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Late Tertiary and Early Pleistocene Paleosols in Northwestern Canada[1]

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ABSTRACT. Late Tertiary paleosols occurring in the unglaciated portion of the Yukon Territory of northwestern Canada have either Podzolic or Luvisolic soil development. The early Pleistocene paleosols in this area also display Luvisolic soil development in addition to cryogenic soil properties resulting from frost action. Most of these latter paleosols have deeply weathered sola and they usually have rubified argillic horizons. These soil properties suggest that the climate during the late Tertiary and early Pleistocene was warmer than at present. The cryogenic soil properties found in the early Pleistocene paleosols suggest that these soils were exposed to cold climates during subsequent glacial periods.

Key words: paleosols, late Tertiary, early Pleistocene, northwestern Canada, soil environments, soil development

RÉSUMÉ. Les paléosols du Tertiaire tardif qui s'étendent dans la partie du Yukon (nord-ouest du Canada) n'ayant pas subi l'action des glaciers présentent les caractéristiques d'un sol soit podzolique, soit luvisolique. Les paléosols du Pléistocène précoce de cette région présentent eux aussi les caractéristiques d'un sol luvisolique en plus de posséder les propriétés d'un sol cryogène résultant de l'action du gel. La plupart de ces derniers paléosols ont un solum profondément érodé et ils contiennent habituellement des horizons argilliques rubéfiés. Ces propriétés indiquent que le climat durant le Tertiaire tardif et le Pléistocène précoce était plus chaud qu'actuellement. Les propriétés des sols cryogènes présents dans les paléosols du Pléistocène précoce laissent supposer que ces sols ont été exposés à des climats froids durant les périodes glaciaires subséquentes.

Mots clés: paléosols, Tertiaire tardif, Pléistocène précoce, nord-ouest canadien, environnements pédologiques, formation des sols

РЕФЕРАТ. Палеосолы конца третичного периода, встречающиеся в не охваченной оледенением части территории Юкон на северо-западе Канады, сформировались в результате развития подзолистых или лювисольных процессов. Раннеплейстоценовые палеосолы этого района также носят характер лювисолов, а кроме того обладают свойствами мерзлотного происхождения. Для большей части раннеплейстоценовых палеосолов характерен сильно выветренный солюм. В их составе также часто встречаются горизонты красной глинистой почвы. Эти черты указывают на то, что в конце третичного периода и в начале плейстоцена климат в этих районах был теплее, чем в настоящее время. Присущие раннеплейстоценовым палеосолам свойства мерзлотного происхождения говорят о том, что эти почвы подвергались воздействию холодного климата в течение более поздних ледниковых периодов.

Ключевые слова: палеосолы, конец третичного периода, ранний плейстоцен, северо-запад Канады, экология почв, почвообразование.

INTRODUCTION

Late Tertiary paleosols were studied in the unglaciated Old Crow and Bluefish River areas in the northern Yukon (Tarnocai, 1987a,b,c). These Podzolic and Luvisolic soils developed on fluvial, colluvial and residual materials. Early Pleistocene paleosols were studied in the central Yukon (Tarnocai *et al.*, 1985; Smith *et al.*, 1986) and the Mackenzie Mountains. These early Pleistocene paleosols are Luvisolic soils that developed on pre-Reid (pre-Illinoian) glacial materials (Hughes *et al.*, 1972, 1983; Hughes, 1987). Bostock (1966) inferred two pre-Reid glacial advances, the Nansen (older) and the Klaza. These two advances have not been differentiated outside the area Bostock mapped and have been combined under the term pre-Reid glaciations (Hughes *et al.*, 1972, 1983; Hughes, 1987). Paleosolic evidence, however, suggests that at least four cold periods, possibly associated with glaciations, occurred during the pre-Reid period.

Paleosols developed in previous environments on landscapes that were stable for a period of time and they retain the imprint of the soil-forming factors active in those environments. The paleosols discussed here were either buried or found at or near the surface. Pedological processes have ceased in the buried paleosols. During burial, however, the soil can be severely truncated. After burial, soil properties can be modified by factors such as ground water. Paleosols that remained on the surface were exposed to varying climates and can thus exhibit contrasting soil properties.

It is therefore necessary to examine a number of pedons in the same geological deposit to reconstruct and establish the range of soil development. In order to determine the soil-forming processes it is also necessary to group the pedons according to parent materials, drainage and elevation. Using this approach, it is possible to reconstruct the soil development in a specific environment (Tarnocai and Valentine, 1989; Tarnocai and Smith, 1989).

In order to develop models to reconstruct the environment under which paleosols developed, analogous modern soils are used to determine which principal climatic, vegetative, hydrologic and cryogenic influences formed them and then these influences are extrapolated to the past. Soil features can be classified as rapidly adjusting, slowly adjusting or irreversible (Yaalon, 1971). The interpretation should be based on the more permanent (irreversible) soil features, since these features provide a reliable indication of the past environment. This is especially important for paleosols that have a polygenic origin, since certain soil properties are direct indicators of the climates under which these paleosols developed.

Climate, vegetation, drainage and relief, together with the time during which these factors acted on the soil, determine the type of soil development and the associated soil properties. Thus, the soil development (Podzolic, Luvisolic,

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Brunisolic and Cryosolic) reflects the soil environment and the climate under which these paleosols developed.

One of the factors that greatly affected the climate of the central Yukon during this period was the tectonic history of the St. Elias Mountain Range of Alaska. There is evidence that the coastal mountain ranges in Alaska were much lower in elevation during the Tertiary period and the early part of the Pleistocene epoch and thus permitted the flow of warm, moist Pacific air masses into the central Yukon (Armentrout, 1983).

This paper provides a review of the work carried out on paleosols in northwestern Canada and includes both published and previously unpublished information. Special emphasis has been placed on soil development, which provides information concerning the late Tertiary and early Pleistocene (pre-Illinoian) environments.

MATERIALS AND METHODS

The Burnt Hill paleosol occurs near the mouth of the Old Crow River (67°35′N lat., 139°47.5′W long.), approximately 10 km from Old Crow (Fig. 1). The Bluefish River paleosols occur along the Bluefish River Valley, approximately 60 km from the confluence of the Bluefish and Porcupine rivers. Some of the Bluefish River paleosols are located in the lower portion of the banks of the Bluefish River (67°07′02″N lat., 140°48′24″W long.), while others occur on the adjacent limestone upland (67°08′04″N lat., 140°46′56″W long.) (Fig. 1). Some portions of the Bluefish River dry up during the summer, and the paleosols occurring in the dried-up river bank are accessible at that time. The Stirling Bend paleosol occurs in the geological section at Stirling Bend (63°31′N lat., 137°21′W long.) on the Stewart River (Fig. 1). This paleosol is situated in the lowest part of the section, slightly above the water level. The Wounded Moose paleosols have developed on areas covered by pre-Reid glacial deposits in the central Yukon (Fig. 1). The Little Bear River section lies in the Mackenzie Mountains on the right bank of the Little Bear River, 62 km southwest of the mouth of the river (64°27.7′N lat., 126°43.3′W long.) (Fig. 1). Five buried paleosols occur in this geological section, with the lower four considered to be of pre-Reid (pre-Illinoian) age. Table 1 shows these late Tertiary and early Pleistocene paleosols in chronological order with their associated environments.

The paleosols were described according to the Expert Committee on Soil Survey (1983), and soil horizon designators

TABLE 1. Late Tertiary and early Pleistocene paleosols and associated environments in northwestern Canada (chronology according to Fulton and Prest, 1987)

General chronostratigraphy				Glaciations	Oxygen isotope stages	Event	Paleosols and associated environments*		
Time (Ma)	Period	Epoch	Stage and substage		(ka)		Central Yukon	Old Crow area	Little Bear River area
0.13					130				
	QUATERNARY	PLEISTOCENE	MIDDLE	ILLINOIAN	Reid Thomsen	6 — 185 7 — 235 8 — 275 9 — 320	Illinois Glaciation			
0.32									
				PRE-ILLINOIAN	Unnamed Glac. Klaza	15 790	Pre-Reid Glac.			Paleosol 4 (b) Paleosol 3 (b)
0.79									
			EARLY		Nansen, Banks Unnamed Glac.		and Interglacial periods	Wounded Moose paleosols (dt, op) Stirling Band paleosols (a)		Paleosol 2 (b) Paleosol 1 (b)
1.10									
1.70									
	TERTIARY	PLIOCENE							Burnt Hill and Bluefish R. paleosols (b)	
5.00									

*The associated environments, given in brackets, are as follows: dry temperate (dt), open parkland (op), boreal (b), alpine (a).

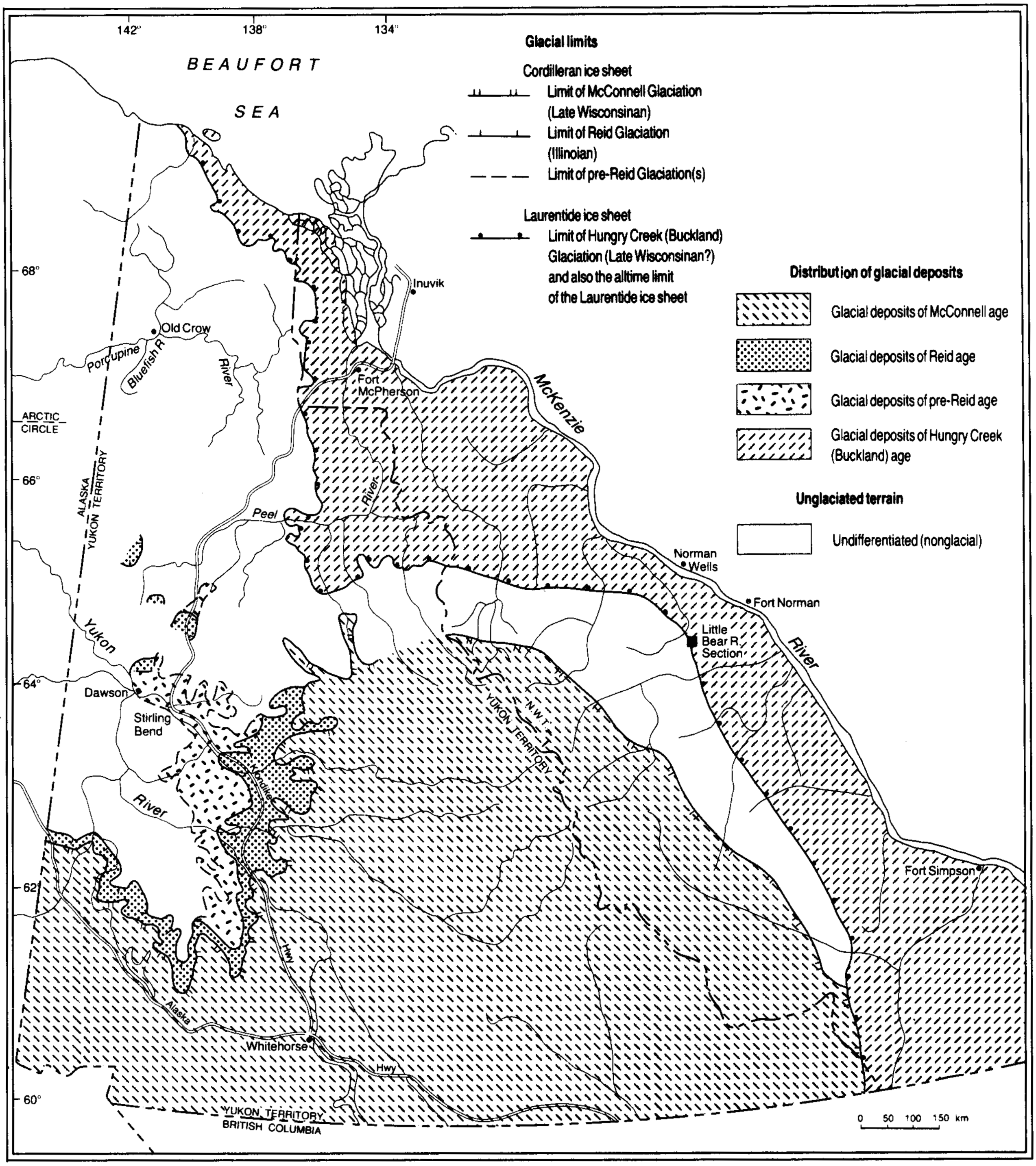

FIG. 1. Location of paleosol sites in northwestern Canada.

were used according to Agriculture Canada Expert Committee on Soil Survey (1987). The soil classification is given according to the Canadian System of Soil Classification (Agriculture Canada Expert Committee on Soil Survey, 1987). The American soil classification (Soil Survey Staff, 1975) equivalents are: Inceptisols (Brunisols), Pergelic subgroups (Cryosols), Boralfs and Udalfs (Luvisols), Histosols (Organic soils) and Spodosols (Podzols).

Fossil pollen was extracted from sediment samples using a $ZnBr_2$ heavy liquid separation followed by acetolysis.

The analytical methods used for soil analysis are outlined in a manual edited by Sheldrick (1984). The methods used are as follows: pH was determined in 0.01M $CaCl_2$; total C and N were determined using a Leco-600 determinator; cation exchange capacity (CEC) was determined by the neutral salt method; particle size distribution was determined by pipette analysis; the exchangeable cations were determined by extraction with 2N NaCl; the $CaCO_3$ equivalent was determined by the gravimetric method; and extractable Fe and Al were determined by the dithionite citrate, ammonium oxalate and sodium pyrophosphate methods.

It should be noted here that there are indications that the sodium-pyrophosphate-extractable Fe and Al values change with time. Calderoni and Schnitzer (1984) and Schnitzer and Calderoni (1985) found that carbon compounds undergo a conversion with time. The final result is that after 30 ka burial only the carboxylic and aromatic carbon compounds remain in the paleosols. This suggests that the larger and more soluble fulvic acids, to which the Fe and Al ions are attached and which are determined by the pyrophosphate method, degrade very early and are converted into smaller and more stable carbon compounds. These compounds identified by Schnitzer and Calderoni (1985) have little or no metallic-ion-holding capability. This would indicate that the use of the sodium-pyrophosphate-extractable Fe and Al criteria developed for recent Podzols is questionable when attempting to identify podzolization in paleosols. Therefore, the identification of these podzolic paleosols is based on their morphology and the dithionite-citrate and ammonium-oxalate-extractable Fe and Al values, not on the sodium-pyrophosphate-extractable Fe and Al values, which are used to identify and classify Holocene Podzolic soils (Agriculture Canada Expert Committee on Soil Survey, 1987).

LATE TERTIARY PALEOSOLS

Late Tertiary paleosols were found at a number of locations in the Old Crow area, a portion of the Yukon that has never been glaciated. Although most of these paleosols were buried by fluvial deposits (the Burnt Hill paleosol and some of the Bluefish River paleosols), others lay on the surface (the upland Bluefish River paleosol) covered by only a thin loess cap.

Burnt Hill Paleosol

The Burnt Hill paleosol was examined at the Burnt Hill exposure along the Old Crow River (Fig. 2). This Podzolic paleosol formed on gravelly sand of fluvial origin and has a well-developed, reddish (5YR 3/3, moist) Bf horizon overlain by a leached Ae horizon. The Ae horizon has a loose, single-grained structure, while the Bf horizon has a moderately cemented, granular structure. The pH of the Ae horizon is 4.6, that of the Bf and BC horizons is 6.7 and that of the C horizon is 6.4 (Table 2).

The morphology and chemistry of the Burnt Hill paleosol reflect the effects of advanced podzolization processes. Although the sodium-pyrophosphate-extractable Fe and Al values (Table 2) are lower than in the contemporary (Holocene) Podzolic soils because of the change of these values over time, the ammonium-oxalate-extractable Fe and Al values are very similar (Wang and McKeague, 1982; McKeague *et al.*, 1983).

Pollen analysis of sediments immediately overlying the paleosol indicates that the area had been dominated by spruce, pine, alder, birch, *Corylus* sp., ericaceous shrubs and moss species (Schweger, unpubl. data). The pine pollens were identified as both *Haploxylon* (white pine) and *Diploxylon* (yellow pine) types. Small amounts of *Tsuga* and *Abies* pollens were also present. The pollen assemblage found in this soil indicates that the vegetation was a mixed, closed-canopy coniferous forest with abundant alder, an understory dominated by *Corylus* sp. and ericaceous shrubs, and a forest floor rich in moss species. Similar pollen assemblages were found in the late Pliocene Gubik Formation (Nelson and Carter, 1985) at the Oceanic Point site in Alaska, although *Corylus* was absent and *Salix* pollen was much less common than in the Burnt Hill paleosol. Based on this pollen data

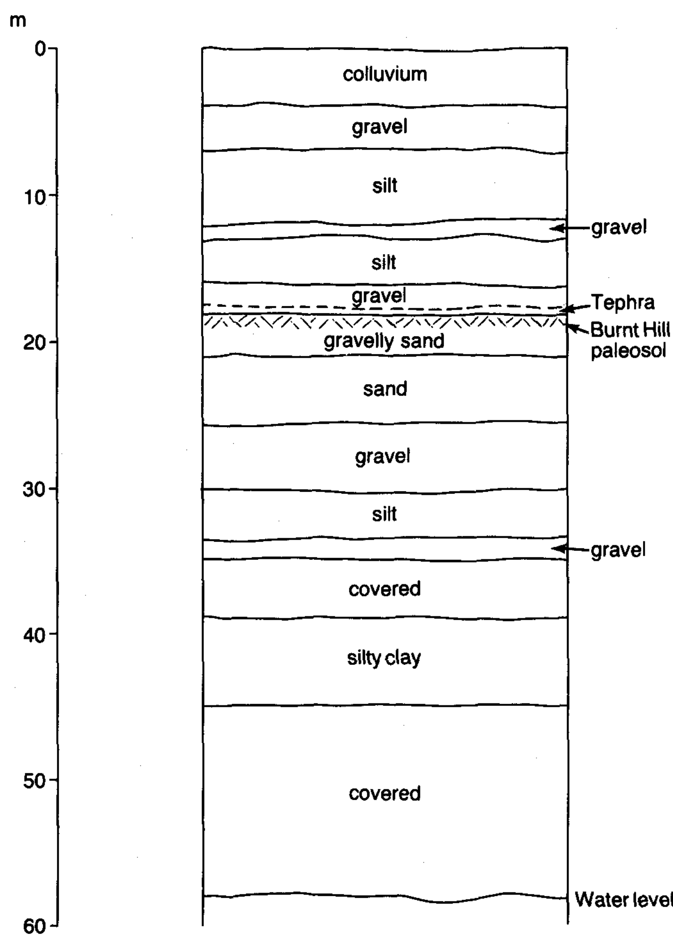

FIG. 2. The Burnt Hill section (J.V. Matthews, Jr., and O.L. Hughes, written comm. 1988) showing the location of the Burnt Hill paleosol. The layer marked "covered" is covered by slump material.

TABLE 2. Analytical data for the Burnt Hill paleosol

Soil and parent material	Soil horizon	Number of samples	$CaCO_3$ equiv. (%)	pH	C (%)	N (%)	Dithionite citrate (%)		Ammonium oxalate (%)		Sodium pyrophosphate (%)		C.E.C.* (me/100g)	Total sand (%)	Silt (%)	Clay (%)
							Fe	Al	Fe	Al	Fe	Al				
Burnt Hill	Ae	1	0.0	4.6	0.06	0.02	0.43	0.04	0.31	0.03	0.05	0.01	2.80	92.9	5.5	1.6
(fluvial)	Bf	1	0.0	6.7	0.31	0.02	3.94	0.04	3.54	0.03	0.02	0.00	3.90	91.7	5.9	2.3
	BC	1	0.0	6.7	0.23	0.02	0.81	0.04	0.97	0.03	0.05	0.00	3.93	92.5	5.6	2.0
	C	1	0.0	6.4	0.23	0.01	0.75	0.04	0.92	0.03	0.05	0.00	2.87	89.7	8.5	1.7

*Calculated.

obtained from the Burnt Hill paleosol, this paleosol is considered to be a soil that had developed during the late Pliocene epoch (Schweger, unpubl. data).

Bluefish River Paleosols

Paleosols in the Bluefish River area (Fig. 3) developed on colluvial and residual calcareous materials derived from limestone bedrock. They have well-developed Bt horizons with strong colours, dominantly 5YR 4/5 moist. The Bt horizons contain significant clay accumulations (Table 3). The presence of these Bt horizons is indicative of Luvisolic soil development. All of the Bluefish River paleosols are strongly truncated and what now remains is only the lower, weakly developed B horizon or the transitional BC horizon. The lack of weathering of clay minerals also results from the presence of free carbonates in the soil, since no advanced weathering takes place until all free carbonates have been removed from the system.

The Bluefish River paleosols have average pH values of 7.4 in the uppermost paleo Bt horizons and 7.5 in the Ck horizons, which would normally indicate that very little leaching has occurred. The difference in concentration of calcium carbonate in these two horizons, however, indicates that a significant amount of leaching has taken place. The average calcium carbonate concentration in the Ck horizon is 63.5%, while in the Bt horizon it is 17.0%. These paleosols contain high amounts of total carbon (2-8%). Since the concentration of carbon is generally higher in the parent material than in the overlying Bt horizons (Table 3), this carbon is most likely derived from the bedrock. Detailed information relating to the morphology and development of these paleosols is given in Tarnocai (1987b,c).

Soil material from the surface horizon of a buried Bluefish River paleosol was analyzed for pollen (Schweger, unpubl. data). It had essentially the same pollen assemblage as recovered from the Burnt Hill paleosol. The pollen data suggest that the Bluefish River paleosols are also of late Pliocene age.

Soil Development and Environments

During the late Tertiary period Podzolic and Luvisolic soil development probably occurred throughout northwestern Canada, supporting closed-canopy temperate and boreal forest vegetation.

Luvisolic and Podzolic soil development extended to at least 68°N lat., in the area of Old Crow. At the present time Luvisolic soils extend to 61°N, while Podzolic soils extend to 58°N in western Canada (Clayton *et al.*, 1977; Valentine *et al.*, 1978). This indicates that the climate was much warmer and moister than it is today. Luvisolic and Podzolic soils are both considered to be forest soils and are associated with forest vegetation. The pollen data confirm this, indicating that these paleosols supported a coniferous forest with spruce, white and yellow pine and hemlock in the tree layer and an understory of alder and *Corylus*. The northern limit of the *Corylus* sp. now lies in central British Columbia at approximately 56°N (Drumke, 1964). This indicates that the late Tertiary climate of the Old Crow area may have been similar to that now present in the central interior of British Columbia, which has a mean annual temperature of approximately 4°C and total annual precipitation of 550 mm (Atmospheric Environment Service, 1982a). At the present time Old Crow has a mean annual temperature of -10.1°C and total annual precipitation of 214 mm (Atmospheric Environment Service, 1982b).

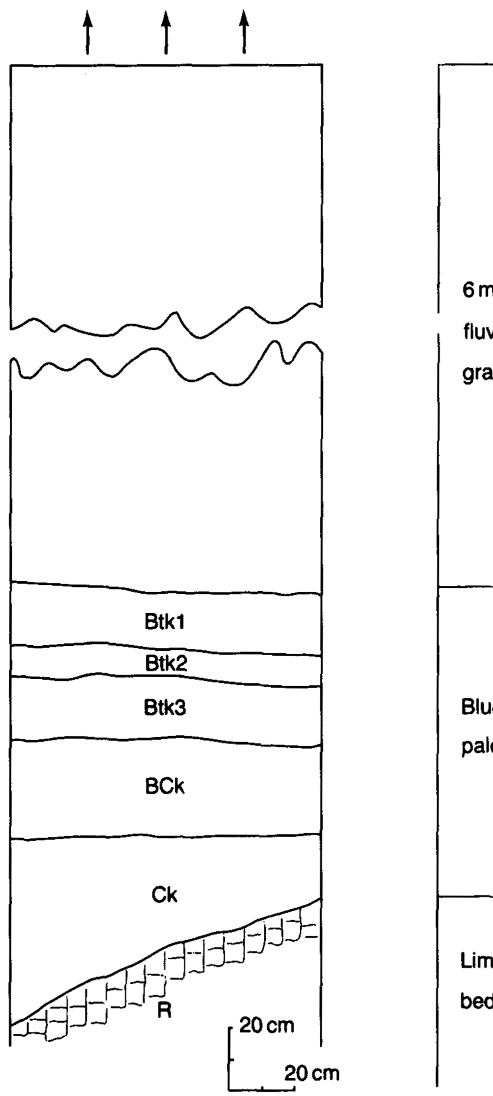

FIG. 3. Diagram of the Bluefish River paleosol found in the Bluefish River bank showing the soil profile on the left and the corresponding geological section on the right.

TABLE 3. Average values of various parameters for the uppermost B horizons and the C horizons of a Bluefish River paleosol

Soil and parent material	Soil horizon	Number of samples	$CaCO_3$ equiv. (%)	pH	C (%)	N (%)	Dithionite citrate (Fe + Al) (%)	Ammonium oxalate (Fe + Al) (%)	Sodium pyrophosphate (Fe + Al) (%)	Total sand (%)	Silt (%)	Clay (%)
Bluefish River	IIBt	3	17.0	7.4	2.13	0.06	1.76	0.27	0.05	51.5	30.8	18.0
(residual)	IICk	3	63.5	7.5	7.68	0.24	0.79	0.11	0.03	43.9	44.8	11.3

EARLY PLEISTOCENE PALEOSOLS

Stirling Bend Paleosol

The Stirling Bend paleosol occurs in the lowest part of the Stirling Bend geological section, slightly above the water level (Fig. 4). This paleosol displays Cryosolic soil development, which took place during the early pre-Reid (pre-Illinoian) cold, possibly glacial, period. It has a well-developed hummocky microtopography (Fig. 5) similar to that of earth hummocks now found in the Canadian Arctic and Subarctic (Tarnocai and Zoltai, 1978). The surface organic horizon (Ohy) is composed of moderately to well-decomposed humic peat that is very much compressed, as can be seen from the macro plant remains occurring in this horizon. The underlying Ahy and Cgy horizons have wavy, contorted boundaries with intrusions of organic, or organic-rich, mineral materials, most likely the result of cryoturbation (Fig. 5). The lowest Cg horizon shows no evidence of cryoturbation. The Ahy, Cgy and Cg horizons all have many coarse, distinct mottles. The morphological features associated with this paleosol are very similar to those occurring in Gleysolic Turbic Cryosols (Agriculture Canada Expert Committee on Soil Survey, 1987) commonly found in the Canadian Arctic at the present time. The lack of cryoturbation in the Cg horizon of this paleosol suggests that this horizon was below the permafrost table.

Pollen analysis has been carried out on the paleosol and on overlying sediments from a 3 m section located approximately 6 m upstream and slightly higher in the section than the soil for which the soil description is given. Samples for pollen analysis were collected from soil horizons that were laterally equivalent to those shown in Figure 5. The lowest two samples (Fig. 6), from the grey silty Cgy and Cg horizons, are dominated by Cyperaceae pollen and other herbaceous taxa, particularly Tubuliflorae and Liguliflorae. The next two samples, which come from the mineral Ahy and organic Ohy horizons of the paleosol, are dominated by *Betula* pollen with small quantities of Cyperaceae. The dark brown, organic-rich silt and the bedded sands and silts overlying the paleosol are in turn dominated by *Picea* pollen along with *Betula*, Cyperaceae and small amounts of *Alnus* pollen.

The very high percentages first of Cyperaceae and then of *Betula* and *Picea* pollen suggest a series of local pollen rains (Jacobson and Bradshaw, 1981). These represent an initial sedge-dominated tundra that was rapidly invaded, most likely by shrub birch, to form a shrub tundra. Unfortunately, there is no certain way to distinguish whether the *Betula* pollen was derived from arboreal or shrub birch sources (Edwards and Dawe, 1988). Spruce forest quickly replaced the shrub tundra and remained the dominant vegetation over the rest of the record. This sequence of vegetation changes is very similar to that recorded for late Wisconsinan–Holocene sites elsewhere in the Yukon (Cwynar *et al.*, 1987). A late-glacial to nonglacial period is strongly suggested for this fossil pollen sequence. The Stirling Bend paleosol developed during the interval characterized by subarctic birch shrub tundra vegetation.

Wounded Moose Paleosols

The Wounded Moose paleosols (Smith *et al.*, 1986; Tarnocai, 1987d) developed during the pre-Illinoian stage on both till and glaciofluvial materials deposited during the pre-Reid glaciations.

A maximum solum thickness of 2 m was reported for those soils developed on pre-Reid outwash (Tarnocai *et al.*, 1985). The colours of the upper Bt horizons of these soils are 5YR for outwash and 7.5YR for till soils (Table 4). These soils developed strongly weathered, rubified, paleoargillic Bt horizons with thick clay skins. Clay skins occur as coatings on ped and pebble surfaces and form bridges between sand grains. As a result of cryoturbation, the clay skins in the upper B horizon are usually fragmented and dispersed. These paleosols are strongly leached, with an average pH of 4.7–4.8 in the IIBt horizon. In addition, they are relatively low in carbon, exchangeable cations and nitrogen (Table 5).

According to Foscolos *et al.* (1977) and Rutter *et al.* (1978), Wounded Moose soils contain kaolinite, illite and montmorillonite-kaolinite mixed-layer clay minerals. Chlorite

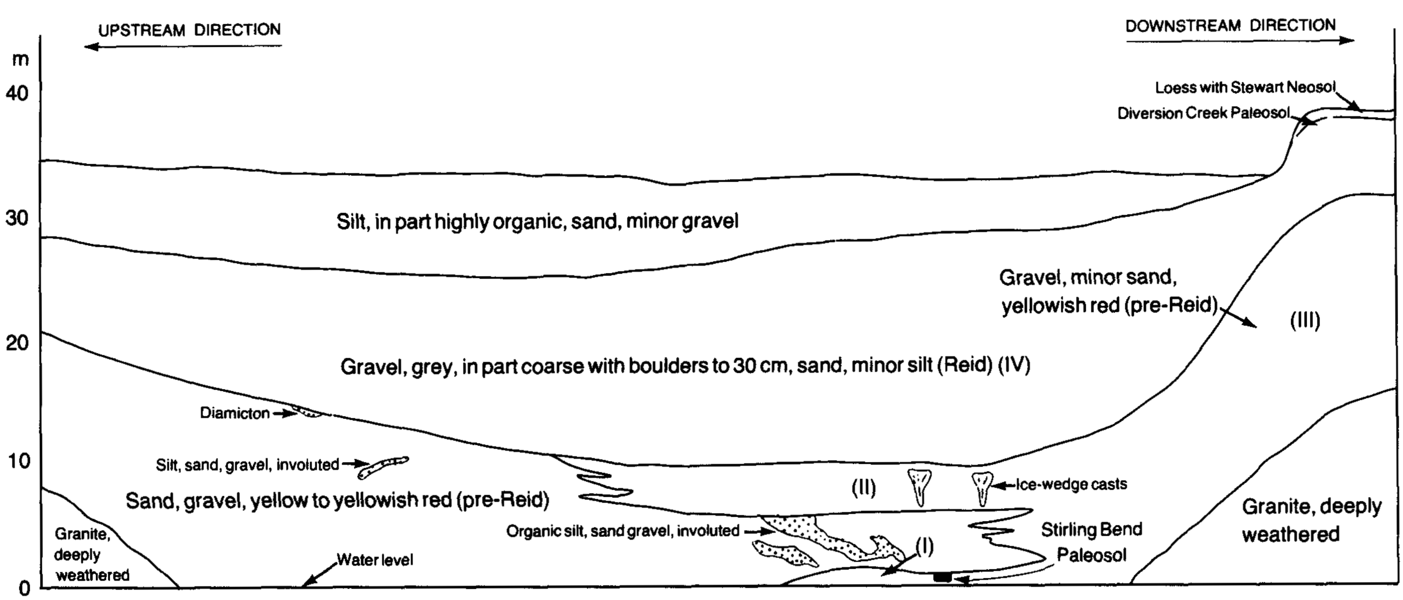

FIG. 4. Revised Stirling Bend section (Hughes *et al.*, 1987) showing the location of the Stirling Bend paleosols with the cold, possibly glacial, periods indicated by the bracketed Roman numerals. Cold period V, associated with the McConnell glaciation, is not given on the diagram since no such deposition occurred at this site.

and vermiculite are absent. Chloritic intergrades are present but decrease with depth and no such intergrade is found in the IIC horizon. The montmorillonite-kaolinite mixed-layer clay minerals were identified beyond a depth of 190 cm in these soils (Foscolos *et al.*, 1977; Rutter *et al.*, 1978).

Most Wounded Moose soils display strong cryoturbation in the form of disrupted and displaced soil horizons and oriented and shattered stones. Sand wedges and sand involutions of various sizes are also common. Ventifacts are commonly found at the paleosol surface. These cryogenic features developed during the cold, glacial periods of the mid- and late Pleistocene epoch.

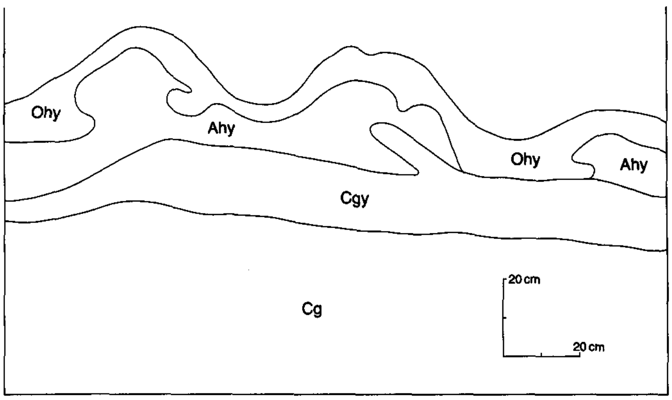

FIG. 5. A cross-section of the Stirling Bend paleosol developed during cold period I (see also Fig. 4).

Little Bear River Paleosols 1-5

The Little Bear River section is of special interest because it contains a stacked sequence of five paleosols associated with five different mountain tills (Fig. 7). In addition, a modern soil developed on bouldery outwash gravel of Laurentide origin occurs on the surface. Brunisolic paleosols developed on the top of each till layer as a result of prolonged intervals of soil formation during the interglacial periods. Erosion, however, has greatly affected the Little Bear River paleosols, since none has an A horizon. It is possible that the upper parts of the B horizons have been eroded during burial and what now remains may be the lower, less-developed, parts of the solum.

The Munsell colour values of Paleosols 1-4 were 5YR and 7.5YR and they generally became redder with increased age of the paleosol. The redness ratings were calculated according to the formula given by Torrent *et al.* (1980) and Torrent *et*

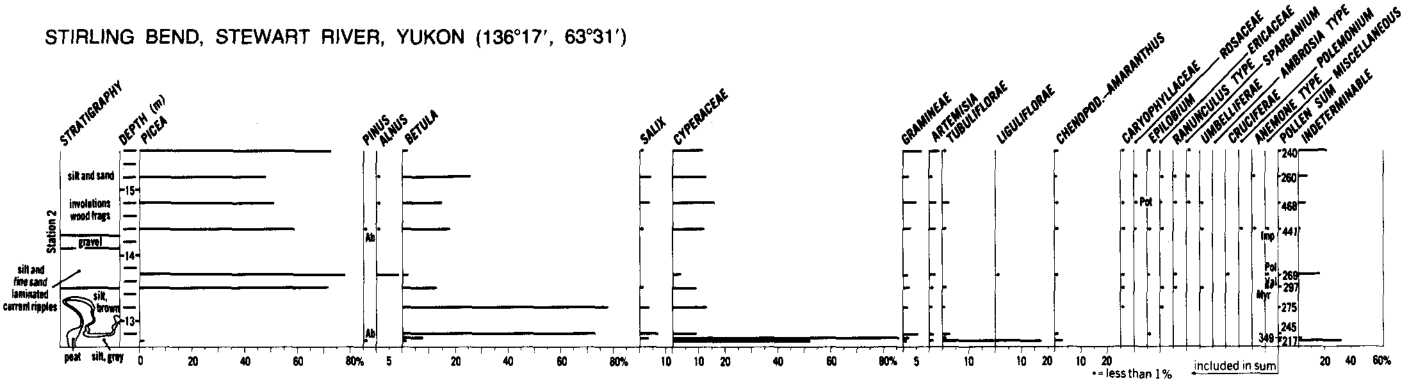

FIG. 6. Relative percent pollen diagram through the Stirling Bend paleosol (peat at 13 m) and associated sediment.

TABLE 4. A summary of soil morphologies of Wounded Moose paleosols

Soil and parent material	Solum thickness+ (cm)	Dominant colour hue*: Uppermost IIB**	Dominant colour hue*: Lower IIB**	Dominant primary structure: Type	Dominant primary structure: Grade	% of soils with IIBt horizons**	% of IIB horizons** with clay skins	% of soils with sand wedges and involutions	% of soils with strong cryoturbation	Coarse fragments: Degree of weathering	Coarse fragments: Frost orientation	Coarse fragments: Ventifacts
Wounded Moose (outwash)	109 (58-205)	5YR	7.5YR	blocky	weak - moderate	100	100	34	50	strong chemical alteration	common	common
Wounded Moose (till)	91 (50-123)	7.5YR	7.5YR	blocky = granular	moderate - strong	100	100	75	100	strong chemical alteration	common	common

+Mean thickness, range of values in brackets.
*Munsell soil colour notation.
**For definition of soil horizons see Agriculture Canada Expert Committee on Soil Survey (1987).
= Equal proportions.

TABLE 5. Average values of various parameters for the uppermost B horizons and C horizons of the Wounded Moose paleosols

Soil and parent material	Soil horizon	Number of samples	C (%)	N (%)	pH	Sodium pyrophos. (Fe+Al) (%)	Exchangeable cations (meg/100g): Ca	Mg	K	Total sand (%)	Silt (%)	Clay (%)
Wounded Moose (outwash)	IIBt	14	0.22	0.01	4.8	0.10	7.19	3.85	0.09	57.2	23.0	19.8
	IIC	6	0.12	0.01	5.3	0.06	2.46	0.84	0.05	90.4	5.0	4.6
Wounded Moose (till)	IIBt	6	0.23	0.02	4.7	0.10	10.70	3.85	0.09	50.9	30.3	18.7
	IIC	3	0.09	0.00	5.0	0.06	6.80	1.73	0.10	81.5	11.8	6.7

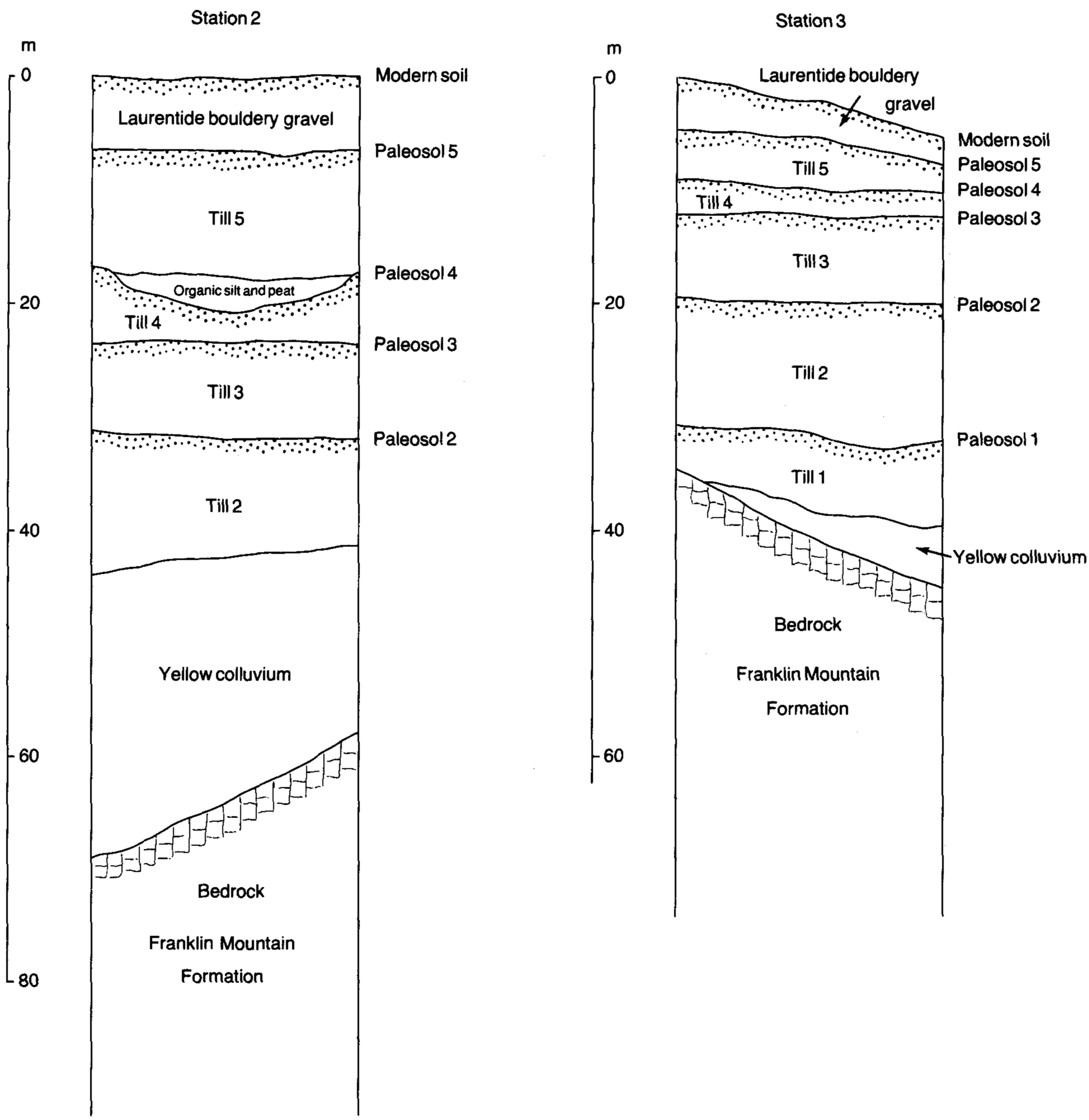

FIG. 7. Geological columns from the Little Bear River section, Stations 2 and 3 (O.L. Hughes, written comm. 1988).

al. (1983), and it was found that the older paleosols had ratings of 3, with this value dropping to approximately 1 for the younger paleosols. Although all of these paleosols were truncated, the remnants of the pedons were significantly thicker than the modern soil. All of the Little Bear River paleosols have high pH values (6.4 and higher), indicating a lack of leaching. Even though these paleosols developed at high elevations, no evidence of cryoturbation was found in the paleo-pedons examined. The chemical and physical properties of these five paleosols and the modern soil are given in Table 6.

Spruce logs found in a peat deposit on the top of Paleosol 4 (Fig. 7) gave a radiocarbon date greater than 47 000 years B.P. (O.L. Hughes, pers. comm. 1988). Pollen data obtained from this deposit indicate that the area, which is now a treeless alpine tundra, was covered by a closed-canopy coniferous forest at that time. This information and the degree of soil development indicate that Paleosol 5 (Fig. 7) likely developed during the Sangamonian stage, while Paleosols 1–4 (Fig. 7) probably developed during the pre-Illinoian interglacial stage, with the tills being deposited by pre-Reid glaciations.

Soil Development and Environments

Paleosols that developed during the early Pleistocene interglacial stages were still Luvisolic, with deep paleoargillic horizons. These paleosols, however, remained on the surface and were exposed to severe arctic climates during the subsequent glacial stages. Cryogenic soil features thus overprinted the former temperate soil features and resulted in a polygenic soil. No such cryogenic overprint is found in those early Pleistocene interglacial paleosols that were buried. This perhaps indicates that soil climates were not cold enough for cryogenic processes.

TABLE 6. Average values of various parameters for the uppermost B horizons of the Little Bear River paleosols

		Uppermost B horizon										
Soil	No. of pedons	Thickness* (cm)	Colour	Redness** rating	pH	$CaCO_3$ (%)	N (%)	C (%)	Dithion. cit. (Fe+Al) (%)	Amm. ox. (Fe+Al) (%)	Na pyroph. (Fe+Al) (%)	Clay (%)
Paleosol 1	0	—	—	—	—	—	—	—	—	—	—	—
Paleosol 2	2	68	5YR 4/4	3.1[x]	7.2	1.3	0.10	0.16	1.29	0.13	0.03	10.9
			7.5YR 4/2									
Paleosol 3	1	95	7.5YR 4/2	1.2	7.4	1.4	0.01	0.28	1.92	0.19	0.06	8.3
Paleosol 4	1	68	10YR 3/2	0.0	7.4	18.2	0.05	2.32	1.92	0.46	0.06	26.8
Paleosol 5	3	81	7.5YR 4/6	1.2[x]	7.3	0.6	0.03	0.29	1.90	0.25	0.06	20.6
			10YR 4/6									
			10YR 4/6									
Modern soil	1	42	10YR 4/6	0.0	6.4	0.0	0.16	2.63	2.33	1.15	0.56	18.7

*Total thickness of B horizons.
**Redness rating = $[(10-H)\times C]/V$, where H is the YR hue, C is the choma and V is the colour value (Torrent *et al.*, 1980; Torrent *et al.*, 1983).
[x]Mean value.

The presence of cold glacial periods during the early Pleistocene is indicated by the cryogenic Stirling Bend paleosols and the presence of cryogenic features overprinted on the Luvisolic Wounded Moose paleosols. Soil features in the Stirling Bend section (Fig. 4) indicate that three cold, possibly glacial, periods (cold periods I-III) affected this site during the pre-Reid period. The Stirling Bend paleosol developed during cold period I. Pollen analysis of the materials from this paleosol and the sediments overlying it indicate the presence of a sedge and birch shrub tundra (Fig. 6). This pollen record, together with soil evidence contained within the paleosol, indicate that cold period I most likely occurred during a late glacial period. The next cold period, cold period II, triggered the development of ice wedges. The presence of these ice wedges is now shown by ice-wedge casts in the yellowish-red pre-Reid gravel. Finally, cold period III is marked by yellowish-red pre-Reid glacial outwash deposits occurring between the ice-wedge casts and the Reid gravel contact. This site was also subjected to the subsequent Reid glaciation (cold period IV) and affected by the McConnell glaciation (cold period V), although no McConnell deposits have been found in the section (Fig. 4).

During the early Pleistocene interglacial stages, when the Wounded Moose paleosols developed, the climate was warmer and thus favoured the development of deep paleoargillic (Bt) horizons with well-developed, reddish, void and grain argillans. The formation of these argillans requires a temperate climate with moist periods. This climate is necessary both for the initial formation of clay-sized material and for its subsequent mobilization, leading to the formation of argillans.

Foscolos *et al.* (1977) and Rutter *et al.* (1978) suggest that the initial stage of Wounded Moose soil development was associated with a climate that was warm and subhumid with grassland shrub vegetation. This type of climate was favourable for the development of montmorillonite. This was followed by a more temperate and humid climate, which induced the degradation of montmorillonite to kaolinite through an intermediate step of mixed-layer montmorillonite-kaolinite. This latter type of climate was probably responsible for the development of this Wounded Moose soil, with its red colours and very thick Bt horizon.

Smith *et al.* (1987) found that the redness of the paleoargillic horizons of the Wounded Moose paleosols resulted from the small amounts of hematite (<3%) concentrated in submicroscopic zones. Studies carried out by Torrent *et al.* (1980) and Schwertmann *et al.* (1982) have shown that reddening (rubification) through *in situ* hematite formation can take place under temperate climatic conditions with a mean annual temperature of 7°C or greater and total annual precipitation of as little as 500 mm. In the central Yukon, rubification is interpreted as a relict feature. This area (Dawson) now has a mean annual temperature of −5.1°C and total annual precipitation of 306 mm (Atmospheric Environment Service, 1982b), which eliminates the possibility of such rubification at the present time and suggests the presence of a much warmer climate during the early Pleistocene epoch. It has, however, also been suggested by Smith *et al.* (1987) that the length of time over which soil development took place should be considered in addition to climate when explaining the formation of hematite in the Wounded Moose paleosols.

During subsequent glacial stages these Wounded Moose paleosols, since they were not buried, were affected by cryogenic processes and strong erosional forces resulting from the cold arctic climate. Thermal cracking led to the development of sand wedges and sand involutions, while strong cryoturbation led to the development of discontinuous and displaced soil horizons, oriented stones, the breakdown of argillans to papules and the formation of aggregates and oriented features (Tarnocai and Smith, 1989).

Paleosols 1 and 2 (Fig. 7), the oldest soils in the Little Bear River section, developed under a warm climate. Paleosols 3, 4 and 5 (Fig. 7) developed in a cooler, boreal environment dominated by closed coniferous forest vegetation, while the modern soil developed in an arctic-alpine environment, the coldest climate of all. All of the paleosols developed in a relatively dry environment in which the precipitation was probably similar to that occurring today, but because of the higher temperatures, and thus correspondingly higher rate of evapotranspiration, the environment was drier than at the present time.

It should be noted that four pre-Reid glaciations were found in the Little Bear River section on the east side of the Mackenzie Mountains. These glaciations were marked by four till layers, separated from each other by well-developed paleosols. The Stirling Bend section west of the Mackenzie Mountains shows evidence of three glaciations in the pre-Reid period, the oldest one being represented by a Cryosolic soil and tundra pollen record.

The Wounded Moose paleosols had much stronger soil development than did the Little Bear River paleosols. This is probably the result of differences in the climate and erosion history of the two areas, as well as in the length of time over which these soils developed. The climate at the Little Bear

River site (1000 m a.s.l.) is cooler, since it is 500 m higher in elevation than the Wounded Moose paleosol sites. The second difference is in the length of time over which soil development took place. Since the Wounded Moose paleosols were not buried, they were exposed to the effects of all of the early Pleistocene glacial and interglacial climates, and their strong Luvisolic soil development reflects this. The Little Bear River paleosols, on the other hand, were buried by a series of till deposits, and their Brunisolic soil development thus results from exposure to only one interglacial period.

SUMMARY AND CONCLUSIONS

The beginning of the Pleistocene epoch, with its alternating cold glacial and warm interglacial periods, drastically changed the environment. Although cooling had begun during the Pliocene epoch (Wolfe and Poore, 1982), the climate was still equitable and no drastic climate changes occurred. The soils and soil development were in equilibrium with this late Tertiary environment, even though soil erosion and degradation occurred, because soil development and weathering processes maintained a balance. This equilibrium, or balance, was destroyed when the first cold, arid glacial period occurred during the very early Pleistocene. The first effect of this climate change was probably a change in the vegetation. The continuous forests of the late Tertiary period disappeared, giving place to tundra vegetation. Evidence at a number of sites in the Old Crow area suggests that tundra vegetation first appeared at this time (Schweger, unpubl. data). This change of vegetation, coupled with increased aridity and the appearance of permafrost, had a strong degrading effect on the late Tertiary soils and landscapes. Temperate Luvisolic and Podzolic soil development stopped and was replaced by the completely different Cryosolic, or in some cases Brunisolic, soil development. The climate change in the cold glacial periods in conjunction with the much reduced weathering and vegetation cover triggered massive erosion of Tertiary soils. The alternating permafrost and nonpermafrost soil environments during the glacial and interglacial periods further increased the erosional processes, which were especially active on mountainous terrain.

Properties of late Tertiary and early Pleistocene soils in northern Canada suggest that the prevailing climate had a major effect on soil formation. A summary of soil development and the relationship of this development to the environment is given in Table 7 and listed below:

1. Luvisolic and Podzolic soil development probably occurred in all areas of northwestern Canada during the late Tertiary period, suggesting that the climate was warmer and moister than at present. The vegetation associated with these paleosols was a mixed coniferous-deciduous forest containing tree and shrub species now found much farther south.

2. Luvisolic soil development still dominated the area during the early Pleistocene interglacial stages, especially at low elevations. This resulted in the development of deep rubified argillic Bt horizons with well-developed void and grain argillans, an indication that the climate was still warm at this time.

3. The Pleistocene glacial stages resulted in the development of strong cryogenic soil properties in soils occurring in unglaciated areas of northwestern Canada. These properties occur as an overprint on the temperate properties of some paleosols. Sand wedges, sand involutions and ventifacts also developed during these cold glacial stages, as did patterned ground types, such as ice wedges and earth hummocks.

TABLE 7. Soil development and the development of soil-feature indicators of paleoenvironments in northwestern Canada

Development	Tertiary	Early and mid-Pleistocene interglacial	Early and mid-Pleistocene glacial
Soil			
Luvisolic	X	X	
Podzolic	X		
Soil properties			
Argillans	X	X	
Podzolic BF horizons	X		
Rubification	X	X	
Cryoturbation			X
Patterned ground			X
Sand wedges and sand involutions			X
Ice wedge casts			X
Papules			X

4. There are indications of gradual soil development in the succession of soils forming the Little Bear River section, with the best-developed soil being the oldest paleosol. This stronger soil development with age is reflected in the greater solum and B horizon thicknesses, the increase of rubification in the B horizons, and the occurrence of argillans in some of these paleosols. This evidence indicates a slightly, but steadily, moderating climate as one proceeds from Paleosol 5 (youngest) to Paleosol 1 (oldest). The lack of evidence for cryoturbation, especially in paleogleysolic soils, indicates that all of these paleosols (1-5) likely developed without permafrost.

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