Article

"Paleosols of the Interglacial Climates in Canada"

Charles Tarnocai

*Géographie physique et Quaternaire*, vol. 44, n° 3, 1990, p. 363-374.

*Géographie physique et Quaternaire*, 1990, vol. 44, n° 3, p. 363-374, 8 fig.

# PALEOSOLS OF THE INTERGLACIAL CLIMATES IN CANADA*

Charles TARNOCAI, Land Resource Research Centre, Agriculture Canada, Ottawa, Ontario K1A 0C6.

ABSTRACT Although paleosols are useful indicators of paleoclimates, it is first necessary to establish the relationships between the northern limits of the various contemporary soils and the pertinent climatic parameters. It is then necessary to determine the age of the various paleosols and, if possible, their northern limits. Comparison of the distribution and northern limits of the contemporary soils with the distribution and northern limits of the analogous paleosols then permits the reconstruction of the paleoenvironments. For the purposes of comparison the mean annual temperature of the Old Crow area during the Pliocene epoch was also determined (about 4°C) even though this was not an interglacial period. It was found that during the pre-Illinoian interglacial periods the central Yukon had a mean annual temperature of about 7°C while during the Sangamonian interglacial period it had a mean annual temperature of about −3°C. During the Holocene epoch, the current interglacial period, the climate has been similar to or only slightly cooler than that existing during the Sangamonian interglacial period. The fluctuating position of the arctic tree line (and associated forest soils) during the Holocene epoch, however, indicates that the climate has also been fluctuating during this time. The paleoclimatic reconstruction presented in this paper also relies heavily on both diagnostic soil features and the soil development during the various interglacial periods.

RÉSUMÉ *Les paléosols du Canada au cours des périodes interglaciaires*. Pour que les paléosols soient des indicateurs utiles de paléoclimats, on doit d'abord établir les relations entre les limites nordiques des divers sols contemporains et les paramètres climatiques appropriés. On doit ensuite déterminer l'âge des divers paléosols et, si possible, leur limite nordique. La comparaison entre la répartition et la limite nordique des sols contemporains et celles des paléosols analoques permet alors d'effectuer une reconstitution des paléoenvironnements. Pour fins de comparaison ici, la température moyenne annuelle dans la région de Old Crow au cours du Pliocène a également été déterminée (environ 4°C), même s'il ne s'agissait pas d'une période interglaciaire. On a estimé que, durant les périodes interglaciaires pré-illinoiennes, le centre du Yukon avait une température moyenne annuelle d'environ 7°C, alors que durant l'interglaciaire du Sangamonien, la température était d'environ −3°C. Pendant l'Holocène, c'est-à-dire la période interglaciaire actuelle, le climat a été semblable ou très légèrement plus froid que pendant l'interglaciaire du Sangamonien. La fluctuation de la limite des arbres (et des sols forestiers associés) au cours de l'Holocène montre que le climat a également connu des changements. La reconstitution paléoclimatique présentée repose en outre sur des caractéristiques pédologiques diagnostiques et sur le développement du profil au cours des différentes périodes interglaciaires.

ZUSAMMENFASSUNG *Paläoböden zur Zeit der Interglaziale in Kanada*. Obwohl Paläoböden nützliche Indikatoren der Paläoklimas sind, ist es nötig, zuerst die Beziehungen zwischen den nördlichen Grenzen der verschiedenen gegenwärtigen Böden und den betreffenden klimatischen Parametern herzustellen. Dann muss das Alter der verschiedenen Paläoböden bestimmt werden und wenn möglich ihre nördlichen Grenzen. Der Vergleich der Verteilung und nördlichen Grenzen der gegenwärtigen Böden mit denjenigen der analogen Paläoböden erlaubt dann, die Paläoumwelten zu rekonstruieren. Zum Zweck des Vergleichs wurde auch die durchschnittliche Jahrestemperatur in der Gegend von Old Crow während des Pliozän bestimmt (ungefähr 4°C), auch wenn dies keine interglaziale Periode war. Man fand heraus, dass während der prä-illinoischen interglazialen Perioden im Zentrum von Yukon eine durchschnittliche Jahrestemperatur von ungefähr 7°C herrschte, wohingegen es während des sangamonischen Interglazial eine Jahresdurchschnittstemperatur von ungefähr — 3°C gab. Während des Holozän, der gegenwärtigen interglazialen Epoche, war das Klima ähnlich oder nur leicht kühler als das, was während des sangamonischen Interglazial herrschte. Die Fluktuation der arktischen Baumgrenze (und der mit ihr in Verbindung gebrachten Waldböden) während des Holozän weist indessen darauf hin, dass das Klima während dieser Zeit auch fluktuierte. Die in diesem Aufsatz vorgestellte paläoklimatische Rekonstruktion ruht auch in bedeutender Masse sowohl auf diagnostischen Boden-Merkmalen wie auf der Boden-Entwicklung während der verschiedenen interglazialen Perioden.

* Land Resource Research Centre Contribution No. 90-40
Manuscrit reçu le 28 décembre 1988; manuscrit révisé accepté le 8 mai 1990

## INTRODUCTION

The use of paleosols in the reconstruction of paleoenvironments depends on the ability to recognize them and to ascribe, with confidence, the origin of some of their properties to specific environmental conditions (Valentine *et al.*, 1987; Valentine and Dalrymple, 1975). Paleosols can be identified from pedological features whose arrangement is logical according to the theories of soil genesis. Buried paleosols in a geological section can be identified with greatest confidence when they are traceable laterally to show logical changes in the soil profile characteristics corresponding to changes in the landscape (Valentine and Dalrymple, 1975). Brewer (1972) pointed out that buried paleosols must be recognized on the basis of the hypothesized soil formation rather than on the basis of the occurrence of individual pedological features.

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 extrapolate these influences 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 which have a polygenic origin since certain soil properties are direct indicators of the climates under which these paleosols developed.

The terminology relating to soil development and classification used in this paper is that of the Agriculture Canada Expert Committee on Soil Survey (1987). Since this work refers only to modern soils, the definitions were slightly modified for use with paleosols. The following are the criteria used for paleosols:

1. Luvisolic paleosols have a paleoargillic (Bt) horizon.
2. Podzolic paleosols have a Bf horizon as determined by morphology and oxalate-extractable Al and Fe.
3. Brunisolic paleosols have a brownish Bm horizon, but lack both Bt and Bf horizons.
4. Cryosolic paleosols have well developed cryogenic features such as ice wedge casts, sand wedges, cryoturbated soil horizons and cryogenic microfabrics.
5. Organic paleosols have developed on peat materials, possibly in a permafrost-free environment.

The climates of the interglacial periods will be described according to the associated paleosols. In addition, a brief evaluation of the Pliocene climate will be included for comparison. Reference will be made both to climatic implications of paleosols formed in the ice-free areas of the Yukon during the Wisconsinan glacial stage and to some of the relict soil features which indicate the climatic fluctuations that occurred during the Holocene epoch. Few interglacial paleosols have been found in the glaciated areas of Canada because most of the former soils were removed by subsequent glaciations. Therefore, most of the examples given in this paper will be drawn from northwestern Canada, an area for which continuous records of interglacial paleosols are available. This paleosol record provides an excellent opportunity for making predictions and comparisons concerning past climates.

## GLACIAL AND INTERGLACIAL PERIODS

The Pleistocene epoch comprises the major glacial and interglacial periods in Canada. During this epoch almost all of Canada was covered several times by glacial ice. The only unglaciated areas were parts of the western and northwestern Yukon, the Cypress Hills in southern Alberta and Saskatchewan, and some parts of the arctic islands. The Holocene epoch refers to the time since the retreat of the last ice sheet. Figure 1 shows the glacial and interglacial periods and the associated paleosols in chronological order.

Most of the evidence for early and middle Pleistocene glaciation is found in the Yukon. Bostock (1966) identified the Reid (Illinoian) glaciation and inferred two glacial advances during the pre-Reid (pre-Illinoian) stages, the Nansen (older) and the Klaza. Based on dates obtained from two Yukon tephras, the Fort Selkirk Tephra found near Fort Selkirk and the Mosquito Gulch Tephra found near Dawson, Hughes (1987) states that the minimum age of the Nansen glacial advance would be 1.2 Ma (recent evidence indicates it could be >1.79 Ma — Lionel Jackson, personal communication, 1990) while the maximum age for the Klaza glacial advance, based on the Fort Selkirk Tephra date, would be 1 Ma (or possibly as great as 1.5 Ma — Lionel Jackson, personal communication, 1990). Since these two advances could not be differentiated outside of the area mapped by Bostock, they have been combined under the term pre-Reid glaciations (Hughes *et al.* 1972, 1983; Hughes, 1987). In the Stirling Bend section along the Stewart River, however, there are indications of three cold periods, probably glacial, during the pre-Reid period (Tarnocai and Schweger, in press). L. Jackson (personal communication, 1990) may also have found evidence for three pre-Reid glaciations nearby in the Fort Selkirk area. Furthermore, in the Little Bear River section, located in the Mackenzie Mountains, four paleosols have developed in pre-Reid tills as a result of four montane glaciations and the corresponding interglacial periods. These findings suggest that four interglacial periods may have been associated with the pre-Reid period. In this paper the early and middle Pleistocene (pre-Reid) interglacial periods will be referred to as pre-Illinoian interglacial periods.

The Sangamonian stage, which occurred during the early part of the late Pleistocene epoch, was an interglacial period (Fulton and Prest, 1987). The succeeding stage, the Wisconsinan, was glacial (Fulton and Prest, 1987); however, a number of areas of Canada were ice free during this time, permitting biological activity and soil development to take place.

During the Holocene epoch, the current interglacial period, a number of climatic fluctuations have occurred (Ritchie and Hare, 1971; Terasmae, 1972; Sorenson *et al.*, 1971). These climatic fluctuations have produced relict soil features (as defined by Tarnocai and Valentine, 1989) which can be found in contemporary Canadian soils.

## INTERGLACIAL PERIODS AND ASSOCIATED PALEOSOLS

### LATE TERTIARY PALEOSOLS

Although the late Tertiary period (Pliocene epoch) is not considered to be an interglacial period, paleosols developed during this time have been included in this paper for comparison with the early Pleistocene paleosols. The oxygen isotope record indicates that the climate was gradually cooling during this epoch (Fig. 2c). The data given in Figure 2c indicate that there were considerable fluctuations in climate during this time with the major cool period occurring at 2.4 Ma.

Late Tertiary paleosols have been found at a number of locations in the Old Crow area, a portion of the Yukon that has never been glaciated, in southwestern Alberta, and in the Cypress Hills area of southeastern Alberta and southwestern Saskatchewan. Although most of these paleosols were buried by fluvial deposits (the Mokowan Butte paleosols, the Burnt Hill

| Time (Ma) | Period | Epoch | | Stage and substage | Glaciations | Oxygen isotope stages (ka) | Event | Central Yukon | Old Crow area | Little Bear River area | Other areas |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | General chronostratigraphy | | | | | | | Paleosols and associated environments* | | | |
| 0.01 | QUATERNARY | HOLO. | | | | 1 (13) | Holocene Interg. | (hb, sa, sp, a) | (sa, a) | (a) | |
| 0.02 | | PLEISTOCENE | LATE | WISCONSINAN: LATE | McConnell and Buckland | 2 (32) | Wisconsin Glaciation | | Old Crow paleosol (la) | | |
| 0.03 | | | | MIDDLE | | 3 (65) | | | | | |
| 0.06 | | | | EARLY | | 4 (80) | | | | | |
| 0.08 | | | | SANGAMONIAN | | 5 (130) | Sangamon Interglaciation | Diversion Creek paleosols (b) | | Paleosol 5 (b) | |
| 0.13 | | | MIDDLE | ILLINOIAN | Reid Thomsen | 6 (185) 7 (235) 8 (275) 9 (320) | Illinois Glaciation | | | | |
| 0.32 | | | | PRE-ILLINOIAN | Unnamed Glac. | | Pre-Reid Glac. | | | Paleosol 4 (b) Paleosol 3 (b) | |
| 0.79 | | | | | Klaza | 15 (790) | and | | | | |
| | | | EARLY | | Nansen, Banks | | Interglacial | Wounded Moose paleosols (dt, op) | | Paleosol 2 (b) | |
| 1.10 | | | | | Unnamed Glac. | | periods | | | Paleosol 1 (b) | |
| 1.70 | TERTIARY | PLIOCENE | | | | | | | Burnt Hill and Bluefish R. paleosols (b) | | Cypress Hill paleosols (t) |
| 5.00 | | | | | | | | | | | |

* The associated environments, given in brackets, are as follows: temperate (t), dry temperate (dt), open parkland (op), boreal (b), high boreal (hb), subarctic (sa), subalpine (sp), alpine (a), low arctic (la), and high arctic (ha).

FIGURE 1. Glacial and interglacial periods and the associated paleosols in Canada (chronology according to Fulton and Prest, 1987).

*Les périodes glaciaires et interglaciaires au Canada et les paléosols qui y sont associés (chronologie selon Fulton et Prest, 1987).*

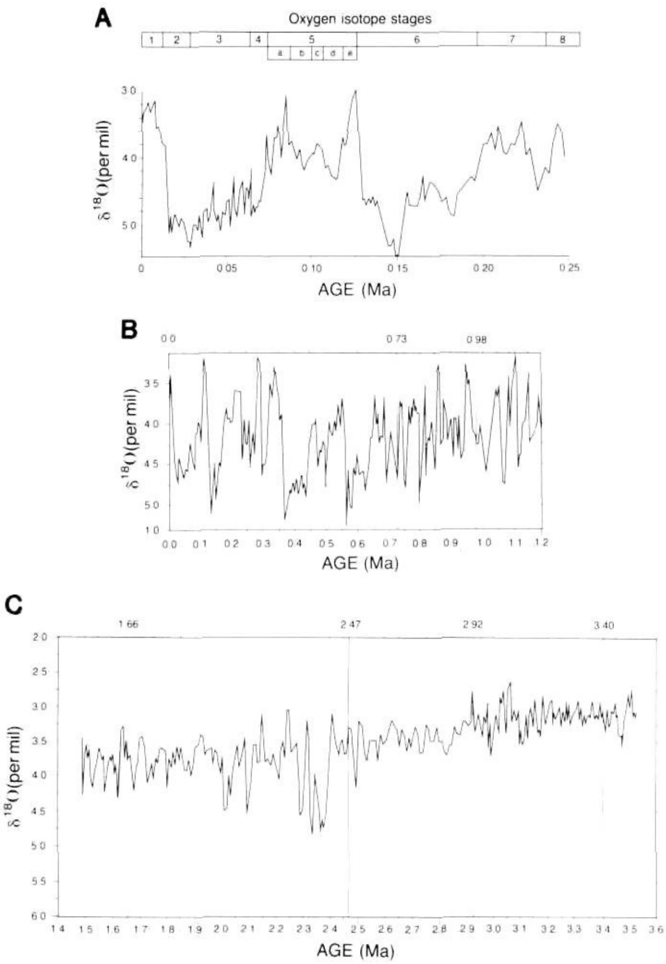


FIGURE 2. Oxygen isotope records according to Ruddiman and McIntyre (1981) and Shackleton *et al.* (1984). The vertical lines (with values in Ma) in graphs B and C indicate the time of magnetic reversals.

*Courbes isotopiques selon Ruddiman et McIntyre (1981) et Shackleton* et al. *(1984). Les lignes verticales (valeurs en Ma) dans les graphiques B et C montrent les moments d'inversion magnétique.*

paleosol and some of the Bluefish River paleosols), others lay on the surface (the upland Bluefish River and Cypress Hills paleosols) covered by only a thin loess cap.

*Burnt Hill paleosol:* This Podzolic paleosol occurs 5 km from Old Crow, along the Old Crow River (Fig. 3). It 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 (Tarnocai, 1987a). Based on pollen data, the Burnt Hill paleosol is considered to be a soil which developed during the late Pliocene epoch (Tarnocai and Schweger, in press; Schweger, in press).

*Bluefish River paleosols:* These Luvisolic paleosols developed from calcareous residual material in the Bluefish River area, approximately 60 km south of Old Crow (Fig. 3). Their Bt horizons are dominantly 5YR 4/5 moist and contain significant clay accumulations (Tarnocai, 1987a, 1987c). Soil material from the surface horizon of one of these paleosols had essentially the same pollen assemblage as did the sediments near the paleosol at the Burnt Hill exposure (Schweger, in press; Tarnocai and Schweger, in press). The soil development and, especially, the pollen data suggest that the Bluefish River paleosols are also of late Pliocene age.

*Cypress Hills paleosols:* The Cypress Hills area in southern Alberta and Saskatchewan (Fig. 3) is a plateau which was not overrun by Quaternary glaciers. A reddish-yellow weathered surface lies over the bedrock of the Cypress Formation, which is of Oligocene and Miocene age (Storer, 1975). A dark reddish-brown paleo B horizon is found in this material (Jungerius and Mucher, 1972; Westgate *et al.*, 1972). According to Jungerius and Mucher (1972), the paleo B horizon formed under forest vegetation in a climate somewhat warmer and moister than that of the Holocene epoch.

*Mokowan Butte paleosols 1-3:* Mokowan Butte stands at an elevation of about 1800 m along the eastern boundary of Waterton Park in southwestern Alberta. A stacked sequence of five paleosols was found in the area (Karlstrom, 1987 and 1988). The three oldest paleosols, Paleosols 1, 2 and 3 occur in late Pliocene till or diamict. These three paleosols have strongly developed, rubified, argillic horizons over calcic, petrocalcic or leached B horizons. In Paleosols 1 and 2 the argillic horizons are 40-150 cm thick while in Paleosol 3 they are 1-5 m thick.

## EARLY AND MIDDLE PLEISTOCENE PALEOSOLS

Paleopedological evidence suggests the occurrence of four interglacial periods during the early Pleistocene epoch (Tarnocai and Schweger, in press). These interglacial periods produced the most highly developed paleosols of the Quaternary period, not only because the climate was favourable for soil development but also because of the long period of time during which these conditions existed.

An examination of the oxygen isotope record (Fig. 2, b and c) also indicates that between 1.2 Ma, approximately the time of the Nansen glacial advance, and 0.27 Ma, approximately the beginning of the Reid glaciation, four major warm peaks occurred (at 1.1 Ma, 0.95 Ma, 0.86 Ma, and a double warm peak at approximately 0.3 Ma), possibly representing four interglacial periods. The first warm period was the warmest.

Foscolos *et al.* (1977) and Rutter *et al.* (1978) suggested that the initial stage of Wounded Moose soil development was associated with a climate which 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.

*Wounded Moose paleosols:* The Wounded Moose paleosols (Smith *et al.*, 1986) occur in central Yukon (Fig. 3) areas with elevations less than 1000 m. They developed during the pre-Illinoian stage on till and glaciofluvial materials deposited during the pre-Reid glaciations (Tarnocai, 1987d). These soils developed strongly weathered, rubified, paleoargillic Bt horizons with thick clay skins or argillans (Tarnocai and Smith, 1989; Smith *et al.*, 1987). As a result of cryoturbation, the clay skins in the upper B horizon are usually fragmented and dispersed.

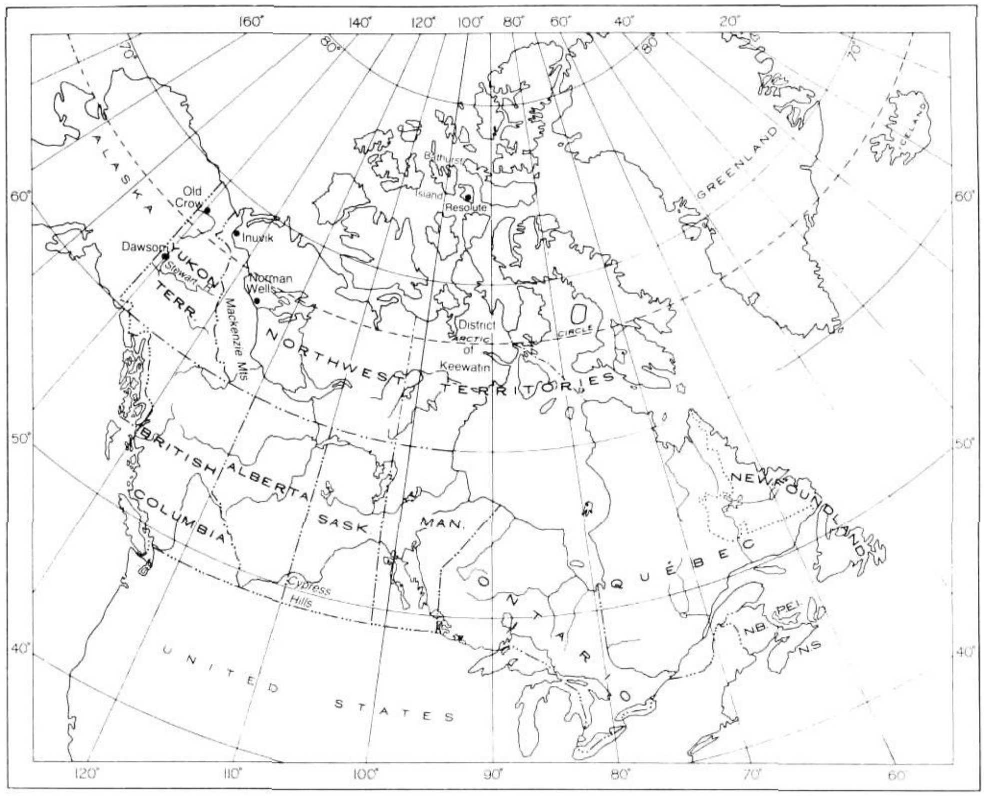


FIGURE 3. Locations of geographic features and settlements.

*Localisation des entités géographiques et des sites.*

Most Wounded Moose soils display strong cryoturbation in the form of disrupted and displaced soil horizons and oriented 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 Pleistocene epoch. It should be noted that the oxygen isotope record indicates the occurrence of a long cold period, especially between 0.37 and 0.84 Ma. Perhaps these well developed and numerous cryogenic features originate mainly from this period.

*Mokowan Butte paleosols 4 and 5:* Paleosols 4 and 5, the more recent paleosols in the Mokowan Butte section (Karlstrom, 1987 and 1988), developed during the early Pleistocene. They are characterized by 1 to 5 m thick, leached, rubified argillic horizons overlying indurated petrocalcic, calcic or leached B horizons.

*Little Bear River paleosols 1-4:* The Little Bear River paleosols are found in the Mackenzie Mountains, approximately 80 km southwest of Norman Wells (Fig. 3). This area lies near the boundary between the Mackenzie Plain and the Mackenzie Mountains, in a zone between the former extent of the local montane glaciers originating in the Canyon Ranges of the Mackenzie Mountains and the maximum westward extent of the Laurentide Ice Sheet. In a section 40 to 50 m thick, five montane tills separated by paleosols are overlain by Late Wisconsinan Laurentide boulder gravel. The five paleosols have been numbered 1 to 5 from oldest to youngest; Paleosols 1 to 4 are considered to have developed in the pre-Illinoian interglacial periods while Paleosol 5 developed in the Sangamonian stage and will be considered later. The greater solum and B horizon thicknesses, the increase of redness in the B horizons, and the occurrence of some argillans in Paleosols 1 to 4 indicate stronger soil development with increased age. This suggests that, since the formation of the oldest paleosols, the climate has steadily cooled. The lack of evidence for cryoturbation indicates that these paleosols were not associated with permafrost.

*If these paleosols developed during the warm periods identified on the oxygen isotope record* (Fig. 2, b and c) then, because these paleosols were buried, each is the result of the single interglacial climate under which it developed. Unlike the Wounded Moose paleosols, these paleosols showed no long-term cumulative effect of several warm interglacial and cold glacial periods. The increased redness and deeper sola of the older Little Bear River paleosols correlate with the oxygen isotope record and indicate that the climates under which these paleosols developed were much warmer than the present climate.

## LATE PLEISTOCENE PALEOSOLS

The late Pleistocene epoch was composed of two stages, the Sangamonian interglacial stage and the Wisconsinan glacial stage. Although variable, the Sangamonian stage provided a favourable environment for soil development. According to *St-Onge's (1987) interpretation of the oxygen isotope record* (Fig. 2a), the climate was somewhat cooler in oxygen isotope stage 5a, cooler still in stage 5c, and colder in stages 5b and 5d than it is now. In stage 5e, however, the climate was the same as, or warmer than, the present climate.

The development of the Diversion Creek paleosols indicates that the Sangamonian climate of the central Yukon was slightly warmer than the present climate. The oxygen isotope record, however, indicates that this warmer period only occurred for a relatively short period of time (between approximately 120 ka and 128 ka) and not during the entire length of the Sangamonian interglacial period.

Foscolos *et al.* (1977) and Rutter *et al.* (1978) suggest that the cool and humid climate that existed during this period was responsible for the Brunisolic or weak Luvisolic soil development. This cooler climate resulted in weaker soil development than is found in the Wounded Moose paleosols.

*Diversion Creek paleosols:* The Diversion Creek paleosols, which are found in the central Yukon (Fig. 3), began to form during the Sangamonian interglacial period (Smith *et al.*, 1986; Tarnocai *et al.*, 1985; Tarnocai, 1987a). They developed on both till and glaciofluvial materials produced by the Reid (Illinoian) glaciation. These paleosols have moderately well developed B horizons with the dominant colour of the uppermost B horizon being 7.5YR. The Bt horizons, which are found only in Diversion Creek paleosols developed on till, have weakly developed grain argillans (Tarnocai and Smith, 1989). Sand wedges are present, but they are not common. Cryoturbated features such as oriented stones, silt cappings and distorted horizons are more common on the Diversion Creek till paleosols than on the outwash paleosols. Ventifacts occur on all of these Diversion Creek paleosol surfaces. Weathering of coarse fragments in these paleosols is moderate and frost-shattered coarse fragments commonly occur.

*Little Bear River paleosol 5:* This paleosol possibly developed in the Sangamonian interglacial period. It has a redness rating (Torrent *et al.*, 1980) of 1.2, which is very similar to that for Paleosol 3, which is also found in the Little Bear River section. Little Bear River Paleosol 5 has weakly developed void and grain argillans very similar to those found in the Diversion Creek paleosols (Tarnocai and Smith, 1989).

*Old Crow paleosols:* These Cryosolic paleosols were found buried within a dominantly fluvial succession overlain by Late Wisconsinan lake sediments in the Old Crow Basin. They developed in a permafrost environment and were associated with gleyed horizons, mottles, cryoturbated features, patterned ground and ice wedges. A bone buried in an Old Crow paleosol gave a radiocarbon date of 42 ± 1.2 ka BP (R. E. Morlan, personal communication, 1987). Although Cryosolic soils are common in the Old Crow Basin at the present time, the ice wedge formations found in the Old Crow paleosols indicates the presence of a colder climate than now occurs. This is confirmed by the oxygen isotope record (Fig. 2a), which indicates the occurrence at that time of a cold period which was much colder than the climate at the present time.

*Buried organic layers on Bathurst Island:* Buried organic matter found in Cryosolic soils (Fig. 4) at Goodsir Inlet, Bathurst Island, one of the Queen Elizabeth Islands in the Canadian arctic archipelago (Fig. 3), yielded a radiocarbon date of 38.5 ± 1.4 ka BP (GSC-3048). The morphology and composition of this cryoturbated organic horizon indicate that this organic material was incorporated in the subsoil by cryoturbation and that the soil was a Cryosol 38 ka ago. The soil at that time was most likely very similar to the present-day Cryosolic soils. This suggests that the climate of the area was favourable for biological activity and Cryosolic soil formation. Buried peat layers at Goodsir Inlet yielded a radiocarbon date of 35.0 ka BP (GSC-178) (Blake, 1964) while those from the nearby Scoresby Hills area yielded a date of 38.0 ka BP (GSC-1878) (Blake, 1964). The presence of these peat layers also indicates that the climate was favourable for peat deposition.

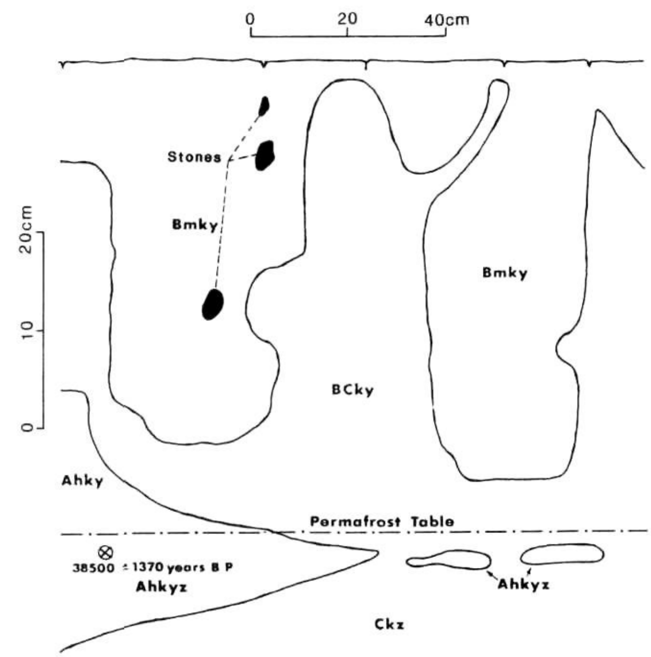


FIGURE 4. Cross section of a Cryosolic soil with cryoturbated organic horizons from Goodsir Inlet, Bathurst Island, N.W.T.

*Coupe d'un sol cryosolique avec horizons organiques géliturbés, de Goodsir Inlet, à l'île de Bathurst (T.N.-O.).*

## HOLOCENE RELICT SOIL FEATURES

*Buried cryoturbated organic materials in earth hummocks:* Radiocarbon dating was carried out on buried organic materials from earth hummocks in the arctic and subarctic regions of Canada (Zoltai *et al.*, 1978; Tarnocai, 1987b). Most of the buried organic materials were younger than 4.8 ka. Cryoturbation, as indicated by Zoltai *et al.* (1978), began about 4.5 ka and was very intense between 3.0 ka and 3.5 ka. The formation of earth hummocks also began about 4.5 ka. In the Old Crow area of the Yukon, cryoturbated organic material from a Cryosolic soil associated with patterned ground yielded radiocarbon dates between 3.6 ka and 3.7 ka (Tarnocai, 1987b). This period was also considered to have had a cooler climate that initiated extensive cryogenic activities and patterned ground formation. This patterned ground (circles) is now covered with a continuous thick mat of humus and high organic content mineral materials.

*Relict earth hummocks:* Relict earth hummocks have been found at a number of locations in Canada. Tarnocai (1973) reported the occurrence of relict earth hummocks with continuous soil horizons (Fig. 5) in the southern part of the Mackenzie Valley. These soil horizons showed no evidence of cryoturbation, suggesting that when hummock formation and the associated cryoturbation ceased, continuous soil horizons were able to develop in these fossil earth hummocks. Similar fossil earth

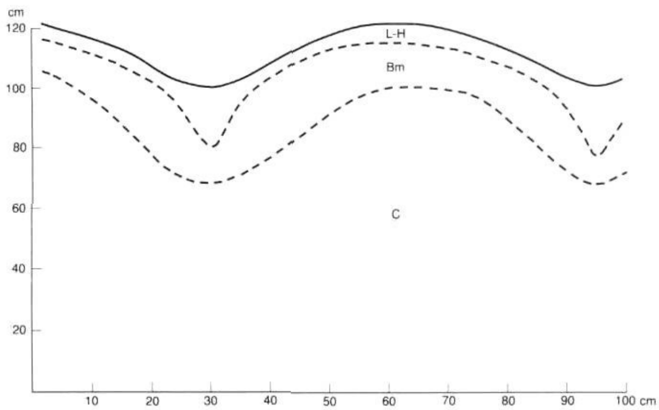


FIGURE 5. Cross section of a fossil earth hummock found in the southern Mackenzie Valley, N.W.T.

*Coupe dans une butte de terre fossilisée observée dans le sud de la vallée du Mackenzie (T.N.-O.).*

hummocks were found in the South Indian Lake area of northern Manitoba (H. Veldhuis and G. F. Mills, personal communication, 1987).

Scotter and Zoltai (1982) reported relict earth hummocks and cryoturbated features in alpine soils in the southern Canadian Rocky Mountains. They concluded that these features resulted from the cooler climatic conditions associated with neoglacial activities.

*Organic soil development during the Hypsothermal Maximum:* Radiocarbon dates of basal peat materials indicate that peat deposition in continental Canada did not begin until several thousand years after the continental ice sheet melted. A comparison of all of the radiocarbon dates available from the continent indicates that the majority of peat deposits began to develop between 4 and 6 ka BP (Tarnocai, 1978). On the Canadian arctic islands, however, the basal peat dates are older, ranging from 8.5 to 9 ka BP (Tarnocai, 1978; Tarnocai and Zoltai, 1988). Tarnocai and Zoltai (1988) also indicated that the peat deposits in the high arctic accumulated at a greater rate between 5 and 10 ka BP than did the low arctic peat deposits.

These basal dates indicate that peat development in the high arctic began shortly after deglaciation and, as was suggested by Tarnocai (1978), probably resulted from the favourable climatic conditions existing there at that time. There is evidence that, after the retreat of glacial ice from the North American continent, there was a relatively warm and dry period lasting several thousand years (Ritchie and Hare, 1971; Terasmae, 1972; Delorme *et al.*, 1977). Tarnocai (1978) suggested that it is possible that the climate was generally too warm and dry in the south during this period for optimum peat development. In the high arctic areas, however, the climate was assumed to have been cooler and moister (although warmer than at present) after the retreat of the glacial ice, and consequently, conditions were favourable for peat development. As the climate became colder and peat development virtually ceased in the high arctic, the boreal and subarctic regions became established as the areas of optimum peat development.

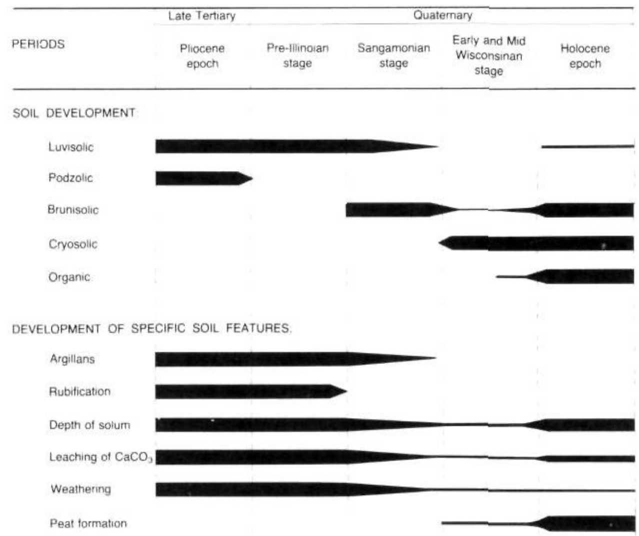


FIGURE 6. Soil development and the development of some soil features during the late Tertiary and Quaternary periods, including the Holocene epoch.

*Développement de profil et développement de certaines caractéristiques du sol à la fin du Tertiaire et au Quaternaire, y compris à l'Holocène.*

*Forest soils north of the arctic tree line:* The distribution of paleosols makes it possible to reconstruct the positions of the arctic tree line and to estimate characteristics of the past climate (Sorenson, 1973 and 1977; Sorenson and Knox, 1974). According to these authors, the arctic tree line varied from 280 km north to at least 50 km south of its present position. In the Keewatin District, the occurrence of buried charcoal and associated Podzolic soils confirms that at some time during the Holocene the tree line was up to 280 km north of its present position (Bryson *et al.*, 1965). It should be noted, however, that the soils Bryson *et al.*, (1965) identified as Podzols are now classified as Brunisols (Agriculture Canada Expert Commitee on Soil Survey, 1987). These paleobrunisolic soils are frequently buried by eolian sands on which Arctic Brown soils (Brunisolic Static Cryosols) developed, often in association with polygonal patterned ground (Sorenson *et al.*, 1971). Bryson *et al.* (1965) and Nichols (1967, 1970) give evidence for southern shifts of the arctic tree line. According to Sorenson (1973, 1977) and Sorenson and Knox (1974) major northward shifts of the arctic tree line occurred about 2.9, 1.8 and 0.8 ka BP and southward movements occurred about 3.5, 2.6 and 1.6 ka BP. The pollen records presented by Ritchie and Hare (1971) give further evidence of these fluctuations.

## DIAGNOSTIC SOIL FEATURES USED IN PALEOCLIMATIC RECONSTRUCTION

Argillic horizons (Fig. 6) are diagnostic of Luvisolic soils. During the late Tertiary and early Pleistocene, Luvisols were very common soils throughout the Yukon. The development of Luvisolic soils, and thus the presence of argillans, was reduced considerably in the Yukon during the late Pleistocene and was even further reduced in the Holocene.

The presence of redness, or rubification, is characteristic of the late Tertiary and early Pleistocene (pre-Illinoian) paleosols. Rubification was found in all of these paleosols, even the high-elevation Little Bear River paleosols. 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. Smith *et al.* (1987) studied the pre-Illinoian Wounded Moose paleosols occurring in the central Yukon. They found that the redness of the paleoargillic horizons resulted from small amounts of hematite ($<3\%$) concentrated in submicroscopic zones. This rubification was 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.

The depth of the soil can indicate its age and give some idea of the climate under which it formed. In most soils this depth was established by the presence of argillans, redness, leaching of carbonates, and soil structure. The deeper sola are common in paleosols of the pre-Illinoian interglacial periods. In the central Yukon an average solum depth of 2 m was associated with the Wounded Moose paleosols, 1 m with the Diversion Creek paleosols and 0.5 m with the contemporary Stewart soils (Smith *et al.*, 1986).

The degree and depth of leaching of carbonates ($CaCo_3$) is controlled by the carbonate content of the parent material, the availability of water (rainfall) and the time available. The depth of leaching was greatest in the pre-Illinoian interglacial paleosols and much less in the recent soils.

The degree of weathering of both the clay minerals and the coarse fragments is dependent on both the climate (temperature and moisture) and the length of time available. In the Yukon the degree of weathering was greatest in the late Tertiary and pre-Illinoian paleosols, less in the Sangamonian paleosols, and minimal in the Holocene soils.

The formation of peat is mainly dependent on climate. If favourable climatic conditions exist during long periods of time, the organic depositions can reach great thicknesses. If the favourable climatic conditions cease to exist, however, peat formation stops. This was demonstrated by peat or Organic soil development in the early Holocene epoch. During the Hypsothermal Maximum in the early Holocene epoch, climatic conditions were more favourable for peat formation on the arctic islands than in the area that now lies in the boreal and subarctic regions. When the climate cooled following the Hypsothermal Maximum, the climate in the arctic islands became too cold and dry for peat development. Peat development ceased or became very slow in this area and the optimal area for peat development shifted to more favourable areas, now the boreal and subarctic regions (Tarnocai, 1978).

## NORTHERN LIMITS OF SOILS AS CLIMATIC INDICATORS

There is evidence that the northern limit of some groups of soils (*e.g.* Luvisols and Cryosols) is especially sensitive to climate change and could be useful in predicting former climates. It appears that when major changes occur in one of the soil-forming factors (e.g. climate) the system adjusts in a relatively short period of time. This adjustment produces both soil features and soil development which are strongly related to the changed soil-forming factor. Such adjustments occur not only because of a change in climate but also because of changes in other soil-forming factors such as hydrology and vegetation. If climatic change does take place, however, it has an overriding effect on soil development. In a relatively short period of time the change in climate produces certain soil features or soil development which appear as an overprint on the previous soil development, but features developed before the change of climate often remain as relict features in the soil. In some cases this overprint is visible and long lasting.

There are many examples of relict soil features being interpreted in terms of climate change. Bryson and Wendland (1967) and Sorenson (1973) found evidence that the existence of forest soils north of the present arctic tree line can be used to indicate the position of the former tree line. The occurrence of cryogenic features and patterned ground on the northern fringe of the Brunisols and Luvisols indicates that permafrost extended farther south during the colder periods of the Holocene (Tarnocai, 1973). The presence of collapse scars on the northern fringe of the Fibrisols and Mesisols was interpreted as indicating that these scars marked the position of former Organic Cryosols during the Little Ice Age. When the climate warmed during the 1800s, the permafrost melted and produced scars in these areas (Zoltai, 1971). It is thus possible, based on the northern extent of contemporary soils and an interpretation of their features, to develop a model which can be used to predict paleoclimates from soil development and certain soil properties.

This model would be based on a comparison of the palesols and relict features with the present-day soils and soil features and would use information concerning the northern limits of Luvisolic, Podzolic and Cryosolic soils in western and northwestern Canada. This area was selected because of the existence of continuous soil records dating to the late Tertiary period.

The northern limits of contemporary Luvisols and Podzols lie in the interior part of western Canada, at approximately 61° and 58° north latitudes, respectively (Clayton *et al.*, 1977 and Figs. 7 and 8). At latitude 61° north, the Luvisolic limit, the mean annual temperature is −3.5°C and the mean annual precipitation is 375 mm. The corresponding temperature and precipitation at the Podzolic limit are −1.0°C and 450 mm. Luvisols and Podzols are both considered to be forest soils and support various types of forest vegetation. The southern limit of the present Cryosolic soils (Figs. 7 and 8) coincides with the southern limit of the Discontinuous Permafrost Zone, which corresponds approximately to the −1°C isotherm line (Brown, 1967). By using these limits and the associated climatic data it is possible to predict the climate for the northern boundary of the paleosols in the various interglacial periods.

### LATE TERTIARY LIMIT

Evidence from the Burnt Hill and Bluefish River paleosols suggests that the late Tertiary environment in the northern

Yukon was associated with Luvisolic and Podzolic soil development. These types of soil development extended to at least 68° north latitude, in the area of Old Crow (Fig. 8). 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). The occurrence of Podzolic paleosols suggests that at some point during the late Tertiary (Pliocene) the temperature in the Old Crow area was at least 9°C warmer and that the precipitation was at least twice what it is today. Karlstrom (1987) suggested that the late Tertiary Mokowan Butte paleosols in southwestern Alberta also formed in an environment with mean annual temperatures at least 6° to 10°C warmer than today.

The late Tertiary Luvisolic and Podzolic paleosols are also considered to be forest soils, as are the contemporary soils. The pollen data confirm this, indicating that these paleosols supported a coniferous forest with white pine and hemlock in the tree layer and an understory of alder and *Corylus* (Tarnocai and Schweger, in press). The northern limit of the *Corylus* sp. now lies in central British Columbia, at approximately 56° north latitude (Drumke, 1964). This indicates that the Tertiary climate of the Old Crow area was probably comparable to the present climate of 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). The presence of *Corylus* in the Old Crow area indicates that the temperature in this area was at least 14°C higher than at present. It is thus likely that the northern limits of the Luvisolic and Podzolic soils were even further north during the late Tertiary.

## EARLY AND MIDDLE PLEISTOCENE LIMIT

The Wounded Moose paleosols represent the northern limit of rubified Luvisolic soils during the early and middle Pleistocene interglacial periods (pre-Illinoian). In the central Yukon these paleosols extended to approximately 65° north latitude and occur at elevations below 1000 m a.s.l. (Fig. 8). If this was the northern limit of the early and middle Pleistocene Luvisolic soils, the temperature was probably 8°C higher and the precipitation slightly higher that it is now. This limit, however, is arbitrary since the Wounded Moose paleosols are associated with pre-Reid glacial deposits. It is possible that Wounded-Moose-like paleosols also exist in the unglaciated areas of the Yukon, outside of the pre-Reid limit. Smith *et al.* (1987) suggested that the mean annual temperature of the central Yukon was 7°C or higher, which is about 10°C higher than at present.

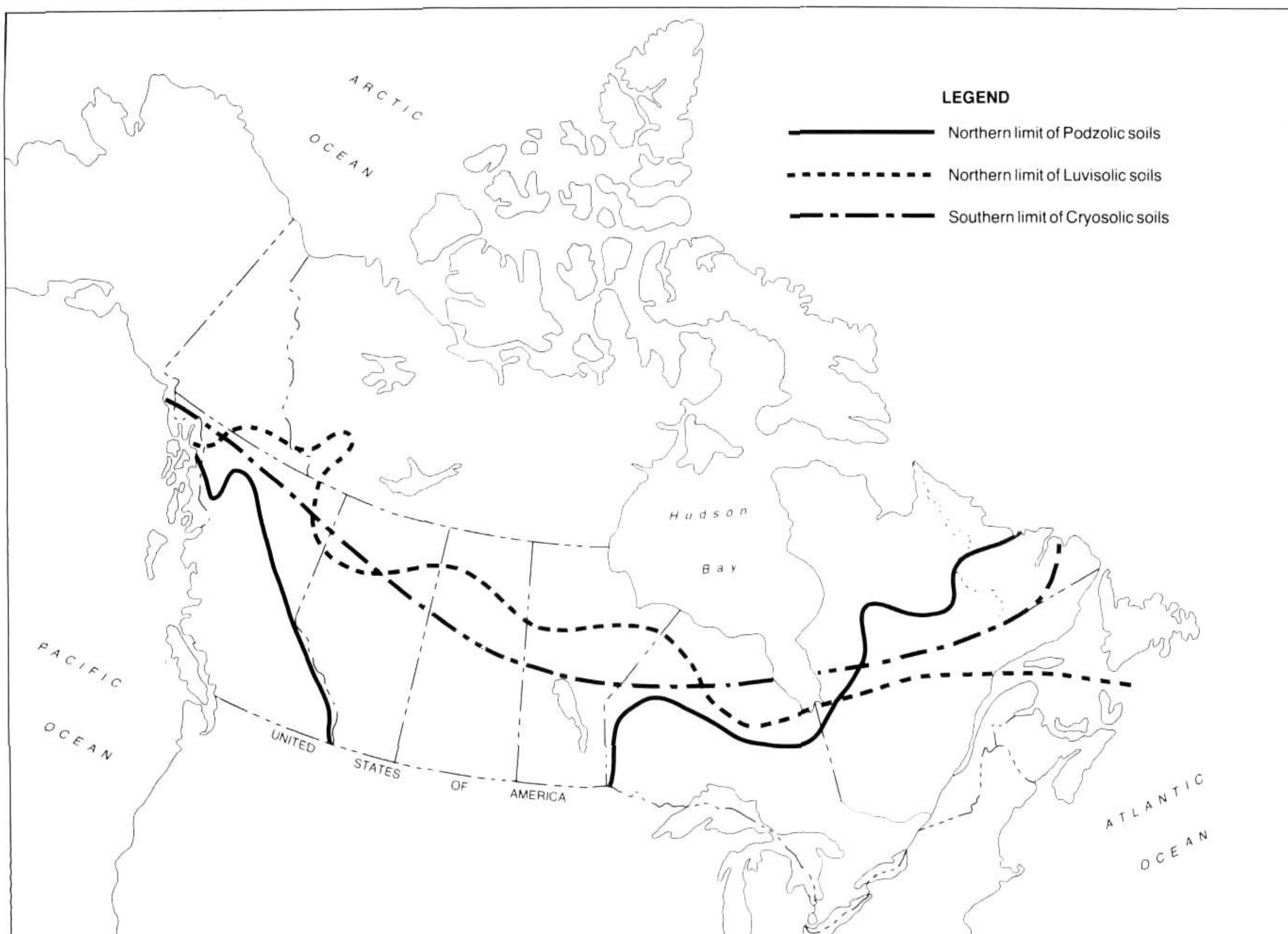


FIGURE 7. The present northern limit of Luvisolic and Podsolic soils and the southern limit of Cryosolic soils in Canada.

*Les limites septentrionales actuelles des sols luvisoliques et podzoliques et la limite méridionale des sols cryosoliques au Canada.*

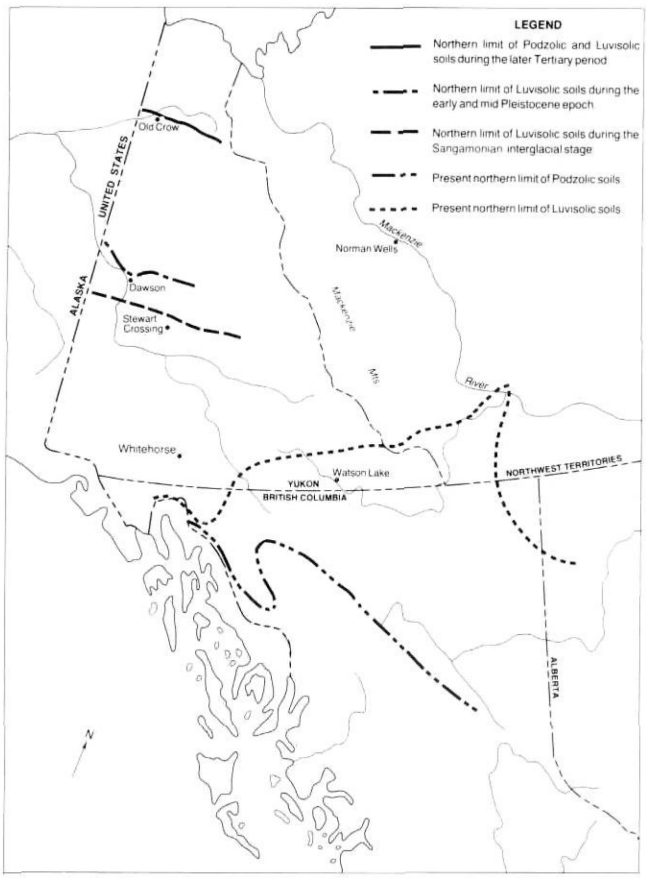


FIGURE 8. The northern boundaries of some soils during the past 5 Ma.

*Les limites septentrionales de quelques sols depuis 5 Ma.*

Karlstrom (1987) found that the early Pleistocene Mokowan Butte paleosols in southwestern Alberta were rubified Luvisolic paleosols with argillic horizons. He suggested that these paleosols formed under an interglacial climate with a mean annual temperature at least 6°C warmer than today.

## LATE PLEISTOCENE LIMIT

The Diversion Creek paleosols mark the northern limit of Luvisolic soils during the Sangamonian stage of the late Pleistocene epoch. Although the most northerly occurrence of these soils is found in the Chandindu and Benson Creek moraines in the Klondike Valley, the Diversion Creek paleosols in these locations are Brunisols. The most northerly occurrence of the Luvisolic type of Diversion Creek paleosols lies at approximately 65.5° north latitude (Fig. 8). These Diversion Creek paleoluvisolic soils are very similar to the Luvisols now found in the Watson Lake area of British Columbia, at the northern limit of the present Luvisolic soils. This suggests that the Sangamonian climate at the Luvisolic soil boundary was at least 1°C warmer and the precipitation was only slightly higher that it is at the present time.

The Little Bear River paleosols had no cryogenic features, indicating that no permafrost was present at that location during the Sangamonian and pre-Illinoian interglacial periods.

## HOLOCENE LIMIT

No major shifts in soil boundaries occurred during the Holocene epoch with the exception of that for the Cryosolic soils. Organic Cryosol development was active in the high arctic for several thousand years after deglaciation, but then almost ceased because the climate changed, becoming cold and dry. The occurrence of paleo forest soils north of the present tree line suggests that the arctic tree line fluctuated by at least 200 km a number of times. If the location of the arctic tree line is considered to coincide with the 10°C July isotherm, then it indicates the occurrence of alternating periods of slight cooling and warming during the Holocene epoch.

## SUMMARY AND CONCLUSIONS

Paleosols developed during the late Tertiary period and the following interglacial periods in the Quaternary period give evidence of a gradually cooling climate. A summary of the climates, based on the soil development and certain soil features found in various paleosols, is as follows:

1. *Late Tertiary (late Pliocene) Period:* The presence of the Bluefish River (Luvisolic) and Burnt Hill (Podzolic) paleosols in the Old Crow area of the northern Yukon suggests that the northern limit of these two soils in the Canadian northwest was at least 68° north latitude or perhaps much further to the north. The occurrence of these paleosols in the Old Crow area together with the paleobotanical data suggests that the mean annual temperature was then at least 4°C and that the mean annual precipitation was at least twice what it is at the present time. Although the pollen record indicates gradual cooling in the late Tertiary period, it also shows that the climate was much warmer than at the present time. Oxygen isotope data suggest that there were considerable fluctuations in the late Tertiary climate, with major cooling occurring at 2.4 Ma.
2. *Early and middle Pleistocene interglacial periods:* The presence of the Wounded Moose (Luvisolic) paleosols in the central Yukon (at elevations below 1000 m a.s.l.) suggests that the northern limit of Luvisols in this area was approximately 65° north latitude, that the mean annual temperature was about 8°C higher than at present and that the precipitation was slightly higher than it is now. The oxygen isotope records indicate the occurrence of four warm periods during this time, at 1.1, 0.95, 0.86, and 0.3 Ma. The first warm period, at 1.1 Ma, was also the warmest.
3. *Sangamonian interglacial stage:* The occurrence of Diversion Creek paleosols, which occur at elevations below 1000 m a.s.l., suggests that the northern limit of Luvisolic soils during the Sangamonian interglacial period was at about 63° north latitude in the central Yukon, approximately 3° further north than at present. Based on the climate at the northern limit of the present Luvisols, which are very similar in development to the Diversion Creek Luvisolic paleosols, the mean annual temperature of the central Yukon was probably only 1°C higher and the precipitation was only slightly higher that it is now. The Brunisolic Little Bear River paleosols, which occur at elevations above

1000 m a.s.l., exhibit no cryogenic features, indicating that no permafrost was present at that location. The oxygen isotope record suggests that the Sangamonian interglacial period was cooler, and at times colder, than the present climate. Only in oxygen isotope stage 5e, lasting for approximately 8 ka, was there a climate similar to or warmer than that occurring now. Although soil development and the distribution of Luvisols suggests that the climate was similar to or slightly warmer than the present climate, the oxygen isotope record indicates that temperatures fluctuated considerably during this period.

4. *Ice-free areas during the Wisconsinan stage:* The Old Crow paleosols, which developed during this interval, are Cryosolic soils with ice wedge casts, evidence of the presence of a permafrost environment. Modern soils in the Old Crow area, which are also Cryosols with earth hummocks, have developed on the same materials as did the paleosols. Ice wedges are now associated mainly with Organic Cryosols, suggesting that when the Old Crow Cryosolic paleosols developed 42 ka ago, the climate was similar to or slightly cooler than the present climate. The occurrence of 38 ka old cryoturbated organic layers on Bathurst Island in the high arctic also indicates that Cryosolic soil development and organic matter production took place at that time, suggesting that the climate was very similar to the present climate.

5. *Holocene interglacial period:* Various relict features found in modern soils indicate that climatic fluctuations have occurred since deglaciation. Organic landforms developed on the arctic islands shortly after deglaciation (7-9 ka BP). The occurrence of these relict landforms in association with strongly eroded Organic Cryosols indicates that the climate was warmer and moister at that time. In continental Canada, however, very little peat deposition occurred at that time, presumably because the climate was warm and dry. Following this early stage the climate cooled. As the high arctic became too cold and dry for peat deposition the area of optimum peat development shifted to the south, to the boreal and subarctic areas of Canada. Buried forest soils occur north of the arctic tree line (10°C July isotherm) and dates obtained from charcoal found in these soils indicate not only a more northerly location for the tree line but also a number of fluctuations in its position during the Holocene epoch. Dates obtained using cryoturbated organic materials from Cryosolic soils associated with earth hummocks suggest increased cryogenic activity and hummock formation about 3.5 ka BP as a result of climatic cooling.

A comparison of the northern limits of various soils during the late Tertiary and the interglacial periods of the Quaternary indicates that none of the interglacial periods before the Holocene epoch were associated with Cryosolic soils to such an extent as during the Holocene. Even though their boundaries fluctuate, Cryosols are the dominant soils during the Holocene epoch, covering approximately 40% of the land area of Canada. The paleosols thus yield evidence of steadily cooling interglacial climates since the end of the Tertiary period.

## REFERENCES

Agriculture Canada Expert Committee on Soil Survey, 1987. The Canadian system of soil classification. Research Branch, Agriculture Canada, Publication No. 1646, second edition, 164 p.

Atmospheric Environment Service, 1982a. Canadian climate normals, temperature and precipitation: the North — British Columbia. Environment Canada, Atmospheric Environment Service, UDC: 551.582(711), 268 p.

——— 1982b. Canadian climate normals, temperature and precipitation: the North — Yukon Territory and Northwest Territories. Environment Canada, Atmospheric Environment Service, UDC: 551.582(712), 55 p.

Blake, W., 1964. Preliminary account of the glacial history of Bathurst Island, Arctic Archipelago. Geological Survey of Canada, Paper 64-30, 8 p.

Bostock, H. S., 1966. Notes on glaciation in central Yukon Territory. Geological Survey of Canada, Paper 65-36, 18 p.

Brewer, R., 1972. The use of macro- and micromorphological data in soil stratigraphy to elucidate surficial geology and soil genesis. Journal of the Geological Society of Australia, 19: 331-344.

Brown, R. J. E., 1967. Permafrost in Canada. 1st ed., Geological Survey of Canada, Map No. 1246A.

Bryson, R. A. and Wendland, W. M., 1967. Tentative climatic patterns for some late-glacial and postglacial episodes in central North America, p. 271-298. *In* W. J. Mayer-Oakes, ed., Life, land and water. University of Manitoba, Winnipeg, Manitoba.

Bryson, R. A., Irving, W. N. and Larsen, J. A., 1965. Radiocarbon and soil evidence of former forest in the southern Canadian tundra. Science, 147: 46-48.

Clayton, J. S., Ehrlich, W. A., Cann, D. B., Day, J. H. and Marshall, I. B., 1977. Soils of Canada. Research Branch, Canada Department of Agriculture, vols. 1 and 2, and accompanying maps.

Delorme, L. D., Zoltai, S. C. and Kalas, L. L., 1977. Freshwater shelled invertebrate indicators of paleoclimate in northwestern Canada: the late glacial times. Canadian Journal of Earth Sciences, 14: 2029-2046.

Drumke, J. S., 1964. A systematic survey of *Corylus* in North America. Ph.D. thesis, University of Tennessee, 142 p.

Foscolos, A. E., Rutter, N. W. and Hughes, O. L., 1977. The use of pedological studies in interpreting the Quaternary history of central Yukon. Geological Survey of Canada, Bulletin 271, 48 p.

Fulton, R. J. and Prest, V. K., 1987. Introduction: The Laurentide Ice Sheet and its significance. Géographie physique et Quaternaire, 41: 181-186.

Hughes, O. L., 1987. Quaternary geology, p. 12-16. *In* S. R. Morison and C. A. S. Smith, eds., Guidebook to Quaternary Research in Yukon. XIIth INQUA Congress, Ottawa, National Research Council of Canada, Ottawa.

Hughes, O. L., Rampton V. N. and Rutter, N. W., 1972. Quaternary geology and geomorphology, southern and central Yukon. Guidebook for field excursion A-11, 24th International Geological Congress, Montreal, 59 p.

Hughes, O. L., van Everdingen, R. O. and Tarnocai, C., 1983. Regional setting — physiography and geology. *In* H. M. French and J. A. Heginbottom, ed., Northern Yukon Territory and Mackenzie Delta. Guidebook for Field Trip 3, 4th International Conference on Permafrost, Fairbanks, 186 p.

Jungerius, P. D. and Mucher, H. J., 1972. The micromorphology of fossil soils in the Cypress Hills, Alberta, Canada, p. 617-627. *In* S. Kowalinski, ed., Soil micromorphology. Panst. Wydawn. Nauk., Warszawa.

Karlstrom, E. T., 1987. Stratigraphy and genesis of five superposed paleosols in pre-Wisconsinan drift on Mokowan Butte, southwestern Alberta. Canadian Journal of Earth Sciences, 24: 2235-2253.

——— 1988. Multiple paleosols in pre-Wisconsinan drift, northwestern Montana and southwestern Alberta. Catena, 15: 147-178.

Nichols, H., 1967. The postglacial history of vegetation and climate at Ennadai Lake, Keewatin, and Lynn Lake, Manitoba. Eiszeitalter und Gegenwart, 18: 176-197.

——— 1970. Late Quaternary pollen diagrams from the Canadian Arctic barren grounds at Pelly Lake, northern Keewatin, N.W.T. Arctic and Alpine Research, 2: 43-61.

Ritchie, J. C. and Hare, F. K., 1971. Late Quaternary vegetation and climate near the arctic tree line of northwestern North America. Quaternary Research, 1: 331-342.

Ruddiman, W. F. and McIntyre, A., 1981. Oceanic mechanism for amplification of the 23,000-year ice volume cycle. Science, 212: 617-627.

Rutter, N. W., Foscolos, A. E. and Hughes, O. L., 1978. Climatic trends during the Quaternary in central Yukon based upon pedological and geological evidence, p. 309-395. *In* Proceedings of the Third York Quaternary Symposium on Quaternary Soils. Geo Abstracts, Norwich.

St-Onge, D. A., 1987. The Sangamonian Stage and the Laurentide Ice Sheet. Géographie physique et Quaternaire, 41: 189-198.

Schweger, C. E., in press. Late Tertiary — early Pleistocene palynology, Old Crow — Bluefish Basins, northern Yukon, Canada. Arctic.

Schwertmann, U., Murad, E. and Schulze, D. G., 1982. Is there Holocene reddening (hematite formation) in soils of axeric temperate areas? Geoderma, 27: 209-223.

Scotter, G. W. and Zoltai, S. C., 1982. Earth hummocks in the Sunshine area of the Rocky Mountains, Alberta and British Columbia. Arctic, 35: 411-416.

Shackleton, N. J., Backman, J., Zimmerman, H., Kent, D. V., Hall, M. A., Roberts, D. G., Schnitker, D., Baldauf, J. G., Desprairies, A., Homrighausen, R., Huddlestun, P., Keene, J. B., Kaltenback, A. J., Krumsiek, K. A. O., Morton, A. C., Murray, J. W. and Westberg-Smith, J., 1984. Oxygen-isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region. Nature, 307: 620-623.

Smith, C. A. S., Tarnocai, C. and Hughes, O. L., 1986. Pedological investigations of Pleistocene glacial drift surfaces in the central Yukon. Géographie physique et Quaternaire 40: 29-37.

Smith, C. A. S., Spiers, G. A. and Tarnocai, C., 1987. Why are the mid-Pleistocene soils of the central Yukon red? XIIth INQUA International Congress Abstracts. National Research Council of Canada, Ottawa, p. 266.

Sorenson, C. J., 1973. Interrelationships between soils and climate and between paleosols and paleoclimates: forest/tundra ecotone, north central Canada. Ph.D. thesis, University of Wisconsin, Madison, 237 p.

——— 1977. Reconstructed Holocene bioclimates. Annals of the Association of American Geographers, 67: 214-222.

Sorenson, C. J., Knox, J. C., Larsen, J. A. and Bryson, R. A., 1971. Paleosols and forest border in Keewatin, N.W.T. Quaternary Research, 1: 468-473.

Sorenson, C. J. and Knox, J. C., 1974. Paleosols and paleoclimates related to late Holocene forest/tundra border migration: Mackenzie and Keewatin, N.W.T., Canada, p. 186-203. *In* S. Raymond and P. Schledermann, ed., International Conference on the Prehistory and Paleoecology of Western North American Arctic and Subarctic. Archaeology Association, University of Calgary.

Storer, J. E., 1975. Middle Miocene mammals from the Cypress Hills, Canada. Canadian Journal of Earth Sciences, 12: 520-522.

Tarnocai, C., 1973. Soils of the Mackenzie River area. Environmental-Social Committee, Northern Pipelines, Task Force on Northern Oil Development, Report No. 73-26, 136 p.

——— 1978. Genesis of organic soils in Manitoba and the Northwest Territories, p. 453-470. *In* Proceedings of the Third York Quaternary Symposium on Quaternary Soils, Geo Abstracts, Norwich.

——— 1987a. Quaternary soils, p. 16-21. *In* S. R. Morison and C. A. S. Smith, ed., Guidebook to Quaternary Research in Yukon. XIIth INQUA International Congress, National Research Council of Canada, Ottawa.

——— 1987b. Stop 29B: Recent, strongly cryoturbated soil, p. 84-87. *In* S. R. Morison and C. A. S. Smith, ed., Guidebook to Quaternary Research in Yukon. XIIth INQUA International Congress, National Research Council of Canada, Ottawa.

——— 1987c. Stop 29E: Buried paleosol overlain by gravel in the Bluefish River bed., p. 90-95. *In* S. R. Morison and C. A. S. Smith, ed., Guidebook to Quaternary Research in Yukon. XIIth INQUA International Congress, National Research Council of Canada, Ottawa.

——— 1987d. Stop 22: Wounded Moose paleosol developed on pre-Reid gravel, p. 61-65. *In* S. R. Morison and C. A. S. Smith, ed., Guidebook to Quaternary Research in Yukon. XIIth INQUA International Congress, National Research Council of Canada, Ottawa.

Tarnocai, C., Smith S. and Hughes, O. L., 1985. Soil development on Quaternary deposits of various ages in the central Yukon Territory. *In* Current Research, Part A. Geological Survey of Canada, Paper 85-1A: 229-238.

Tarnocai, C. and Zoltai S. C., 1988. Wetlands of Arctic Canada, p. 27-51. *In* Wetlands of Arctic Canada. National Wetlands Working Group, Ecological Land Classification Series, No. 24, Sustainable Development Branch, Environment Canada, Ottawa, and Polyscience Publications Inc., Montréal.

Tarnocai, C. and Smith, C. A. S., 1989. Micromorphology and development of some central Yukon paleosols, Canada. Geoderma, 45: 145-162.

Tarnocai, C. and Valentine, K. W. G., 1989. Relict soil properties of the arctic and subarctic regions of Canada, p. 6-39. *In* A. Bronger and J. Catt, ed., Paleopedology: Nature and Applications of Paleosols. Catena Supplement 16.

Tarnocai, C. and Schweger, C. E., in press. Late Tertiary and early Pleistocene paleosols in northwestern Canada. Arctic.

Terasmae, J., 1972. Muskeg as a climate-controlled ecosystem. Proceedings of the 14th Muskeg Research Conference, Kingston, 1971. N.R.C. Technical Memorandum No. 102, p. 147-158.

Torrent, J., Schwertmann, U. and Schulze, D. G., 1980. Iron oxide mineralogy of some soils of two river terrace sequences in Spain. Geoderma, 23: 191-208.

Valentine, K. W. G. and Dalrymple, J. B., 1975. The identification, lateral variation and chronology of two buried paleocatenas at Woodhall Spa and West Runton, England. Quaternary Research, 4: 551-590.

Valentine, K. W. G., King, R. H., Dormaar, J. F., Vreeken, W. J., Tarnocai, C., De Kimpe, C. R. and Harris, S., 1987. Some aspects of Quaternary soils in Canada. Canadian Journal of Soil Science, 67: 221-247.

Westgate, J. A., Bonnischsen, R., Schweger C. and Dormaar, J. F., 1972. The Cypress Hills, p. 50-62. *In* N. W. Rutter and E. A. Christiansen, ed., Guidebook for excursion C-22 of the 24th International Geological Congress, Montréal.

Yaalon, D. H., 1971. Soil forming processes in time and space, p. 29-38. *In* D. H. Yaalon, ed., Paleopedology. International Society of Soil Science and Israel University Press.

Zoltai, S. C., 1971. Southern limit of permafrost features in peat landforms, Manitoba and Saskatchewan. The Geological Association of Canada, Special Paper 9: 305-310.

Zoltai, S. C., Tarnocai, C. and Pettapiece, W. W., 1978. Age of cryoturbated organic materials in earth hummocks from the Canadian arctic. Proceedings of the Third International Conference on Permafrost, Edmonton, Alberta, Canada, National Research Council of Canada, Ottawa, p. 325-331.