adv. Soil Sci. **7**: 53–93.

Arctic Climate Impact Assessment. 2005. Arctic climate impact assessment. Cambridge University Press, Cambridge, UK. 1042 pp.

Buffo, J., Fritschen, L. J. and Murphy, J. L. 1972. Direct solar radiation on various slopes from 0 to 60 degrees north latitude. Research Paper PNW-142, USDA Forest Service, Portland, OR. 74 pp.

Canada Soil Survey Committee, Subcommittee on Soil Classification. 1978. The Canadian system of soil classification. Canada Department of Agriculture, Supply and Services Canada, Ottawa, ON. Publ. 1646, 164 pp.

Carter, M. R., ed. 1993. Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL. 823 pp.

Clague, J. J., Evans, S. G., Rampton, V. N. and Woodsworth, G. J. 1995. Improved age estimates for the White River and Bridge River tephras, western Canada. Can. J. Earth Sci. **32**: 1172–1179.

Clayton, J. S., Ehrlich, W. A., Cann, D. B., Day, J. H. and Marshall, I. B. 1977. Soils of Canada. Vol. 1: Soil report. Research Branch, Canada Department of Agriculture, Ottawa, ON. 243 pp.

Côté, M. M., Burn, C. R. and Smith, C. A. S. 2008. Soil development as a function of air temperature, vegetation cover and permafrost distribution, Keno Hill area, central Yukon. Page 56 *in* Program and Abstracts. Canadian Society of Soil Science, 2008 Jul. 6–10. University of Northern British Columbia, Prince George, BC.

Ecological Stratification Working Group. 1995. A national ecological framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of Environment Directorate, Ottawa/Hull. 125 pp.

Environment Canada. 2007. Canadian Daily Climate Data [CD-ROM].

Expert Committee on Soil Survey. 1983. The Canadian soil information system (CanSIS) manual for describing soils in the field. 1982 revised. Agriculture Canada, Ottawa, ON. 164 pp.

Fenger, M. 1982. Characteristics and distribution of Chernozemic soils in the Ashcroft map area. Pages 133–146 *in* A. C. Nicholson, A. McLean, and T. E. Baker, eds. Grassland ecology and classification symposium proceedings. Miscellaneous Report 037, B.C. Ministry of Forests, Victoria, BC

Fenger, M. and Kowall, R. C. 1992. Biophysical soil landscape inventory of the Stikine-Iskut area (mapsheets 104F, 104G, and parts of 104B and 104H). BC Ministry of Environment, Lands, and Parks, Victoria, BC. 77 pp.

Gee, G. W. and Bauder, J. W. 1986. Particle-size analysis. Pages 331–362 *in* A. Klute, ed. Methods of soil analysis. Part I. Physical and mineralogical methods. Agronomy Monograph 9. SSSA, Madison, WI.

Green, A. J., Valentine, K. W. G. and Brierly, A. 1978. Are there Black Chernozemic soils above treeline in British Columbia? Page 312 *in* Abstracts. Vol. 1, 11th International Congress of Soil Science, Edmonton, AB.

Heginbottom, J. A., Dubreuil, M. A. and Harker, P. A. 1995. Canada – Permafrost *in* National Atlas of Canada. 5th ed. National Atlas Information Service, Natural Resources Canada, Ottawa, ON.

Jackson, L. E., Jr. 2000. Quaternary geology of the Carmacks map area, Yukon Territory. Bulletin 539. Geological Survey of Canada, Ottawa, ON. 74 pp.

Jacobs, P. M. and Mason, J. A. 2007. Late Quaternary climate change, loess sedimentation, and soil profile development in the central Great Plains: a pedosedimentary model. Geol. Soc. Am. Bull. **119**: 462–475.

Laxton, N. F., Burn, C. R. and Smith, C. A. S. 1996. Productivity of loessal grasslands in the Kluane Lake region, Yukon Territory, and the Beringian "production paradox". Arctic **49**: 129–140.

Lord, T. M. and Luckhurst, A. J. 1974. Alpine soils and plant communities of a stone sheep habitat in northeastern British Columbia. Northwest Sci. **48**: 38–51.

McCoy, V. M and Burn, C. R. 2005. Potential alteration by climate change of the forest fire regime in the boreal forest of central Yukon Territory. Arctic **58**: 276–285.

Parfitt, R. L. and Childs, C. W. 1988. Estimation of forms of Fe and Al: a review, and analysis of contrasting soils by dissolution and Moessbauer methods. Austr. J. Soil Res. **26**: 121–144.

Pawluk, S. and Bal, L. 1985. Micromorphology of selected mollic epipedons. Pages 63–83 *in* L. A. Douglas and M. L. Thompson, eds. Soil micromorphology and soil classification. SSSA Special Publication No. 15, SSSA, Madison, WI.

Pennock, D. J. and Acton, D. F. 1989. Hydrological and sedimentological influences on Boroll catenas, central Saskatchewan. Soil Sci. Soc. Am. J. **53**: 904–910.

Pojar, J. 1982. Boreal and subalpine grasslands of northern British Columbia. Pages 249–261 *in* A. C. Nicholson, A. McLean, and T. E. Baker, eds. Grassland Ecology and Classification Symposium Proceedings. Miscellaneous Report 037, B.C. Ministry of Forests, Victoria, BC.

Ponomarenko, E. V. and Anderson, D. W. 2001. Importance of charred organic matter in Black Chernozem soils of Saskatchewan. Can. J. Soil Sci. **81**: 285–297.

Roering, J. J., Almond. P., Tonkin, P. and McKean, J. 2004. Constraining climatic controls on hillslope dynamics using a coupled model for the transport of soil and tracers: application to loess-mantled hillslopes, South Island, New Zealand. J. Geophys. Res. 109: F01010, doi:10.1029/2003JF000034.

Sanborn, P. and Jull, A. J. T. 2009. The pedological record of loess deposition, fire, and slope processes, Kluane Lake, Yukon. Abstracts and program. Canadian Quaternary Association, May 3–8, 2009, Simon Fraser University, Burnaby, BC.

Sanborn, P. and Pawluk, S. 1989. Microstructure diversity in Ah horizons of Black Chernozemic soils, Alberta and British Columbia (Canada). Geoderma **45**: 221–240.

Smith, C. A. S., Meikle, J. C. and Roots, C. F., eds. 2004. Ecoregions of the Yukon Territory – Biophysical properties of Yukon landscapes. Agriculture and Agri-Food Canada, PARC Technical Bulletin 04-01, Summerland, BC. 313 pp.

Soil Classification Working Group. 1998. The Canadian system of soil classification. 3rd ed. Agriculture and Agri-Food Canada, Ottawa, ON. Publication 1646,187 pp.

Spooner, I. S. and Osborn, G. D. 2000. Geomorphology and Late Wisconsinan sedimentation in the Stikine River Valley, northern British Columbia. Quat. Int. **68–71**: 285–296.

Stonehouse, H. B. and St. Arnaud, R. J. 1971. Distribution of iron, clay and extractable iron and aluminum in some Saskatchewan soils. Can. J. Soil Sci. **51**: 283–292.

Stoops, G. 2003. Guidelines for analysis and description of soil and regolith thin sections. SSSA, Madison, WI. 184 pp.

Strickland, A. J., Arocena, J. M., Sanborn, P. and Smith, C. A. S. 2005. Secondary mineral formation in the White River tephra in grassland and forest soils in central Yukon Territory. Can. J. Soil Sci. **85**: 637–648.

Van Ryswyk, A. L., McLean, A. and Marchand, L. S. 1966. The climate, native vegetation, and soils of some grasslands at different elevations in British Columbia. Can. J. Plant Sci. **46**: 35–50.

Valentine, K. W. G., Watt, W. and Bedwany, A. L. 1987. Soils of the Taseko Lakes area, British Columbia. Report No. 36, British Columbia Soil Survey. Research Branch, Agriculture Canada, Ottawa, ON. 131 pp.

Young, G., Fenger, M. A. and Luttmerding, H. A. 1992. Soils of the Ashcroft map area. Report No. 26, British Columbia Soil Survey. MOE Technical Report 23. BC Environment, Victoria, BC. 233 pp.

Zazula, G. D., Froese, D. G., Schweger, C. E., Mathewes, R. W., Beaudoin, A. B., Telka, A. M., Harington, C. R. and Westgate, J. A. 2003. Ice-age steppe vegetation in east Beringia. Nature **423**: 603.