Genesis of Turbic Cryosols on north-facing slopes in a dissected, unglaciated landscape, west-central Yukon Territory

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Smith, C. A. S., Sanborn, P. T., Bond, J. D. and Frank, G. 2009. **Genesis of Turbic Cryosols on north-facing slopes in a dissected, unglaciated landscape, west-central Yukon Territory**. Can. J. Soil Sci. **89**: 611–622. The characteristics and landscape distribution of Histic Dystric Turbic Cryosols were examined on a steep ($>$30%) northerly slope in the unglaciated Klondike Plateau, near Dawson City, Yukon Territory. Based on texture, major element geochemistry, and clay mineralogy, the mineral parent materials were crudely stratified, with a silty material of likely aeolian origin overlying sandy gravelly colluvium. Discontinuous organic matter-enriched horizons occurred 50 cm or more below the active layer, and contained abundant partially decomposed plant detritus. Eight accelerator radiocarbon dates, ranging from 350 ± 40 to 3680 ± 40 ^{14}C years BP, suggested that incorporation of organic materials within and below the active layer was geologically recent, and had likely occurred by a combination of cryoturbation and slope processes. The widespread and rapid initiation of mass movements on slopes containing permafrost that followed forest fires in 2004 on the Klondike Plateau may be an analogue for the processes that contributed to organic matter burial in these Cryosols. These soils may represent a significant reservoir of C, as similar sites occupy at least 15% of a representative portion of the Plateau. This reservoir may be vulnerable to mobilization if future climatic warming increases the frequency of forest fires and resulting slope instability.

Key words: Turbic Cryosol, Yukon Territory, cryoturbation, soil organic carbon, mass movement

Smith, C. A. S., Sanborn, P. T., Bond, J. D. et Frank, G. 2009. **Genèse des Cryosols turbiques sur le versant nord des pentes dans un relief non glaciaire disséqué du centre-ouest du Yukon.** Can. J. Soil Sci. **89**: 611–622. Les auteurs ont examiné les caractéristiques et la distribution du relief des Cryosols histiques dystriques turbiques sur une pente abrupte ($>$30 %) orientée au nord du plateau non glaciaire du Klondike, près de Dawson City, au Yukon. Selon leur texture, la géochimie des principaux éléments et la minéralogie de l'argile, les minéraux mères ont été grossièrement stratifiés avec un matériau limoneux, sans doute d'origine éolienne, qui s'est déposé sur des colluvions de gravier sablonneux. À 50 cm ou plus sous la couche active, on a retrouvé des horizons discontinus enrichis de matière organique contenant une abondance de détritus végétaux partiellement décomposés. Huit dates établies par accélérateur au radiocarbone, allant de 350 ± 40 à $3\,680 \pm 40$ années ^{14}C avant aujourd'hui, laissent croire que l'incorporation des matières organiques à la couche active ou sous celle-ci est relativement récente, géologiquement parlant. On la doit sans doute à une combinaison des processus de géliturbation et de formation de pente. La vaste et rapide initiation des mouvements de masse sur les pentes à pergélisol après les feux de forêt survenus en 2004 sur le plateau du Klondike pourrait équivaloir aux mécanismes qui ont concouru à l'enfouissement de la matière organique dans ces Cryosols. Ces sols pourraient constituer un important réservoir de C, des sites similaires occupant au moins 15 % d'une partie représentative du plateau. Toutefois, ce réservoir pourrait être vulnérable à la mobilisation si le réchauffement climatique accélère la fréquence des feux de forêt et l'instabilité subséquente des pentes.

Mots clés: Cryosol turbique, Yukon, géliturbation, carbone organique du sol

The unglaciated, highly dissected landscapes of west-central Yukon Territory are distinctive environments for soil formation and the study of soil-forming processes. These landscapes lie within the zone of extensive, discontinuous permafrost (Heginbottom et al. 1995) wherein aspect and slope position are strong controls of permafrost distribution and vegetation patterns. Initial descriptions of soil development and distribution in the region were provided by scientific field excursion guidebooks (Pettapiece et al. 1978; Tarnocai et al. 1993), soil surveys (Walmsley et al. 1987) and geological reports (Bond and Sanborn 2006). These efforts provided few details on soil genesis on undisturbed north-facing slopes where soils have been difficult to study due to steep terrain and the presence of near-surface permafrost. Soil descriptions were limited to the active layer and the uppermost few centimetres of the top of permafrost, and therefore provided only a glimpse of

Abbreviations: ICP-AES, inductively coupled argon plasma-atomic emission spectroscopy soils formed on mixed, colluvial parent materials, rich in buried organic matter.

Previous work on the genesis of Cryosolic soils in similar sub-arctic environments in central Alaska have also demonstrated the importance of geomorphology, slope aspect, and slope position in controlling soil thermal regime and related attributes of internal drainage, surface organic matter accumulation and biological productivity (Swanson 1996a; Ping et al. 2005). These and other studies have highlighted the importance of permafrost and cryoturbation in stabilizing large stores of soil organic carbon in arctic and sub-arctic environments (Ping et al. 1997; Shur et al. 2005; Zimov et al. 2006; Bockheim 2007; Ping et al. 2008).

In this study, we present full pedological characterizations of perennially frozen soils on north-facing slopes in the Klondike region of west-central Yukon Territory. Knowledge of soil formation is important to understanding landscape evolution and ecosystem dynamics in this environment. More specifically, we discuss the pedological development of Turbic Cryosols on north-facing slopes, their regional distribution, the potential role of forest fires in their evolution, and the amount and age of soil organic carbon that they contain.

STUDY AREA

The study area is located in the Klondike Goldfields area of west-central Yukon Territory, within the Klondike Plateau, an unglaciated, Tertiary-aged upland that has undergone uplift and subsequent downcutting (Mathews 1986) to produce a landscape of V-shaped headwater stream valleys characterized by uniform steep sidewalls and narrow floodplains. Within this study area we selected a study site in the upper reaches of Bonanza Creek approximately 25 km south of Dawson City, at 63°53′N, 139°13′W to sample a set of representative soil pedons (Fig. 1). The underlying bedrock is a complex of Carboniferous and Permian metamorphic rocks belonging to the Klondike Schist (Gordey and Makepeace 2003). These rocks consist predominantly of quartz-chlorite schist, quartz-muscovite schist, and micaceous quartzite.

Ecologically the study area belongs to the Klondike Plateau Ecoregion (Smith et al. 2004). The climate is strongly continental with warm summers and long cold winters. For the period 1971–2000, the nearest climate station (Dawson Airport, 20 km to the north) reported daily average July temperature of 22°C, daily average January temperature of -31°C, mean annual temperature of -4.4°C and average annual precipitation of 325 mm, most of it falling during the summer months (Environment Canada 2004). The vegetation cover is northern boreal, strongly influenced by slope aspect within valleys. In the absence of recent ($<$ 50 yr) forest fire, northerly slopes are covered with open black spruce (*Picea mariana*) forest with occasional paper birch (*Betula papyrifera*) and underlain by low and medium shrubs particularly *Betula glandulosa, Alnus crispa, Ledum palustre* and *Salix glauca* and a layer of S*phagnum* mosses and lichens 20 to 40 cm thick. Under these vegetation conditions, the permafrost table typically lies approximately 50 cm below the ground surface. In contrast, warmer, drier sites on southerly aspects typically have open tree canopies of white spruce (*Picea glauca*) and aspen (*Populus tremuloides*) and low shrubs including *Rosa acicularis*, *Juniperus communis* and *Linnaea borealis* underlain by feathermosses and lichens (*Cladonia* spp.). These sites are generally permafrost-free.

METHODS

Field

In the summer of 2006, mineral exploration in the upper Bonanza Creek watershed created fresh exposures of soils and underlying colluvium along two 300-m-long, 2-m-deep trenches oriented parallel to the contour at approximately 910 and 960 m elevation, across the upper portion of a north- to northeast-facing 30–35% slope (Fig. 2). Three pedons were examined, of which the two (Y06-04, Y06-05) from the lower trench represent the range of observed soil morphological variation and are reported on in this paper. At each site, a fresh vertical exposure of thawed and still frozen soil was prepared. 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, and an undisturbed sample of the active layer in pedon Y06-04 was collected for thin section preparation.

Analytical

Standard characterization analyses were performed on the air-dry, $<$2 mm fractions. Particle size analysis by the pipette method (Gee and Bauder 1986) after removal of organic matter by hydrogen peroxide, and of sesquioxides by the citrate-bicarbonate-dithionite extraction (Cantest, Winnipeg, MB). Soil chemical analyses (Analytical Chemistry Laboratory, Ministry of Forests and Range, Victoria, BC) included total carbon (C) and nitrogen(N) (LECO CHN-600 Elemental Analyzer), total S (LECO SC-32 Analyzer for organic horizons only), and pH [Fisher Accumet pH Meter (model 915)] using soil:water ratios of 1:1 for mineral soils and 1:2 for forest floors, and a soil:0.01 M $CaCl_2$ ratio of 1:2 for both mineral soils and forest floors. Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, Fe^{3+}, Al^{3+}, Mn^{2+}) were determined by the $BaCl_2$ method (Hendershot and Duquette 1986) with 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,

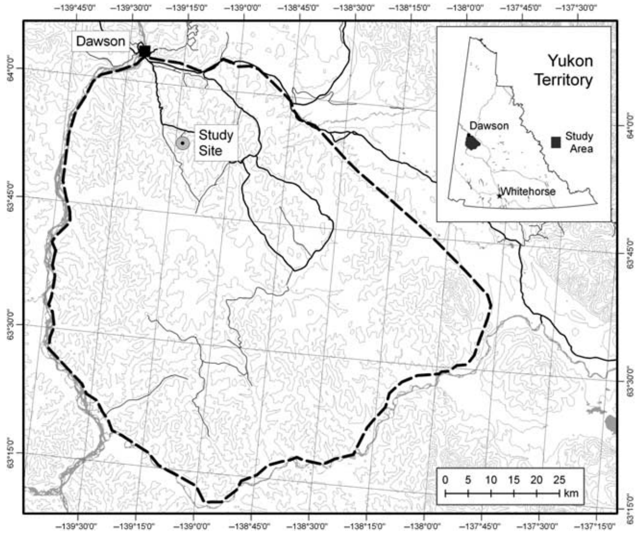

Fig. 1. Location of study area in west-central, Yukon Territory. The dashed line outlines that portion of the Klondike Plateau region utilized for digital landscape analyses to extrapolate the results of the site investigations in the upper reaches of Bonanza Creek south of Dawson City.

acid ammonium oxalate, and citrate-bicarbonate-dithionite methods (Carter 1993) with elemental concentrations in the extracts determined by ICP-AES. Thin sections (30 μm thick) were prepared from an intact sample after impregnation with Spurr Resin (System Three Resin, Auburn, WA).

Sand, silt and clay fractions of selected horizons of pedon Y06-05 were separated by sedimentation after removal of organic matter by hydrogen peroxide, and of sesquioxides by the citrate-bicarbonate-dithionite extraction. Total concentrations of major elements in sand and silt fractions were determined by ICP-AES after lithium metaborate fusion (ALS Chemex, North Vancouver, BC). Clay minerals were identified by X-ray diffraction analysis (Co Kα radiation; Bruker AXS D8 Discover diffractometer) after standard humidity, heating and solvation treatments (Ca-saturated: 54% relative humidity, ethylene glycol, glycerol; K-saturated: 0% and 54% relative humidity, 300°C, 550°C) (McKeague 1978), using criteria summarized by Arocena and Sanborn (1999) and Moore and Reynolds (1997).

Eight samples of buried organic materials collected below the active layers of pedons Y06-04 and Y06-05 were submitted for radiocarbon dating by accelerator mass spectrometry (Beta Analytic, Miami, FL).

RESULTS

Pedons Y06-04 and Y06-05 represent the range in soil morphological variability exposed along the exploration trenches (Figs. 3 and 4; Tables 1 and 2). Both pedons had a surficial cover of 20–30 cm of poorly decomposed peat, which insulates the soil from thawing during the summer months. In July 2006, when we sampled these soils, seasonal frost was encountered at approximately 50 cm below ground level, less than 10 cm below the base of the O horizons. The permafrost table is likely 60–70 cm below the surface. Field observations and soil texture data (Tables 3 and 4) suggest a crude stratification of parent materials, with an upper silty material approximately 1 m thick containing few coarse fragments, overlying IICz horizons formed in coarser colluvium consisting of fragmented schistose bedrock with a sandy loam matrix.

Ground ice content within the upper silty material below the permafrost table was estimated at 1 to 2% by volume and composed of vesicular pore ice and very fine ice lenses typically 1 mm thick. Within the underlying coarser colluvial material total ice content was much higher. Pore ice content was estimated at close to 5% and many coarse fragments were surrounded by clear, ice coatings up to 5 mm thick estimated at 20% by volume.

There appears to have been some mixing of the two parent materials in pedon Y06-04 producing an irregular boundary between them, while in Y06-05 the contact between parent materials is smoother (Figs. 3 and 4). The upper mineral parent material is highly cryoturbated and includes the current active layer and both mineral and organic horizons below the permafrost table. Some horizons within this parent material, both within and below the active layer are rich in organic matter and have been designated as Ahy or Omy depending on their total C concentrations (Tables 3 and 4). (Field testing indicated that carbonates were not present in any of the horizons, so total C can be taken as a reasonable estimate of organic C concentration.) This organic material is not highly decomposed, with C:N ratios ranging from 25 to 35, and appears in the field to have been incorporated at depth through physical mixing by cryoturbation and slope processes. As a result, total C concentrations exceed 2% in all horizons except the IICz in pedon Y06-05.

All of the horizons are extremely to very strongly acidic in reaction with pH increasing slightly with depth (Tables 3 and 4). Ca^{2+} or Al^{3+} is the most abundant exchangeable cation in all horizons (data not shown).

Relative concentrations of pyrophosphate-, oxalate- and dithionite-extractable Fe are broadly similar in all horizons formed in the silty parent material, suggesting that most of the Fe is organically complexed (Tables 3 and 4). Pyrophosphate- and oxalate-extractable Al concentrations are also similar in these horizons, also suggesting a dominance of organically complexed Al. Oxalate-extractable Si is negligible in all horizons. Three A and one B horizon, of which two are below the permafrost table, meet the chemical criteria for Bhf horizons. However, the detrital nature of the organic matter in these horizons and the environmental setting precludes classifying these as Podzolic B horizons or

Fig. 2. Landscape view, facing west, of study site on the north side of the divide between Bonanza and Eldorado Creeks. Pedons Y06-04 and Y06-05 were sampled in an exploration trench constructed in 2006 (inside white ellipse).

these soils as members of the Podzolic order within the Canadian System of Soil Classification.

In addition to prominent, discontinuous horizons with more than 10% C both within and below the active layer, horizons that are less obviously enriched in organic matter have localized zones of concentrated plant residues that are visible on the microscopic scale. In the Bmy of pedon Y06-05, organic components are distributed in a patchy fashion throughout (Fig. 5). These include intact plant residues showing birefringence, indicating the presence of cellulose, as well as more fragmented and occasionally charred organic materials (Fig. 5b–e). Mineral-rich zones are dominated by silt, with only scattered sand grains (Fig. 5a), and display the banded fabric characteristic of soils in which segregated ice lenses have formed (Fig. 5a).

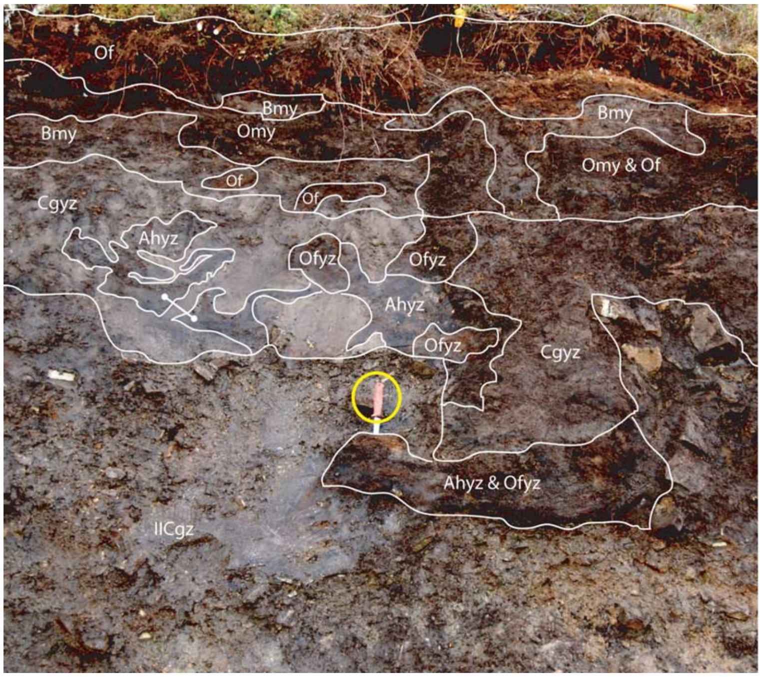

Fig. 3. Horizon boundaries of pedon Y06-04. Knife handle is 11 cm long.

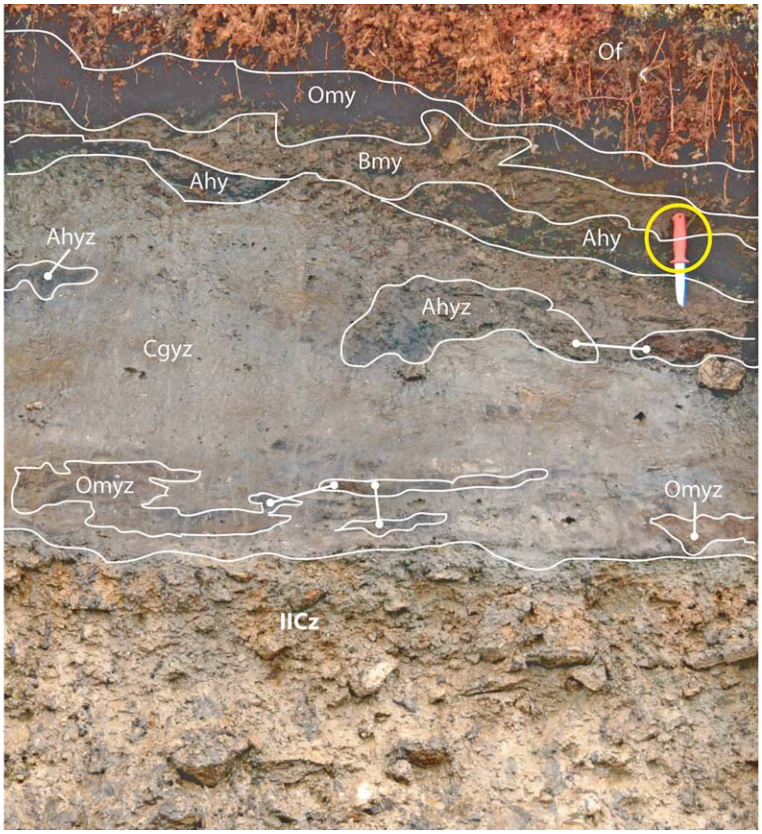

Fig. 4. Horizon boundaries of pedon Y06-05. Knife handle is 11 cm long.

Although the small number of samples precludes a statistical comparison, the major element geochemistry of both the silt and sand fractions (Table 5) suggests the Bmy and Cgyz horizons have more in common with each other than with the IICz. In particular, the two upper horizons have conspicuously higher SiO_2 and CaO, and lower Al_2O_3, Fe_2O_3, MgO, and K_2O concentrations than the IICz horizon.

Clay fraction mineral assemblages (Fig. 6) were similar in the Bmy and Cgyz horizons of pedon Y06-05, with the following relative abundances based on diffraction peak heights: mica > chlorite ~ vermiculite > chlorite-vermiculite intergrade > quartz. In the IICz horizon, the major differences appeared to be a greater relative abundance of vermiculite, yielding a ranking of: mica > vermiculite > chlorite ~ chlorite-vermiculite

Table 1. Morphological description of pedon Y06-04 (Histic Dystric Turbic Cryosol). Depth intervals are not reported due to disruption of horizons by cryoturbation (see Fig. 3)

Horizon	Description
Of	Brown (7.5YR 4/4 m) and strong brown (7.5YR 4/6 m) poorly decomposed moss peat; abundant very fine, fine, and medium roots; common wood and charcoal fragments; clear wavy boundary; 10–20 cm thick; extremely acid.
Omy	Very dark gray (7.5YR 3/1 m) and dark brown (7.5YR 3/2 m) moderately decomposed moss peat; plentiful very fine and fine roots; occasional wood and charcoal fragments; clear, broken boundary: 0–20 cm thick; extremely acid.
Bmy	Very dark gray (10YR 3/1 m); silt loam; weak to moderate, fine and medium subangular blocky; friable, slightly sticky, slightly plastic; few very fine roots; < 5% coarse fragments; clear, broken boundary; 0–20 cm thick; extremely acid.
Cgyz	Dark gray (2.5Y 4/1 w); silt loam; massive; plentiful very fine roots; 5% coarse fragments; 5% fine pore ice (1–2 mm diameter), with occasional ice veins up to 5 mm thick; clear, broken boundary; 0–60 cm thick; extremely acid.
Ofyz	Dark brown (7.5YR 3/4 w) and strong brown (7.5YR 4/6 w); fibrous, poorly decomposed moss peat; few fine roots; some charcoal; 1% coarse fragments; 100% pore ice; abrupt, broken boundary; 0–10 cm thick; extremely acid.
Ahyz	Very dark gray (10YR 3/1 w); silt loam; massive; plentiful very fine roots; 0% coarse fragments; < 5% pore ice; abrupt, broken boundary; 0–20 cm thick; extremely acid.
IICgz	Very dark grayish brown (2.5Y 3/2 w); sandy loam; massive; 75% coarse fragments; ~30% ice content, consisting of common ice lenses (up to 5–10 mm thick) associated with coarse fragments, with finer ice veins throughout matrix; extremely acid.

Table 2. Morphological description of pedon Y06-05 (Histic Dystric Turbic Cryosol) (see Fig. 4)

Horizon	Depth (cm)	Description
Of	0–20	Yellowish red (5YR 5/6 m) fibrous *Sphagnum* peat; abundant fine and medium roots; clear wavy boundary; 18–27 cm thick; extremely acid.
Omy	20–30	Very dark brown (10YR 2/2 m) moderately decomposed moss peat; common wood fragments; abundant very fine and fine roots; clear, wavy boundary; 4–10 cm thick; extremely acid.
Bmy	30–48	Dark brown (10YR 3/3 m), with streaks of black (10YR 2/1 m); silt loam; weak to moderate, fine and medium subangular blocky; friable; few very fine and fine, very few medium roots; 15% coarse fragments; clear, wavy boundary; 15–25 cm thick; extremely acid.
Ahy	48–50	Very dark grayish brown (2.5Y 3/2 m) and black (10YR 2/1 m); silt loam; weak, fine and medium platy; friable; slightly sticky; few very fine roots; 5% coarse fragments; few wood fragments; clear, broken boundary; 0–5 cm thick; extremely acid.
Cgyz	50–130	Very dark grayish brown (2.5Y 3/2 m); loam; few, fine and medium, prominent, strong brown (7.5YR 4/6 m) mottles; massive; occasional charcoal fragments up to 5 mm diameter; 10% coarse fragments; pore ice and clear ice lenses up to 10 mm thick beneath clasts in upper 1/3 of horizon; abrupt, wavy boundary; 35–80 cm thick; extremely acid.
Ahyz	70–85	Black (10YR 2/1 m); silt loam; massive; 0% coarse fragments; clear, broken boundary; 0–20 cm thick; extremely acid.
Omyz	100–130	Black (10YR 2/1 m); silt loam; massive; common charcoal fragments up to 5 mm thick; 10% coarse fragments; clear, broken boundary; consists of parallel bands 1–5 cm thick, including thin bands (~1 cm thick) of peat concentrated in lowest 30 cm of Cgyz; 25–35 cm thick; extremely acid.
IICz	130–180+	Brown (7.5YR 4/4 m) and dark grayish brown (2.5YR 4/2 m); sandy loam; massive; 75% coarse fragments; common silt coatings 1–2 mm thick on clasts; extremely acid.

intergrade > >quartz. Kaolinite was absent, based on the lack of doublet reflections at 0.357 and 0.354 nm.

All of the radiocarbon dates for organic materials recovered from below the active layer in pedons Y06-04 and Y06-05 were mid- to late Holocene, ranging from 350 ± 40 to 3680 ± 40 ^{14}C years BP, with older dates at greater depth (Table 6).

Both pedons meet the criteria of the Histic Dystric Turbic Cryosol subgroup within the Cryosol order of the Canadian System of Soil Classification (Soil Classification Working Group 1998) based on the presence of highly cryoturbated surface horizons above a near-surface permafrost table, the highly acidic reaction within the solum and a peaty surface horizon >15 cm thick.

DISCUSSION

These recent exposures provided an unusual opportunity to examine Cryosol horizons and parent materials well below the permafrost table, and to consider their

Table 3. Selected physical and chemical properties of pedon Y06-04

		%					Exch. cations[z]		
Horizon	Depth (cm)	Sand	Silt	Clay	Total C	Total N	cmol (+) kg^{-1}	pH(H_2O)	pH($CaCl_2$)
Of	N/A				52.9	1.03	45.68	4.10	3.50
Omy					25.1	1.04	36.04	4.54	3.96
Bmy		21.9	64.2	13.9	7.7	0.33	13.10	4.72	3.99
Cgyz		28.9	59.3	11.8	5.7	0.25	9.76	4.74	3.97
Ofyz					40.0	1.24	46.74	4.74	4.14
Ahyz		19.1	66.0	14.9	12.3	0.48	13.37	4.61	3.90
IICgz		57.6	35.3	7.1	2.6	0.11	5.95	5.08	4.17

		%					
Horizon	Depth (cm)	Al_p[y]	Al_o	Fe_p	Fe_o	Fe_d	Si_o
Of							
Omy							
Bmy		0.258	0.213	0.484	0.470	0.528	0.052
Cgyz		0.264	0.224	0.403	0.416	0.423	0.066
Ofyz							
Ahyz		0.352	0.270	0.752	0.788	0.814	0.044
IICgz		0.152	0.117	0.294	0.355	0.424	0.038

[z] Exchangable cations equal the sum of $BaCl_2$-extractable Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Fe^{3+}, Al^{3+}, and Mn^{2+}.

[y] Subscripts for Al, Fe, and Si extractions: p = pyrophosphate, o = oxalate, d = dithionite.

Table 4. Some physical and chemical properties of pedon Y06-05

		%					Exch. cations[z]		
Horizon	Depth (cm)	Sand	Silt	Clay	Total C	Total N	cmol (+) kg^{-1}	pH(H_2O)	pH($CaCl_2$)
Of	0–20				50.6	0.57	27.36	3.78	2.95
Omy	20–30				34.3	1.31	28.34	4.29	3.56
Bmy	30–48	40.6	50.3	9.1	2.4	0.09	4.24	4.92	3.90
Ahy	48–50	20.1	65.1	14.8	15.4	0.53	12.28	4.69	3.90
Cgyz	50–130	45.9	45.4	8.8	2.7	0.11	4.23	4.89	3.97
Ahyz	70–85	27.1	59.6	13.4	9.4	0.35	8.22	4.90	4.02
Omyz	100–130	21.1	62.5	16.4	18.4	0.51	12.09	5.05	4.23
IICz	130–180+	63.8	32.9	3.4	0.4	0.02	5.26	5.43	4.37

		(%)					
Horizon	Depth (cm)	Al_p[y]	Al_o	Fe_p	Fe_o	Fe_d	Si_o
Of	0–20						
Omy	20–30						
Bmy	30–48	0.193	0.181	0.342	0.471	0.563	0.062
Ahy	48–50	0.385	0.416	1.518	1.810	1.785	0.043
Cgyz	50–130	0.192	0.151	0.345	0.425	0.529	0.044
Ahyz	70–85	0.261	0.257	0.846	1.006	1.026	0.033
Omyz	100–130	0.553	0.621	2.583	3.570	3.261	0.064
IICz	130–180+	0.055	0.085	0.157	0.466	1.091	0.065

[z] Exchangable cations equal the sum of $BaCl_2$-extractable Ca^{2+}, Mg^{2+}, K^+, Na^+, Fe^{3+}, Al^{3+}, and Mn^{2+}.
[y] Subscripts for Al, Fe, and Si extractions: p = pyrophosphate, o = oxalate, d = dithionite.

origins in relation to the geomorphic setting. Although pedons Y06-04 and Y06-05 differ in their morphological complexity, both contain organic matter-enriched horizons more than 50 cm below the permafrost table, as well as two strongly contrasting parent materials.

The Holocene radiocarbon ages yielded by the deeply incorporated organic and Ah horizons indicate that considerably deeper thawing and/or mass movement has occurred repeatedly at these upper slope sites in the geologically recent past. The presence of charcoal in most of these horizons suggests that such episodes may be triggered by forest fires, such as those that occurred during the summer of 2004 in the Dawson City area (Lipovsky et al. 2006; Coates 2008; Coates and Lewkowicz 2008). According to Coates (2008), active layer detachment failures occurred up to 2 yr after these fires and were largely restricted to areas underlain by extensive permafrost, similar to our study site. At the toe of such detachment failures, rafted and in situ organic material becomes buried and subsequently folded within the debris pile (Coates 2008). These processes could have occurred at our study site in the past, but its upper slope position was far enough above the runout zones of such failures that organic materials were incorporated and buried without completely obscuring the contrast between the differing mineral parent materials. Swanson (1996b) found a similar pattern of fire-induced permafrost thaw in interior Alaska that indicated north-facing upper slope positions (but not necessarily lower slope positions) as susceptible to the kind of thaw that could initiate mass movements if slope angle was sufficient. Burial of organic materials by similar events, followed by re-establishment of permafrost in the reworked colluvium, may be the mechanisms responsible for formation of these intermixed organic and mineral horizons. The youthfulness of the radiocarbon ages (<4000 ^{14}C years BP) suggests that the upper silty horizons are actively involved in mass movements, so that the residence time of these materials will likely be limited to the current interglacial.

The upper parent material at these sites differs in texture, major element composition, and clay mineralogy from the underlying coarser colluvium, suggesting a different geological origin. The former is similar in its texture and organic matter content to the much thicker "muck" deposits found in toe slope and valley bottom settings throughout the Klondike Goldfields (Fraser and Burn 1997; Sanborn et al. 2006). Muck has been interpreted as reworked loess that accumulated primarily during the McConnell (Wisconsinan) glaciation (Fraser and Burn 1997), although more recent tephrochronological studies indicate that muck also accumulated during earlier Pleistocene glacial climates (Sanborn et al. 2006; Westgate et al. 2008). Unlike the weakly calcareous muck, the silty materials at these sites are quite acidic, both within and below the active layer, indicating that any original carbonates were removed by weathering.

Apart from one earlier report of abundant mica and chlorite in bulk samples of silty muck (Fraser and Burn 1997), there is no comparative published information

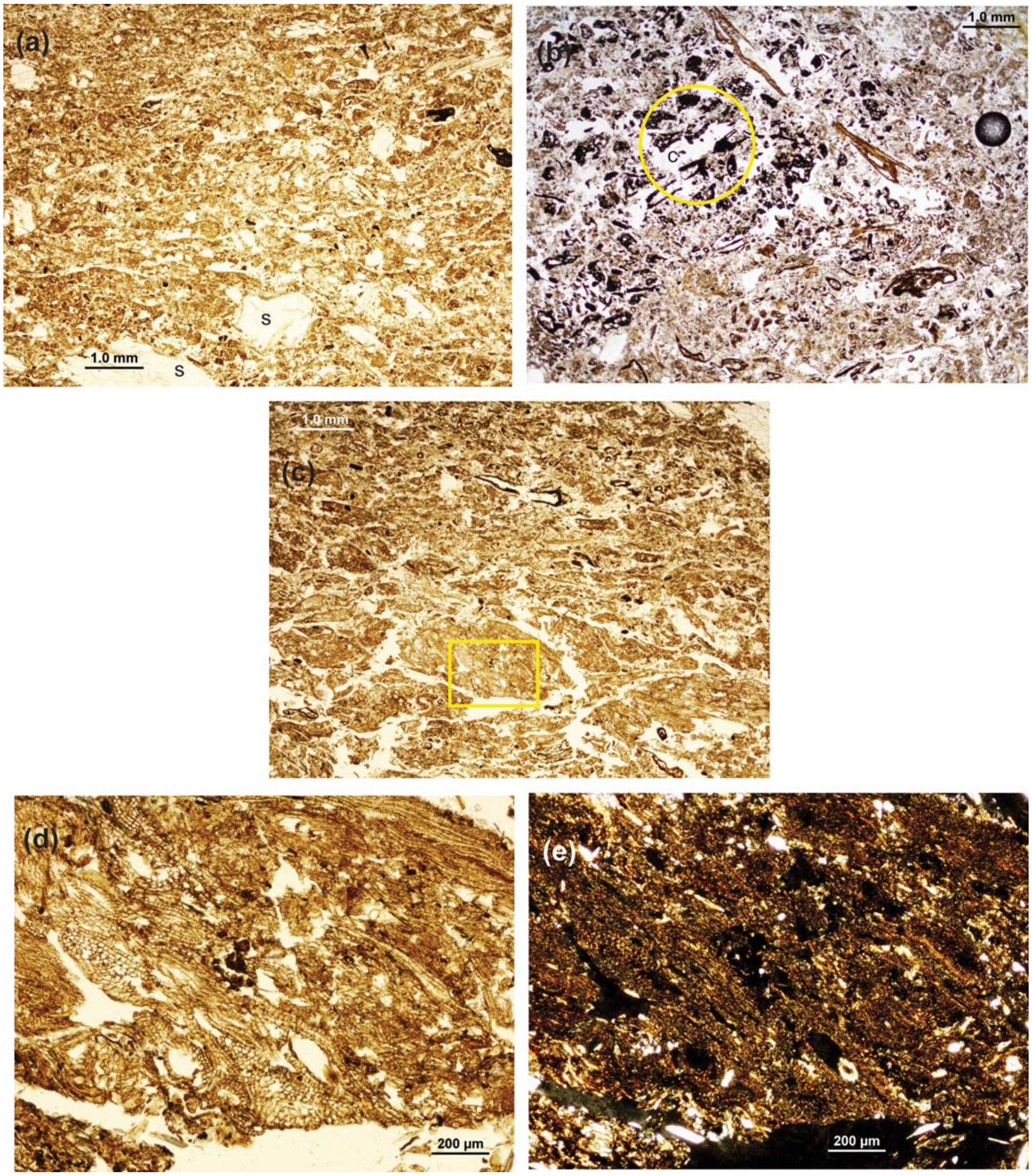

Fig. 5. Micromorphology of Bmy horizon, pedon Y06-05 (plane light, except as noted otherwise): (a) banded fabric with predominance of mineral components (s = sand grains); (b) spongy mixture of fresh, partially humified, and charred (= c; circled) organic materials; (c) organic components dominate lower half of image, with cellular structure clearly visible in boxed area shown at higher magnification under plane (d) and polarized (e) light.

available for the clay mineralogy of this soil parent material in the Klondike goldfields. For a limited number of central Yukon soils formed on Quaternary glacial deposits (Foscolos et al. 1977), the clay mineralogy of surficial aeolian veneers of presumed McConnell age broadly resembled that of the upper silty material at our site, with the major difference being that kaolinite was also reported. In the case of the lower colluvial unit at our site, the presence of vermiculite and a chlorite-vermiculite intergrade may be the cumulative legacy of weathering in previous interglacials that were warmer and/or longer than the current one. An indication of the depth and character of such weathering was provided by a site approximately 400 m to the west, where much older trenching had resulted in complete thawing of the permafrost, exposing more than 5 m of weakly coherent schist-derived saprolite and colluvium. In clay fractions separated from this material, chlorite-vermiculite intergrades appeared to rank second in abundance after mica (Sanborn, unpublished data). Mineralogical studies in

Table 5. Major element geochemistry of silt and sand fractions for selected horizons of pedon Y06-05

	Silt			Sand		
Element oxide (%)	Bmy	Cgyz	IICz	Bmy	Cgyz	IICz
SiO_2	73.30	71.70	65.60	78.50	80.10	74.30
Al_2O_3	12.55	11.80	15.45	9.98	9.64	11.65
Fe_2O_3	3.28	3.00	4.15	1.58	1.36	2.42
CaO	1.57	1.62	1.01	0.44	0.39	0.24
MgO	1.86	1.76	2.53	0.94	0.88	1.25
Na_2O	1.97	1.90	1.83	2.84	2.88	2.41
K_2O	2.38	2.22	3.96	1.83	1.73	3.06
Cr_2O_3	0.01	0.01	0.02	0.02	0.01	0.01
TiO_2	0.85	0.86	0.84	0.35	0.35	0.47
MnO	0.04	0.04	0.04	0.02	0.01	0.02
P_2O_5	0.05	0.07	0.08	0.04	0.05	0.07
SrO	0.02	0.02	0.02	0.01	0.01	0.01
BaO	0.18	0.19	0.29	0.15	0.15	0.23
LOI[z]	3.20	2.36	3.84	1.52	1.43	1.90
Sum	101.26	97.55	99.66	98.22	98.99	98.04

[z] LOI = loss on ignition (1000°C).

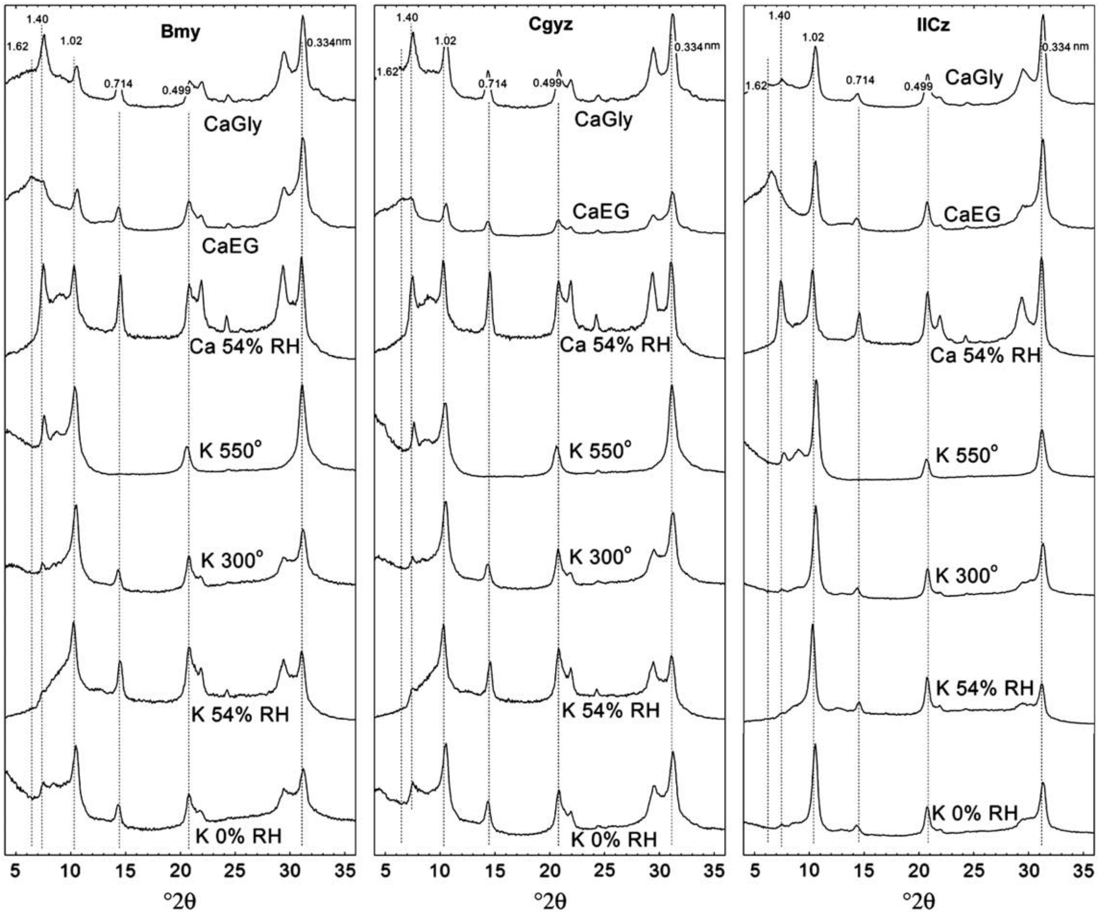

Fig. 6. X-ray diffractograms for clay fractions of selected horizons, pedon Y06-05. Treatment codes for Ca- and K-saturated samples: relative humidity (0% RH, 54% RH), heating (300°C, 550°C), salvation (EG = ethylene glycol, Gly = glycerol).

Table 6. Accelerator radiocarbon dates for organic materials sampled below the active layer in pedons Y06-04 and Y06-05

Sample no.	Lab no.	Horizon	Material	Depth (cm)	Radiocarbon age (^{14}C yr BP)
Y06-04-C2	Beta-226023	Ofyz	Peat	60	350 ± 40
Y06-04-C3	Beta-226024	Ofyz	Peat	50	420 ± 40
Y06-04-C4	Beta-226025	IICgz	Charcoal	130	2070 ± 40
Y06-04-C5	Beta-226026	Ahyz & Ofyz	Peat	125	2300 ± 40
Y06-05-C2	Beta-226027	Ahyz	Charcoal	80	1270 ± 40
Y06-05-C3	Beta-226028	Omyz	Charcoal	110	3680 ± 40
Y06-05-C4-A	Beta-226029	Omyz	Charcoal	110	3260 ± 40
Y06-05-C4-B	Beta-226030	Omyz	Peat	110	2810 ± 40

progress for other Klondike Plateau soils formed in colluviated weathered bedrock with varying admixtures of loess (Bond and Sanborn 2006), will provide a stronger basis for understanding the weathering history of upland soils in the unglaciated Klondike Plateau.

The deep (up to 2 m) incorporation of organic matter by cryoturbation and periglacial slope processes has a broader significance beyond that of soil genesis at the scale of individual pedons. Carbon budget studies (Ping et al. 2008) are now recognizing the global significance of sub-surface C stocks in perennially frozen soils and sediments in arctic and subarctic environments. Though not collected with C budget studies in mind, our observations contribute to the limited soil C data available for the discontinuous permafrost zone. Fig. 7 illustrates our estimate of the potential extent of these Turbic Cryosols occurring under similar site conditions in the study region. Utilizing a digital elevation model (GeoBase® 1:50 000 Canadian Digital Elevation Data), ArcINFO GRID™ software and a set of programmed decision rules to create slope, aspect and elevation rasters, we estimate these soils to occupy approximately

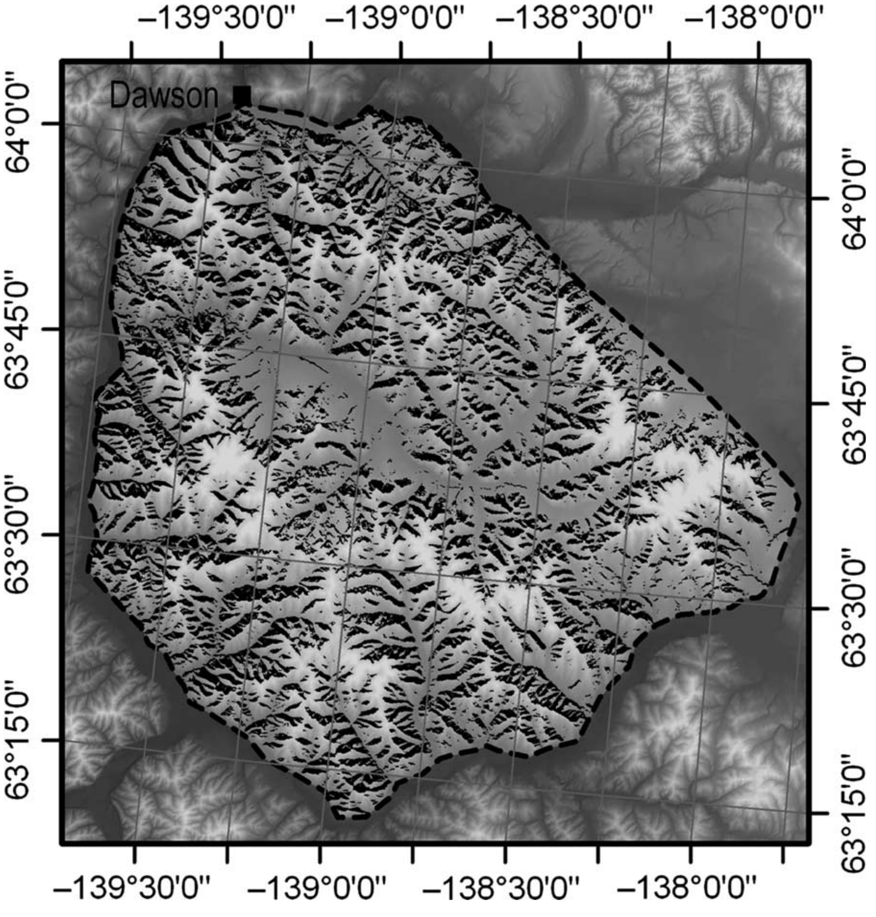

Fig. 7. Dark areas highlight the potential distribution of Histic Dystric Turbic Cryosols as described in this paper in the study region based on the landform characteristics of slopes >30%, elevation <950 m asl, and slope aspect between 300° and 60°.

15% (900 km^2) of our study area (see Fig. 1), which is broadly representative of the regional physiography. Scaling these values up to the entire Klondike Plateau ecoregion (Smith et al. 2004), these soils potentially cover as much as 5800 km^2 in west-central Yukon.

New evidence for the longevity of permafrost in muck-like valley bottom sediments in the Klondike Goldfields is reassuring with respect to the preservation of associated C stocks in future warmer climates (Froese et al. 2008). Based on the available digital elevation model and geographic information system calculations, prior to the advent of placer mining the areal extent of such deposits may have been approximately 5% of our study region. However, the much more extensive mid- and upper-slope portions of this landscape, particularly on northerly aspects, also need to be considered in any regional estimate of soil C stocks. C retained on sites similar to those described here may be much more vulnerable to loss if climate-related changes to forest fire regimes trigger more frequent and widespread exposure of organic matter stored in the upper 1–2 m of hillslope Cryosols.

More data on C concentration, bulk density, and soil thickness would be needed to enable this preliminary modeling exercise to provide a first estimate of C stocks across the range of landscape positions in this region.

CONCLUSIONS

Histic Dystric Turbic Cryosols are a common soil type on north-facing slopes in the dissected plateau landscapes of west-central Yukon. These soils form through the interaction of landscape position, slope aspect, slope angle, the presence of near-surface permafrost and a frequent forest fire cycle. We observed two distinct mineral parent materials within these soils: an upper silty material composed primarily of reworked loess of presumed Wisconsinan age, and an underlying gravelly sandy loam interpreted as local bedrock-derived colluvium. Fire-induced thawing lowers the permafrost table and releases excess water within the upper solum. This can initiate debris flow mass movements, mixing parent materials if the depth of thaw is sufficient, and incorporating surface organic materials into the flow. Subsequent freeze-back and cryoturbation during the decades following the disturbance, traps and preserves these well to poorly decomposed organic materials. Over time, a significant mass of organic carbon may build up within the top of permafrost. This is apparently an active transport process; all of the dated organic materials from the pedons studied were of mid- to late Holocene age. Given the concentrations of carbon preserved in these soils and their apparent extensive geographic distribution in the central Yukon, they represent a significant and vulnerable store of soil organic carbon in this region of the discontinuous permafrost zone of northern Canada.

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