SOIL GENESIS IN RELATION TO GLACIAL HISTORY, CENTRAL YUKON

by

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ABSTRACT

Upland soils formed in three different parent materials in the Lewes Plateau of the Central Yukon were studied: till from the McConnell (MIS 2) and penultimate (MIS 4 or 6) glaciations, and weathered bedrock beyond the penultimate limit. Soils at penultimate and McConnell sites have solum thicknesses of 50-75 cm and <50 cm respectively but other field and chemical observations did not identify differences in weathering patterns between age groups. The two groups have distinctive clay mineral assemblages, with smectite present in the youngest deposits. These results contrast with reconnaissance studies conducted in the 1970s and 1980s on low-elevation soils in the Klondike Plateau. My study shows that field criteria are insufficient for differentiating between McConnell and penultimate deposits in upland landscape positions in the Lewes Plateau and that the presence of smectite clay may be attributable to different parent materials and source areas for ice and not solely changing paleoclimatic conditions.

Soils formed on weathered bedrock have characteristics consistent with both limited and significant weathering. These pedons have solum thicknesses that exceed the depth of the excavated pits (85-110 cm) as well as distinctive clay mineralogy, but chemical data suggest that only limited weathering has occurred. Sola are strongly cryoturbated despite the restricted occurrence of permafrost in the contemporary environment. Two scenarios for the genesis of these soils are proposed which favour either preservation of relict soil features beneath cold-based ice, or prolonged interglacial soil formation following erosion of till deposited by warm-based ice. Alternatively, the area may have remained ice-free throughout the Quaternary so that soil evolution was shaped by multiple glacial-interglacial climatic cycles.

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DEDICATION

To my parents, Judi and Paul Dampier, for giving me a love of learning and for introducing me to the Yukon;

and

to my husband, Malcolm McDonald, for everything. Contorted beds, of unknown age, My weary limbs shall bear, Perhaps a neat synclinal fold At night shall be my lair.

Dips I shall take in unnamed streams, Or where the rocks strike, follow Along the crested mountain ridge Or anticlinal hollow ...

Where long neglected mountains stand Just crumbling into shreds And laying bare on every hand The treasures of their beds ...

> Untitled poem fragments, George Mercer Dawson, 1878

1 INTRODUCTION

Soils developed along the former margins of the Cordilleran Ice Sheet (CIS) have complex histories reflecting periods of development, solum removal and addition of fresh parent material. Soil is a dynamic entity, reflecting interactions of climate, parent material, biota, topography and time (Jenny 1941). Active geomorphic processes, such as erosion, deposition of colluvium and eolian sediments, and periglacial activity result in periods of both removal and rejuvenation which impact soil production (Humphreys and Wilkinson 2007). Soil partially records history, both by preserving features of past environments that could not develop under modern conditions, and erasing evidence of these events through erosion and fresh inputs of parent material. Studies of soil genesis attempt to explain the origin of complex pedological features in order to better understand the environments in which they formed.

Early studies of soil genesis in the Tintina Trench of the central Yukon focussed on reconstructing past climates through the use of pedological evidence obtained from Quaternary glacial deposits of different ages (Tarnocai *et al.* 1985; Smith *et al.* 1986; Tarnocai and Smith 1989). Similar to other chronosequences in glacial landscapes (e.g. Taylor and Blum 1995; Bach and Elliottfisk 1996; Darmody *et al.* 2005a), these studies in the Tintina Trench showed strong soil morphological differences between deposits of different age and provide important evidence for characterizing climatic conditions in former glacial and interglacial periods. As the sites selected for these studies are in geomorphically stable, low-elevation landscape positions, the applicability of this research to other landscape positions along the margins of the CIS is unknown.

Glaciated landscapes in upland areas of central Yukon are actively being eroded through colluviation, thus till from Early and Middle Pleistocene glaciations has typically

been removed. In these regions soil is forming directly in weathered bedrock. In Fennoscandinavia, relict landforms in formerly glaciated terrain, including tors, have survived glaciation due to the presence of cold-based ice (Kleman and Stroeven 1997; Stroeven *et al.* 2002; Darmody *et al.* 2008). The soils associated with these landscapes retain evidence of a local history that predates glaciation. In the central Yukon, similar landforms are found in upland landscapes near the limit of glaciation. However, no geologic or pedologic studies have been undertaken to assess whether they represent relict weathering environments or if they have formed since the areas were last glaciated.

Recent refinements in the chronology of glaciation in the Yukon raise questions about the applicability of early pedological studies to glaciated regions beyond the Tintina Trench. Although the penultimate glaciation has been considered to be synchronous across the central Yukon, new research suggests that separate lobes of the CIS behaved differently and may be marine isotope stage (MIS) 4 or 6 (Ward *et al.* 2007, 2008; Westgate *et al.* 2008). Expanding the geographic extent of soil genesis studies in central Yukon into formerly glaciated upland environments may help elucidate the extent and relative age of glaciation. In this document, the term "Reid" is used to describe the penultimate glaciation either where there is a confirmed age of MIS 6, or where it has been used in referenced literature. The more general term "penultimate" is used where the age of the deposits have not been confirmed.

The purpose of this study is to examine soil development in relation to time and glacial history on the Lewes Plateau in central Yukon (Figure 1.1). The study area is located approximately 25 km southwest of the community of Carmacks, within the western half of the Carmacks NTS 115I map sheet and the northern half of the Aishihik Lake 115H map sheet, south of areas studied by Tarnocai *et al.* (1985) ("area of previous research" Figure 1.2). This area was affected by the Cassiar lobe of the CIS. Two main groups of sites were

examined: sites underlain by till of McConnell and penultimate glaciations; and sites formed in weathered granitic bedrock beyond the penultimate glacial limit.

This chapter provides the regional physiographic, geologic and climatic context for the study. I review previous work on glacial chronology development and soils in the Yukon as well as work on relict landscapes from glacial environments. Common pedological tools for assessing soil development and weathering are reviewed within the context of cold climates and relict pedogenic features. Chapter 2 examines the genesis of upland soils on McConnell and penultimate glacial sediments, and Chapter 3 examines the genesis of high elevation granitic soils. Chapter 4 includes a general discussion and conclusions.

1.1 Regional overview

1.1.1 Physiography

The Yukon Territory is part of the North American Cordillera, an active orogenic belt that extends south from Alaska to Mexico. The Yukon is a complex landscape resulting from tectonism, volcanic activity, Pleistocene glaciation, erosion and weathering (McKenna and Smith 2004). It comprises several mountain ranges, the Arctic Plains and the Yukon Plateau, each of which is divisible into smaller physiographic units (Figure 1.1).

The Yukon Plateau is the main physiographic unit in central Yukon. It is an erosional, low to moderate relief landscape, ranging from 1000 m to 3000 m above sea level (asl) and consisting of uplands and lower plateaus (Bostock 1948; Tempelman-Kluit 1980). It was formed largely during Tertiary time through denudation, and gradual uplift. The plateau has been dissected by rivers and is crossed by two large, fault-controlled valleys that trend northwest – the Tintina Trench on the east and the Shakwak trench on the west (Figure 1.1; Jackson *et al.* 1991). These valleys are located along strike-slip faults that have been the locus of Late-Miocene and Pliocene normal faulting (Tempelman-Kluit 1980).

Figure 1.1: Physiographic regions of the Yukon. Adapted from Mathews (1986) and Smith *et al.* (2004).



The Yukon Plateau is bordered by the St. Elias, Coast, Pelly and Selwyn Mountains to the southwest, south, southeast and east respectively (Figure 1.1). All of these ranges have been sources of glaciers during the Pleistocene. The St. Elias Mountains today support large ice fields and valley glaciers, and rise to over 5900 m asl (Jackson *et al.* 1991). The Selwyn and Pelly Mountains have peaks that rise up to 2500 m asl (Jackson *et al.* 1991).

1.1.2 Surficial geology

Parts of the Yukon were repeatedly covered by the CIS and by independent or semiindependent montane glaciers, whereas other parts were never glaciated. The territory can be divided into; 1) the area covered by the CIS (southern and central Yukon Plateau and the edge of the Coast and Selwyn Mountains), 2) the area affected by large valley and piedmont glaciers that were more or less independent of the CIS (the eastern part of the St Elias Mountains, the Shakwak Trench and the Ruby Range), 3) an area of independent, relatively small valley glaciers (the Ogilvie Mountains), and 4) the large area of northern Yukon that was ice-free throughout the Pleistocene (Hughes 1969; Hughes *et al.* 1989).

The study area is dominated by landforms and sediments indicative of ice-sheet glaciation (Figure 1.2), including till, glaciofluvial sediments, disrupted drainage, streamlined hills, meltwater channels, outwash terraces, and underfit streams. Steep slopes and uplands have thin colluvial veneers and blankets; in some areas bedrock is exposed in tors and ridges (Hughes 1990; Jackson 2000; Smith *et al.* 2004). The glacial history of the Yukon is reviewed in more detail in Section 1.2.1.

Figure 1.2: Glacial limits in the Yukon showing major ice lobes of the Cordilleran ice sheet and ice flow from the Late Wisconsinan event. Locations of both the area of previous soil research and current study are shown. Ash Bend (AB), Fort Selkirk (FS), Ketza River Section (KZ), Mayo Village (MY), Snag (SG). After Jackson and Mackay (1990), Duk-Rodkin (1999), and Ward *et al.* (2007).



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1.1.3 Climate

The modern climate of the Yukon is dry sub-arctic continental, with large daily and seasonal temperature ranges (Wahl 2004). Topography has an important influence on precipitation patterns - major orographic barriers impede the predominantly southwesterly flow of moist air from the Pacific Ocean (Wahl 2001). In general, precipitation increases with elevation. Moist Pacific air rises and cools over the St. Elias-Coast Mountains, producing large amounts of precipitation on the southwestern flank of those ranges. In the lee of the mountains, descending warm air creates dry conditions in the Kluane, Aishihik and Southern Lakes regions. The rain shadow effect is reinforced as air moves over the Pelly and Cassiar Mountains farther east. Annual precipitation ranges from 2000 to 3500 mm in coastal Alaska to only 250 to 300 mm in the valleys of central Yukon (Wahl 2001).

Air temperature is also closely related to elevation. The standard rate of temperature change with altitude, known as the lapse rate, is about 6.5°C per 1000 m (Ahrens 2000). In the Yukon, temperature decreases with elevation only from spring until fall (Wahl 2001). As winter approaches, surface heat loss increases and cold air blankets the landscape. Heavy, cold air descends into valleys, causing a temperature inversion in winter (Wahl 2004). Cold arctic air may exacerbate the inversion, but mixing of air masses may locally and temporarily eliminate it. In the winter, temperature may increase moving up from the valley floor at a rate of 3 to 5°C per 1000 m up to approximately 1500 m asl, remain isothermal until 2500 m asl, and begin cooling at a rate of approximately 5°C per 1000 m at higher elevations (Wahl 2004). Table 1.1 summarizes climate data from the period 1971 to 2000 for Carmacks, the closest weather station to the study area (Environment Canada 2008). The January and July monthly summaries are typically the coldest and warmest months of the year, respectively.

Parameters	January	July	Annual Mean				
Temperature							
Daily average (°C)	-25.0	15.5	-2.5				
Extreme maximum (°C)	6.0	33.0	35.0				
Extreme minimum (°C)	-56.7	-0.6	-56.7				
Precipitation							
Mean rainfall (mm)	0	57	194				
Mean snowfall (cm)	17	0	90				
Mean precipitation (mm)	17	57	284				

Table 1.1: Selected climate data for Carmacks weather station 2100300 (1971-2000).

Permafrost, defined as ground that is at or below 0°C for two or more years (French 2008), underlies much of the Yukon. Permafrost is continuous in the northern Yukon but becomes discontinuous and patchy in central and southern parts of the territory. The study area lies within the region of discontinuous permafrost (Hegginbottom *et al.* 1995). Regional and local variations in permafrost distribution and thickness are common and are influenced by aspect, lithology, the presence or absence of organic sediments and seasonal snow cover, and the moisture content of the active layer. Thick vegetation insulates soil and rock from warm summer temperatures, leading to lower ground temperatures and thicker or more extensive permafrost. Similarly, in winter, thick snow cover insulates underlying materials, reducing the depth of frost penetration and leading to thinner or less extensive permafrost. A high rate of evapotranspiration from the active layer decreases the amount of solar energy available to warm the soil and melt ice (Burn 2001). Lesser solar radiation on slopes with northerly aspects results in a greater extent of permafrost in these areas.

1.1.4 Vegetation

The study area is located within the central Yukon Plateau ecoregion described by Smith *et al.* (2004). This ecoregion is dominated by montane boreal forest below 1200 m asl, which transitions into the subalpine zone at higher elevations. Treeline, which marks the boundary between subalpine and alpine zones, is located at approximately 1370 m asl. Large forest fires are common due to dry summers and frequent thunderstorms, thus a range of successional forest communities are found. In young post-fire communities, lodgepole pine (*Pinus contorta*) and trembling aspen (*Populus tremuloides*) are important local components of the landscape. Early-successional post-fire vegetation is eventually replaced by white spruce (*Picea glauca*) and paper birch (*Betula papyrifera*) on drier sites. Vegetation on undisturbed till soils on lower slopes is dominated by white spruce and feathermosses (*Pleurozium schreberi, Hylocomium splendens, Ptilium* spp.) with some shrubs and herbaceous plants. Black spruce (*Picea mariana*) is dominant on colder, undisturbed, northfacing lower slopes where permafrost is more prevalent. Shrub birch (*Betula* spp.) and willow (*Salix* spp.) dominate the subalpine zone, along with mountain blueberry (*Vaccinium* spp.) and crowberry (*Empetrum nigrum*). These plants occur with moss and Labrador tea (*Ledum* spp.) at wetter sites and with lichen at drier sites. Tree distribution in the subalpine zone is patchy and consists of islands of subalpine fir (*Abies lasiocarpa*), white spruce and stunted lodgepole pine.

1.2 Background and previous research

Glaciation was first recognized in the central Yukon by G.M. Dawson in 1887 (Bostock 1966). Since then, much research has been devoted to elucidating regional glacial histories. Reconstructing the chronology and extent of glaciation is important for understanding past climates and landscape evolution, and for mineral exploration. Early soil research in the Yukon contributed to the reconstruction of glacial events through assessment of soils formed on glaciated surfaces at low elevation. Most recent research has focused on soils in the context of mineral exploration in unglaciated regions. Little research has been done on landscapes beyond the limit of the penultimate glaciation. This section provides a

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summary of important research concepts and a review of literature pertinent to glacial history, soil genesis and landscape development.

1.2.1 Glacial history of the central Yukon

Evidence for multiple Pleistocene glaciations in the central Yukon was first described by Bostock (1966). He used the relative degree of preservation of glacial landforms to infer four successively less extensive advances of the CIS. From youngest and least extensive to oldest and most extensive, these are the McConnell, Reid, Klaza and Nansen glaciations. Later researchers suggested that uplift of the St Elias Mountains and Alaska Range during the Pleistocene restricted access of moist Pacific air to the Yukon, causing successive CIS to be less extensive (Westgate *et al.* 2001).

The maximum extents of the McConnell and Reid glaciations are readily delineated on the Yukon Plateau by end moraines and other ice-marginal features (Hughes 1990). In contrast, depositional landforms of the older Klaza and Nansen glaciations are rare, having been all but erased from the landscape by weathering and erosion. Erratics, outwash gravel and patches of till are the only direct evidence remaining of these glaciations. Deposits older than the Reid glaciation, where present, typically cannot be differentiated from one another and are thus grouped into a single category – "pre-Reid" (Hughes *et al.* 1969). The approximate limits of the McConnell, Reid and pre-Reid advances of the CIS are shown in Figure 1.2.

Since multiple glaciations were first identified by Bostock, efforts have been made to establish their ages using a variety of methods including radiocarbon dating (Matthews *et al.* 1990; Jackson and Harington 1991), fission track dating and tephrochronology (Westgate *et al.* 2001; Westgate *et al.* 2008), paleomagnetic and ⁴⁰Ar-³⁹Ar dating (Jackson *et al.* 2003; Huscroft *et al.* 2004), and terrestrial cosmogenic nuclide (TCN) dating (Ward *et al.* 2007).

Although the age of the McConnell glaciation (MIS 2) is known with certainty, the age and extent of the Reid (MIS 4, 6, or 8), and pre-Reid (MIS 8 or older) glaciations are still debated. The following three sections review research conducted to characterize these events and determine their ages.

1.2.1.1 McConnell glaciation

The McConnell glaciation is the most recent and least extensive of the Pleistocene glaciations in the Yukon. It correlates with the Fraser (late Wisconsinan) glaciation of southern sectors of the CIS in British Columbia and Washington State. Because of its youthfulness and the excellent preservation of the deposits, the McConnell glaciation is known in greater detail than any other glaciation (Jackson et al. 1991). The CIS developed by coalescence of glaciers from several montane source areas. In the southern Yukon, lobes of ice spread from divides in the Selwyn, Pelly, Cassiar and Coast Mountains and coalesced with a piedmont glacier flowing from the St. Elias Mountains (Figure 1.2; Hughes et al. 1969; Jackson and Clague 1991; Jackson *et al.* 1991). The CIS was strongly influenced by topography; relief locally exceeded ice thickness, leaving nunataks above the ice sheet surface. Landforms associated with the McConnell glaciation are well preserved; the digitate terminus of the CIS is clearly delineated by moraines and ice-marginal channels (Bostock 1966; Hughes et al. 1969; Hughes 1990; Jackson 2000). Warm-based ice was extensive over most of the landscape, but there is local evidence for areas of cold-based ice. Such evidence includes sheared and drag folded glaciolacustrine sediments and folded and thrust-faulted gravels below McConnell till (Jackson et al. 1991).

The age of the McConnell glaciation is constrained by conventional and accelerator mass spectrometry (AMS) radiocarbon ages. Dating of plant fossils (29.6 ka BP) recovered from an organic unit below McConnell age till near Mayo on the Stewart River place the

glaciation in MIS 2 (~30-11 ka) (Matthews *et al.* 1990). Mammal fossils (~ 26.4 ka BP) below McConnell till along the Ketza River similarly date the glaciation to Late Wisconsinan (Jackson and Harington 1991). Expansion of alpine glaciers in source areas may have begun as early as 29 ka BP but a continuous ice sheet did not develop until after approximately 24 ka BP (Jackson *et al.* 1991). The maximum extent of the St. Elias lobe occurred between 13.7 ka and 14.6 ka (Bond and Lipovsky 2009).

1.2.1.2 Reid (penultimate) glaciation

The term "Reid glaciation" has historically been applied as a name for all penultimate glaciations in the Yukon (Ward *et al.* 2007). Ice flow during this glaciation is assumed to have been similar to that of the McConnell glaciation, although much of the evidence has been removed by McConnell ice (Hughes 1990). However, Reid ice was more extensive and thus likely thicker. The limit of the Reid glaciation is not as clear as that of the McConnell glaciation because of its greater age and longer exposure to erosion.

The age of the Reid glaciation has been subject to controversy and refinement. Different researchers have placed the event in MIS 4 (~75-58 ka), 6 (~195-127 ka), or 8 (~297-244 ka). Radiocarbon dating clearly indicates that the Reid glaciation is no younger than MIS 4; many researchers favour a MIS 6 age (Hughes *et al.* 1989; Westgate *et al.* 2001). Original analysis of Sheep Creek tephra overlying penultimate glacial deposits at Ash Bend on the Stewart River indicated that the Reid glaciation occurred earlier than MIS 6, and probably during MIS 8 (Westgate *et al.* 2001) but recent re-examination of this tephra has led to a reassignment to MIS 6 (Westgate *et al.* 2008). 40 Ar/³⁹Ar ages on basalt flows exposed along the Yukon River downstream from Fort Selkirk supported an MIS 8 age (Huscroft *et al.* 2004). Recent study of sediments containing Old Crow tephra along the Pelly River supports an MIS 6 age for the Reid glaciation in that region (Ward *et al.* 2008).

TCN dating of erratics in the Aishihik Lake area suggests that Reid deposits there date to MIS 4 (Ward *et al.* 2007) which is in disagreement with the inferred MIS 6 age of Reid deposits at Ash Bend on the Stewart River. Ward *et al.* (2007) proposed that what has previously been described as the penultimate Reid glaciation consists of two or more separate glaciations. They named the local MIS 4 event in the Aishihik Lake area the Gladstone glaciation and proposed that differences in the extent of the penultimate CIS may be due to regional variability in precipitation linked to variations in the position and strength of the Aleutian Low. In this report, the term "Reid" is used for MIS 6 events or where utilized in the referenced literature. The more general term "penultimate" is used where the age has not been confirmed locally.

1.2.1.3 Pre-Reid glaciations

The Klaza and Nansen glaciations were distinguished by Bostock (1966) on the basis of poorly preserved landforms and deposits. Later researchers have identified additional glaciations through stratigraphic studies. An extensive area has been mapped beyond the Reid limit as overridden by pre-Reid glaciers based on air photo analysis and the interpolation of limits between ground studies (Duk-Rodkin 1999). Ongoing ground truthing, however, raises questions as to the local extent of ice. In the McQuesten map sheet, upland surfaces have similarly weathered bedrock colluvial cover defined by periglacial processes regardless of whether or not they were glaciated by pre-Reid ice or remained icefree (Bond and Lipovsky, 2010). In the study area, surficial evidence of pre-Reid events is sparse. In the Carmacks map sheet, the distribution of meltwater channels allows an evaluation of ice extent and thickness in some areas (Jackson 2000). In contrast, Hughes (1990) found no erratics or other evidence of glaciation beyond the Reid limit in the Aishihik map area. Despite the limited evidence of these glaciations, they have had an important effect on the landscape through changes to drainage patterns. For example, the Yukon River drainage has been reorganized from a southerly flow, to a northerly flow (Tempelman-Kluit 1980; Duk-Rodkin *et al.* 2001) and evidence of underfit streams exist (Hughes 1990).

The age range of pre-Reid glaciations is generalized to the Late Pliocene (>2.6 Ma) (Froese *et al.* 2000; Duk-Rodkin *et al.* 2001) to Middle-Pleistocene (Hughes *et al.* 1989). The number, extent and ages of the pre-Reid events are not as well constrained (Huscroft *et al.* 2004) but a minimum of seven have been inferred in central and southern Yukon (Jackson *et al.* 1991; Duk-Rodkin *et al.* 2001; Westgate *et al.* 2001). The ages of pre-Reid events at several sites in the Yukon have been determined, including the Liard River area where Klassen (1987) identified two tills older than 232 ka and 765 ka and the Fort Selkirk area where Jackson *et al.* (1996) identified two glacial events of late Matuyama chron (1.77 to 1.78 Ma).

1.2.2 Central Yukon soil research

Soil landscapes of the Yukon are extremely diverse due to differences in the time available for soil development, differences in climate through time, and complex topography. The first studies of soils on Quaternary deposits in the central Yukon attempted to relate soil development at low-elevation sites to paleoclimate (Foscolos *et al.* 1977; Rutter *et al.* 1978; Tarnocai *et al.* 1985; Smith *et al.* 1986; Tarnocai and Valentine 1989; Tarnocai and Smith 1989). More recently, researchers have begun to examine soils developed on other deposits, such as loess (Laxton *et al.* 1996; Sanborn *et al.* 2006) and colluvium (Bond and Sanborn 2006; Smith *et al.* 2009), as well as soils at higher elevations (Jackson *et al.* 1999). This section provides information on previous soil research in central Yukon as it relates to glacial history.

1.2.2.1 Soil formation in glaciated low-elevation landscapes

The first published soil mapping in the valley systems of central Yukon was that of Rostad *et al.* (1977). They described and classified the range of modern soil features and defined soil association names for soils that were of potential agricultural interest but they did not recognize relict features associated with older glacial deposits of the region. Foscolos *et al.* (1977) studied six soils on McConnell, Reid, and pre-Reid glacial deposits based on the model of Yukon glaciations proposed by Bostock (1966). They characterized soils formed in very stable landscape positions and found evidence of increasing development with surface age. Pre-Reid soils are relict Luvisols with thick (>100 cm) sola and red, textural B horizons characterized by significant clay accumulations that include interstratified phyllosilicates. The soils commonly have wide sand wedges, formed by infilling of contraction cracks. Reid soils are relict Brunisols with thinner (~55 cm) sola, less developed B-horizons and no interstratified phyllosilicates. Sand wedges in Reid deposits are smaller than those formed on pre-Reid deposits. McConnell-age soils are Brunisols with thin (~35 cm) sola, poorly developed B-horizons that lack sand wedges.

Tarnocai *et al.* (1985) and Smith *et al.* (1986) extended the work of Foscolos *et al.* (1977) in parts of the McQuesten (NTS 115P), Stewart River (NTS 115N/O) and Dawson (NTS 116B/C) map areas ("area of previous research" in Figure 1.2). They characterized soils of different age on morainal and glaciofluvial surfaces which had optimum soil development and preservation. They further applied names to soils at the type sites of pre-Reid, Reid and McConnell deposits – the Wounded Moose relict paleosols, Diversion Creek relict paleosols, and Stewart neosols, respectively (Smith *et al.* 1986). Their morphological descriptions and chemical and physical data agreed with those of Foscolos *et al.* (1977). The best morphological characteristics for separating these soils were solum depth, colour of the

upper and lower B-horizons, frequency, colour and thickness of clay skins, degree of clast weathering, and periglacial and cryogenic features.

Wounded Moose relict paleosols are well developed Luvisols with deep sola (mean of 109 cm on outwash and 91 cm on till), reddish (5YR to 7.5YR) B-horizons, and abundant, moderately thick reddish-brown clay skins. They are strongly or very strongly weathered; chemical alteration and disintegration of minerals is evident in all but the most resistant materials. Large sand wedges and strong cryoturbation features are associated with these soils. Diversion Creek relict paleosols are moderately developed Luvisols or Brunisols with thinner sola (mean of 45 cm on outwash and 56 cm on till), red-brown (7.5YR to 10YR) B-horizons, with some limited thin, brownish clay skins. Cryoturbation features and sand wedges are present but infrequent and smaller. Chemical analysis showed that oxidation and leaching have significantly altered parent materials of the Wounded Moose and Diversion Creek relict paleosols (Smith *et al.* 1986). Stewart neosols are have formed on McConnell deposits and are classified as Eutric Brunisols with thin sola (mean of 21 cm on till), and light brown (10YR) B horizons, that lack clay skins and cryogenic features. On outwash deposits, all soils are acidic with low carbon values throughout the sola. In contrast, pH and carbon contents in soils developed on till decrease with increasing surface age.

Only a small amount of mineralogical data is available for Yukon relict paleosols, but these data have been repeatedly cited and used to infer soil genesis and paleoenvironments. Wounded Moose and Diversion Creek relict paleosols have argillic (clay-enriched) horizons of varying development. Clays identified through X-ray diffraction (XRD) analysis include kaolinite, illite, and montmorillonite-kaolinite mixed layer clay in the Wounded Moose relict paleosols and kaolinite, illite, chlorite, vermiculite, and chloritic intergrades with no interstratified phyllosilicates in the Diversion Creek and Stewart soils (Foscolos *et al.* 1977).

While clay formation has been postulated as being due in part to *in situ* alteration of ferromagnesian and feldspathic materials due to intense oxidation (Smith *et al.* 1986), reexamination of archived samples is underway to determine the accuracy of this interpretation (Smith, personal communication). Since these data were first reported, only one set of additional analyses has become available for Yukon soils. Huscroft *et al.* (2006) found clay mineralogical assemblages characteristic of Diversion Creek relict paleosols on young pre-Reid surfaces. This finding suggests that mineralogy may not be suitable for differentiating between stable Reid and stable pre-Reid surfaces.

Micromorphological analysis of Yukon relict paleosols has been used to infer environmental changes through time (Fox and Protz 1981; Tarnocai and Smith 1989; Tarnocai and Valentine 1989; Tarnocai *et al.* 1993; Fox 1994). In thin section, Wounded Moose relict paleosols display well developed, rubified, void and grain argillans in the Bt horizon, whereas the Diversion Creek relict paleosols have only rare, poorly developed void and grain argillans of brownish colour. Micromorphological features indicative of cryogenesis, such as the disintegration of argillans into papules and orientation of fabrics, are evident in both the Wounded Moose and Diversion Creek relict paleosols. The rubified argillans noted in some of the Diversion Creek relict paleosols are thought to have been derived from older Wounded Moose relict paleosols (Tarnocai and Smith 1989).

The results of these paleopedological studies were used to infer the duration and environment of interglacial soil-forming periods (Foscolos *et al.* 1977; Rutter *et al.* 1978; Tarnocai *et al.* 1985; Smith *et al.* 1986). Without good chronological control, however, it is difficult to ascertain whether differences in soil development are the result of longer duration of soil formation, differences in climate, or a combination of the two. Based on knowledge of the glacial history of the Yukon existing at the time, the authors proposed a chronology of

events and paleoclimates that explained the observed soil characteristics. They argued that the deep weathering and pedogenic features observed in pre-Reid soils resulted from pedogenesis occurring over a lengthy period under a relatively mild and humid climate (Smith *et al.* 1986). The climate became more temperate and cold in the lead-up to the Reid glaciation. During the interglacial between the Reid and McConnell glaciations, soils formed on Reid drift were exposed to a cool, sub-humid climate that was warmer and moister than the present (Smith *et al.* 1986). Foscolos *et al.* (1977) thought that this interglaciation was much shorter than the pre-Reid-Reid interglaciation. The smaller periglacial features in Reid soils suggest that the cold period that culminated in the McConnell glaciation was shorter than the cold period associated with the penultimate glaciation (Tarnocai *et al.* 1985).

Although this work established a framework for viewing soil landscapes in the central Yukon, its application is largely restricted to till and outwash in low-elevation landscape positions on the Yukon Plateau. The only new study conducted in the past 20 years to test these relationships showed that the mineralogical characterization of Wounded Moose and Diversion Creek relict paleosols are not applicable to pre-Reid and Reid glaciofluvial surfaces along the Yukon River (Huscroft *et al.* 2006).

1.2.2.2 Soil formation in upland landscapes

Some uplands in central Yukon have not been glaciated in the Quaternary, whereas others have been ice-free since the Early or Middle Pleistocene. Additional complexities arise from the fact that environmental conditions affecting soil development in upland regions differ from those at lower elevations. Variable activity of slope processes and cooler summer temperatures, have led to distinctive landform and soil combinations.

Studies of soil weathering and genesis in unglaciated central Yukon landscapes have only begun. Bond and Sanborn (2006) showed that Brunisolic soils on unglaciated, upland areas in the west-central Yukon were strongly modified by slope processes. Smith *et al.* (2009) investigated the distribution and pedogenic characteristics of Histic Dystric Turbic Cryosols on a steep, unglaciated slope with a northern aspect near Dawson City. They determined that these soils are a significant reservoir for carbon which is vulnerable to climatic warming.

A study of soil development in colluvium and weathered bedrock in an upland landscape position (1250 m asl) was conducted on a single drill core collected from a former meltwater channel above the headwaters of Pony Creek, in the Dawson Range (Jackson *et al.* 1999). This area has been ice-free since sometime between 0.99 and 0.78 Ma (Jackson *et al.* 1996). The upper three buried paleosols in the drill core were formed in colluvium and the lowest buried paleosol was formed in weathered bedrock. All four paleosols appear to be largely intact, unlike Pleistocene soils exposed at the surface that are subject to erosion (Jackson *et al.* 1999). The four paleosols are Podzols with well developed Bf horizons; the latter were interpreted as evidence of a much warmer and wetter climate than exists today and persisting for at least tens of thousands of years. Based in part on accompanying palynological evidence, Jackson *et al.* (1999) concluded that the paleosols developed during the Middle Pleistocene, prior to the penultimate glaciation.

1.2.3 Landscape evolution on granitic bedrock

Beyond the limit of the penultimate glaciation is a landscape that was affected by one or more pre-Reid glaciations. Although this area has been glaciated, till and glacial features are largely absent in upland landscape positions (Bond and Lipovsky 2010). Isolated pockets of till at lower elevations demonstrate that upland tills were removed and reworked by erosion processes. The upland pre-Reid study sites are underlain directly by granitoid bedrock and colluvium derived from that bedrock. The long term weathering of granitic rock

leads to the eventual formation of soil environments hospitable to plant growth (Wang *et al.* 1981; Graham *et al.* 2010). The most striking landscape features are tors and adjacent accumulations of grus (Jackson 2000). This section provides information on development of tors in granitic landscapes and the impact of glaciation to the preservation of these features.

1.2.3.1 Tor formation

Tors and associated grus are common landscape features observed in weathered granitic bedrock beyond the penultimate glacial limit. Although the definition and origin of tors are debated (Migoń 2006), I use the definition adopted by Hughes (1990) from Pullan (1959): "an exposure of rock *in situ* upstanding on all sides from the surrounding slopes [that] is formed by the differential weathering of a rock bed and the removal of debris by mass movement". Grus is a product of rock disintegration; it is composed primarily of sand and gravel-size particles (Migoń and Lidmar-Bergstrom 2001).

Tors are characteristic of landscapes with long weathering histories. They may be present in unglaciated terrain, including warm arid regions, in glaciated terrain that has been ice-free for a long period of time, or in terrain covered by cold-based glaciers. Tors are thought to form either through long continuous weathering of bedrock, with removal of weathered material (Palmer and Radley 1961), or through a two-stage cycle in which deep chemical and physical weathering is followed by a period of mechanical stripping and exposure (Linton 1955). The latter hypothesis requires an environmental change to explain the shift from deep weathering to surface erosion. In addition, the first stage of deep weathering must be either very long or the environment be warm and humid, conditions that existed in the Tertiary (Migoń 2006).

Tors, along with boulders and inselbergs, are common features of landscapes developed in granitoid rocks worldwide. They are typically fringed by aprons of grus,

evidence of production of small particles through the physical and chemical breakdown of rock. Weathering profiles are commonly deep but irregular in granitic rocks; weathering may occur selectively along fractures or faults (Migoń 2006). The rate of weathering is influenced by factors intrinsic to the rock (rock chemistry and mineralogy, texture, fabric, frequency and size of discontinuities, nature of stress fields) (Pye 1986) and to the environment (temperature of the soil solution, water supply, residence time of water, pH, presence of organic acids) (Kump *et al.* 2000). Bjornson and Lauriol (2001) showed that it requires tens of thousands to hundreds of thousands of years for granite boulders to weather to grus in northern Yukon. Other research suggests that tors may form on regolith-mantled ridge crests and slopes independently of rock structure (Anderson 2002; Strudley *et al.* 2006). Mathematical modelling of these features suggests that they do not require a two-stage process of deep weathering and exhumation.

Tors in the central Yukon have not been studied, thus the exact mechanism for their formation remains uncertain. However, in other cold climate regions, much of the breakdown that leads to the development of tors and grus has been attributed to frost shattering. Frost shattering occurs by two main mechanisms (Hall *et al.* 2002): freezing of water in pores and cracks, which causes an expansion in volume; and segregation of ice, in which stress develops as water migrates towards growing ice lenses (Walder and Hallet 1986). The weathering efficacy of both processes depends on moisture availability and the frequency of freeze-thaw cycles (Migoń 2006). The importance of frost shattering at the expense of chemical weathering and other physical processes has been challenged with evidence that moisture availability is more limiting to chemical processes than temperature in many periglacial environments (Hall *et al.* 2002).

1.2.3.2 Preservation of tors beneath cold-based ice

Early researchers assumed that tors could not withstand the erosive action of glaciers and were thus indicators of unglaciated landscapes or weathered nunataks (Linton 1955). However, erratics occur around some tors, suggesting that these features may have survived glaciation (Sugden 1968; Sugden and Watts 1977). One possible explanation is that glacial erosion is limited in regions of cold-based ice, where the glacier bed is frozen to its substrate (Bennett and Glasser 1996). Research suggests that tors and related features have survived one or more glaciations in Fennoscandinavia (Kleman and Stroeven 1997; Stroeven *et al.* 2002, 2006; André 2004) and Canada (Sugden and Watts 1977; Marquette *et al.* 2004). Goodfellow (2007) has suggested that an understanding of these relict surfaces within the context of the glaciated landscape is important for several reasons. First, they provide clues to regional glacial histories, especially the ice thermal regime. Second, TCN dating tools can be used to help determine processes and rates of landscape evolution. Third, they may assist in reconstructing pre-glacial landscapes and facilitate better understanding of glacial erosion. Fourth, understanding these features and their origin may help determine environmental conditions during interstadial and interglacial periods.

Stroeven *et al.* (2002) used cosmogenic ¹⁰Be and ²⁶Al ages from tors and a meltwater channel to explore the extent to which landscape is preserved through multiple glacial cycles in Fennoscandinavia. They showed that the tors survived at least two glaciations. Patches of relict features and glacial deposits within a landscape may have exposure ages that are significantly different, suggesting a complex pattern of cold-based ice over a glaciated landscape (Stroeven *et al.* 2006).

Within the Carmacks and Ashihik Lake map areas, tors have been identified in both unglaciated regions and regions inferred to have been covered by pre-Reid ice sheets

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(Bostock 1966; Hughes 1990; Jackson 2000). Few erratics have been found around tors in these regions, but the search for erratics has not been extensive and thus their paucity should not necessarily be used to infer an absence of glaciation. Hughes (1990) suggested that these features may have survived glaciation as roche moutonées and were weathered to their current forms during the current interglaciation. No tors have been found north of Aishihik Lake within the limits of the Reid glaciation (Bostock 1966; Hughes 1990). The restriction of tors to pre-Reid glaciated surfaces suggests that environmental conditions required for tor formation may not have existed since the close of the penultimate glaciation (Hughes 1990).

1.3 Methods in the study of Quaternary soil genesis

Several methods are used by pedologists to characterize soil weathering and development. Some types of evidence can be observed and measured in the field, such as the distribution of fines and horizon rubification. Others, including bulk elemental composition, iron and aluminum content and clay mineralogy, require further laboratory analysis. Micromorphological observations made on thin sections of intact samples can be used to infer *in situ* soil processes. These methods are used to show changes with depth within a profile, and can be used to compare relative weathering and soil development between sites. This section reviews common methods utilized to measure relative weathering and soil development.

1.3.1 Field observations

Evidence of pedogenesis that can be easily observed or measured in the field during a routine description of a pedon provides information on the relative degree of soil development and age. A routine pedon description involves the excavation of a pit to a minimum of one meter in depth. Standard description procedures from the Canadian System of Soil Classification (Soil Classification Working Group 1998) involve the description of

soil horizons and taxonomic classification. Description of horizons includes recording common soil parameters such as colour, texture, structure, consistence, organic matter and vegetation. Two parameters, colour and sub-surface accumulation of fine (clay and fine silt) particles, are characteristics commonly used to evaluate pedogenic processes.

In the soil profile, specific colours are indicative of different soil processes. Brown to red colouration indicates pedogenic changes to iron, typically oxidation of primary Fe^{2+} to Fe^{3+} and the subsequent production of iron oxide minerals (Schwertmann 1993; Birkeland 1999). As soil ages, it changes in colour from yellow to brown to red – in the Munsell soil colour chart, it changes in hue along the following continuum; $2.5Y \rightarrow 10YR \rightarrow 7.5 YR \rightarrow 5YR$ (Birkeland 1999). Comparison of colour intensity between soils of different texture is problematic, however, as the amount of surface area required to impart the same colouration will be much smaller in coarse-textured than fine-textured soil. Because both climate and the duration of weathering (*i.e.* time) can affect the degree of redness in a soil, corroborating evidence commonly is required to determine which of the two is the controlling factor.

Several colour indices have been established that use the Munsell notation and calculate a single metric for comparison between sites. Harden (1982) introduced the Rubification Index, which relates the colour of each horizon in an individual profile to the colour of the parent material. Changes in hue and chroma between the horizon and parent material are both assigned a numeric value. After correcting for horizon thickness, numbers assigned to each horizon are summed to obtain a single number for each soil pit (Harden 1982). Rubification has been used in several glacial chronosequence studies as a measure of soil age and relative weathering (*i.e.* Karlstrom 2000; Karlstrom and Barendregt 2001; Douglass and Mickelson 2007).

Over time, clay produced through weathering accumulates in soil. In well developed soils, pedogenic clay is typically enriched in the B horizon relative to the A and C horizons because: 1) it is translocated from upper horizons and deposited in the B horizon; 2) primary minerals are weathered in the upper profile, moved in solution to the B horizon and precipitate into clay; and 3) clay is formed *in situ* in the B horizon from mineral weathering (Birkeland 1999). Differences in clay concentration may also arise from lithological discontinuities, which should be evaluated prior to interpreting the accumulation of clay as pedogenic in origin. Clay skins or argillans and silt caps are coatings on peds or coarse fragments and are indicative of translocation of fine material. With time, caps become thicker and cover greater proportions of the clast surfaces, eventually forming bridges and ultimately encapsulating entire fragments (Forman and Miller 1984). The two most common clay translocation mechanisms are movement by water (Birkeland 1999) and frost sorting (van Vliet-Lanoë 1985; Bockheim and Tarnocai 1998).

1.3.2 Major element geochemistry and use of weathering indices

Changes in bulk chemistry of weathering profiles, in contrast to mineralogical changes due to weathering, are relatively simple and predictable (Nesbitt and Young 1989). As base cations are relatively mobile, their abundance relative to less mobile elements within a pedon is commonly used as a measure of soil weathering (i.e. April *et al.* 1986; Bain *et al.* 1993; Taylor and Blum 1995). This ratio is known as a weathering index. As weathering progresses, this ratio will change as mobile elements are removed from the solum and immobile elements remain largely unchanged (Darmody *et al.* 2005b). For practical applications, a weathering index must include elements with a range of mobilities and must show trends with respect to chemical composition and increased weathering. In addition, it should be applicable to a range of rock types, have values that differ between weathered and
unweathered material, and change systematically with depth (Price and Velbel 2003). Weathering index values can then be evaluated as a function of depth in the profile or between sites of similar parent material. Weathering indexes are typically calculated with molecular proportions of the major element oxides, so that stoichiometric changes are reflected by the index value (Price and Velbel 2003).

The main value of a weathering index is that it combines several parameters into a single value that can provide a clearer picture of weathering than a single parameter. A drawback is that no element is truly "immobile" in the natural environment (Price and Velbel 2003). Many researchers rely on the immobility of aluminum (Vogt 1927; Ruxton 1968; Nesbitt and Young 1982; Harnois 1988; Fedo *et al.* 1996), whereas others use zirconium (Chittleborough 1991) or titanium (Muir and Logan 1982).

The simplest weathering indexes use the ratio of a single mobile element to an immobile element. More complex indexes combine many elements into a single metric. Feldspars make up approximately 62% of the upper crust of the Earth and are easily weathered, thus the formation of secondary clays from feldspars is an important process in soils (Nesbitt and Young 1982). During weathering, Ca, Na and K are removed in solution, thus the ratio of an immobile reference element to these mobile cations will change as weathering progresses. The Chemical Index of Alteration (CIA) is a measure of this change; it uses Al as the immobile reference element and is calculated as follows:

$$CIA = \left(\frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O}\right) \times 100 \qquad Equation \ l$$

where CaO* is corrected for Ca in carbonates and phosphates (Nesbitt and Young 1982). Values for fresh albite, anorthite and potassium feldspars are approximately 50, whereas values for kaolinite approach 100.

Depletion/enrichment indexes are another metric for describing the movement of mobile elements within a profile. Base cations are related to an immobile internal index element and are referenced to the parent material. The index value is calculated for each horizon and plotted against depth. Depletion and enrichment indexes are only meaningful if the parent material is uniform; that is, the C horizon must be compositionally similar to the parent material of all horizons (Muir and Logan 1982).

In this study, depletion and enrichment factors were calculated using the methods of Taylor and Blum (1995) as follows:

$$x_{i,j} = \frac{c_{i,j}/c_{i,p}}{\tau_{i_j}/\tau_{i_p}} \qquad Equation \ 2$$

where $C_{i,j}$ is the concentration of element *i* in horizon *j*, $C_{i,p}$ is the concentration of the same element in the parent material *p*, and Ti_j and Ti_p are the concentration of titanium in the same horizon *j* and parent material *p*. Values less than one indicate a depletion of the element, whereas values greater than one indicate enrichment. The immobile element, in this case titanium, is plotted as Ti_j / Ti_p . Ti may be enriched (>1) in the upper part of a soil profile due either to additions of the reference element into the profile (i.e. through organic cycling, eolian deposition) or to the loss of more abundant elements (Muir and Logan 1982). Although Zr, Nb and Al have all been used as the immobile element in other studies (Bain *et al.* 1993; Oh and Richter 2005), Ti is used here because it is common in rock-forming minerals and has only been documented to be mobile in highly weathered tropical soils (Schaller *et al.* 2009).

1.3.3 Secondary forms of iron and aluminum

Weathering products of iron and aluminum exist in soils in organically complexed, short-range order (crystalline structure repeats only over a short range), and crystalline forms. Elevated amounts of short-range order and crystalline minerals are indicative of weathering. These diagnostic soil weathering products can be isolated and identified through a series of selective chemical extractions (Parfitt and Childs 1988). Three common extractants are sodium pyrophosphate, acid ammonium oxalate and sodium dithionite-citrate-bicarbonate (Parfitt and Childs 1988). Pyrophosphate-extractable forms (Fe_p, Al_p) are generally interpreted as organically complexed (Loveland and Digby 1984), although organically complexed Fe_p may be overestimated due to the presence of finely colloidal Fe oxides (Schuppli et al. 1983). Centrifugation of samples prior to analysis appears to alleviate this problem (Parfitt and Childs 1988). Oxalate-extractable forms (Fe_o, Al_o) represent the sum of short-range order minerals and organically complexed forms. Fe in these forms occurs in ferrihydrite, lepidocrocite, and maghemite; Al occurs in allophane and imogolite (Borggaard 1982; Farmer *et al.* 1983). Ferrihydrite is typically the dominant Fe-hydroxide in the Fe₀ extraction, thus the values approximate the concentration of this mineral in soil (Parfitt and Childs 1988). Al_o and Si_o values can be used in conjunction with Al_p to estimate allophane and imogolite concentrations in volcanic soils and podzols (Parfitt and Wilson 1985). The dithionite-citrate-bicarbonate extractable iron (Fed) represents the sum of all secondary FE forms (Parfitt and Childs 1988). The crystalline form of iron can be estimated by the difference between the dithionite and oxalate extractable forms ($Fe_d - Fe_o$).

Secondary iron and aluminum products are also characteristic of particular weathering environments and parent materials. Allophane and imogolite are common soil weathering products in soils derived from volcanic or quartzo-feldspathic parent materials, with udic (humid) moisture regimes and good drainage (Parfitt and Kimble 1989; Parfitt 1990). The crystalline Al-hydroxide minerals gibbsite and boehmite are found in highly weathered environments, generally in the tropics (Birkeland 1999). Ferrihydrite is an iron

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hydroxide commonly found in podzolic soils (Lundstrom *et al.* 2000). Goethite is a secondary crystalline iron mineral commonly found in soils in temperate regions, and hematite is found in highly weathered soils in tropical environments (Birkeland 1999).

1.3.4 Clay mineralogy

Weathering of sediments results in a semi-predictable series of mineral alterations (Soller and Owens 1991). Primary clay minerals may result from physical weathering of larger particle sizes. Secondary clay minerals in soil and saprolite form by weathering of primary minerals, and, as a result, their type and amount can be used to assess the degree of weathering. Base cations and silica are initially removed from primary minerals, while iron and aluminum are generally retained to form secondary minerals and oxides. In tropical environments, 2:1 clay minerals are altered to 1:1 clay minerals and ultimately to oxides with prolonged weathering (Brady and Weil 2002) but in cooler environments this transformation is not as direct. Clay transformations are sensitive to climate conditions, thus the production of clay minerals can provide insight into the climate under which they formed. Other important factors include soil solution pH, soil solution residence time, porosity, and availability of weatherable minerals. Because these factors may vary significantly between soil microsites, a given pedon may have different clay mineral assemblages in different parts of the profile (Velde et al. 2008). The Bowen reaction series is often used as a surrogate for weathering potential, with minerals that crystallize at the highest temperatures being least stable at the Earth's surface. The sequence for common crustal minerals, from most to least weatherable, is Ca-plagioclase > Na-plagioclase ~ biotite mica > K-feldspar > muscovite mica > quartz (Bohn *et al.* 2001).

Several transformations occur in the crystal structure of clay minerals to form secondary clays (Velde *et al.* 2008). They include 1) removal of silica layers, 2) addition of

hydroxy ions, and 3) ionic changes within interlayer spaces (Birkeland 1999). Changes typically occur first along crystal edges or between phyllosilicate layers.

Jackson (1965) proposed a general model for weathering of silicate minerals that relates the type of clay mineral formed to weathering intensity and duration. If the intensity of weathering does not change, then the loss of silica is a function of the duration of weathering. According to his model, desilication and concomitant alumination of minerals such as feldspar and vermiculite will yield weathering products that are rich in sesquioxides. Minor desilication yields intergrades of phyllosilicates and allophane. Continued desilication will produce pedogenic chlorite, 1:1 kaolin minerals, and possibly small amounts of gibbsite. Intense desilication leads to the near-total loss of silica and the transformation of silicate minerals into oxides.

In the depotassification of mica, Ca or Mg ions replace K ions to produce vermiculite (Jackson 1965; Bustin and Mathews 1979). Depotassification typically occurs from the edges of the mineral lattice inward, leading to expansion and splitting at the crystal edges. This transformation commonly occurs under temperate humid conditions with slightly acidic soil solutions (Bustin and Mathews 1979).

Smectite minerals form through the increased availability of base cations (Allen and Fanning 1983). The genesis of these expansible clay minerals requires accumulation of solutes (Si, Fe, Al, Mg, Ca and Na) and the presence of mineral colloids. Solutes accumulate under poorly drained conditions where weatherable minerals are present. Poor drainage may result from the topographic position of the soil, the presence of a textural discontinuity, or evaporation of water (Jackson 1965). Where solutes are abundant, smectites can form through the silication of mineral colloids that have been aluminated under temperate, subtropical or tropical conditions (Jackson 1965).

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Several studies have examined the transformation of clay minerals in cold environments. Gibbsite was found in weathering profiles beneath a variety of surfaces in northern Norway despite the harsh environment (Paasche *et al.* 2006). Gibbsite is an extreme end product of weathering and in this study its presence was interpreted as a relict mineral formed under a warmer, more humid environment that existed in Scandinavia in the Tertiary. Allen *et al.* (2001) used clay mineralogy to help document weathering in a periglacial environment in Arctic Sweden and to better understand landscape evolution at their study site. They used clay mineral assemblages to 1) trace source areas for colluviated parent material and 2) identify areas which may have been covered by cold-based ice. It has also been used to help reconstruct pedogenic processes in bisequal soils in the Russian Taiga (Bonifacio *et al.* 2009). A study of smectite formation in the Swiss Alps has challenged the notion that it must form under temperate conditions (Egli *et al.* 2003, 2008).

1.3.5 Micromorphology

Undisturbed soil and regolith can be studied using microscopic techniques. Soil constituents are identified and described to define their relationships in both time and space (Stoops 2003) and to determine the processes responsible for soil genesis. Micromorphology may be used in soil classification and climate interpretations. Several systems have been proposed, including W.L. Kubiëna's manual "Micropedology" published in 1938 (Stoops 2009), and more recent expanded systems (Brewer 1964; Bullock *et al.* 1985; Stoops 2003).

In order to make accurate genetic interpretations, it is important to correctly describe the pedofeatures observed in thin sections. Organic and mineral material, voids, and the relationships among these components must be accurately and precisely described (Stoops 2003). An important concept in micromorphology is "fabric," which is defined simply by Kubëina (1938) as "the arrangements of constituents of the soil in relation to each other" and

more completely by Bullock *et al.* (1985) as "the total organization of a soil, expressed by the spatial arrangements of the soil constituents (solid, liquid, gaseous), their shape, size and frequency, considered from a configurational, functional and genetic viewpoint". Key properties of fabric are the spatial distribution orientation, size, sorting, and shape of soil components, and the distribution of coarse and fine particles and associated pores. Cross-polarized light can be used to identify minerals and oriented clays.

Once described, micromorphological features are used to interpret the environmental conditions under which they formed. Soil micromorphological features that can be formed by cryogenic processes include platy or lenticular structure and associated horizontal planar voids, cutans or grain coatings, reoriented grains and vesiscular voids (Fox and Protz 1981; van Vliet-Lanoë 1985; Fox 1994). Although some of these features can form under non-frost conditions, taken together, they may be diagnostic of cryogenesis. Features that are more characteristic of warm climates include rubification and strong argillan development (Tarnocai and Valentine 1989).

Relict soils show micromorphological features of both past and modern climates (Catt 1991). Polygenetic relict paleosols can be interpreted by reconstructing the sequence of pedogenic events and climates from the "superposition of pedofeatures" (Kemp 1998). In northern Canada, micromorphological pedofeatures show evidence of both cryogenic and warm climate conditions and provide an exceptional example of how these features can be used to reconstruct past climates (Tarnocai and Smith 1989; Tarnocai and Valentine 1989). Based on the model of regional glaciation of Yukon that was developed at the time of these studies, void and grain argillans and extensive rubification observed in Wounded Moose soils were interpreted as having developed during a warm, pre-Illinoian interglaciation. During the cold glacial period that followed, these argillans were broken down and papules,

aggregates, embedded grain argillans, and oriented fragments formed. Further breakdown of relict warm micromorphological features continued during subsequent glacial periods.

1.4 Study area

The study area is located on the Lewes Plateau in the eastern Dawson Range, south of the area of previous soil research in the Tintina Trench (Figure 1.2). Sites are located within the western half of the Carmacks NTS 115I map sheet (137°-138°W and 62°-62°45'N) and the northern half of the Aishihik Lake 115H map sheet (136°-138°W and 61°30'-62°N). The study area is located in the terminal area of the Cassiar lobe of the CIS (Hughes 1990). Limits of the CIS during the McConnell and penultimate glaciations, as mapped by Hughes (1990) and Jackson (2000), were used in conjunction with an air photograph survey and ground investigation to identify sampling locations. Sites were selected in landscape positions that were easily related to mapped glacial limits and where soil development is likely to have been preserved.

Soils were studied at 14 sites – four McConnell sites, six sites on till of the penultimate glaciation, and four pre-Reid sites. Soil in areas covered by ice of the McConnell and penultimate glaciations have formed on till, locally mantled by loess deposited during the McConnell glaciation (Jackson 2000). A thin layer of White River tephra (ca. 1150 years old) occurs above the loess (Clague *et al.* 1995). Till within the Carmacks map sheet has a sand-rich matrix due to derivation from local granitic and schistose rocks (Jackson 2000). Pre-Reid sites selected for the study are located beyond the penultimate glacial limit in upland landscape positions. Soil at these locations is derived primarily from weathered granitic bedrock, locally with a thin patchy cover of loess and White River tephra.

1.5 Research objectives

My research addresses pedogenesis, soil morphology, chemistry and mineralogy along the margins of Pleistocene CIS. It examines soils at upland sites in the central Yukon with a range of glacial and landscape histories in order to improve understanding of regional soil genesis and glacial chronology, and to assess the contribution of relict weathering features to soil development.

The currently established model of soil development on glacial deposits in the central Yukon has only been tested by one study (Huscroft *et al.* 2006). This study and earlier ones focussed on low-elevation sites. My study provides additional data on correlatives of the Stewart and Diversion Creek soils at high-elevation sites, and helps delineate their geographic and physiographic extent.

The glacial history in this region is complex, and the age of the penultimate glaciation remains uncertain and may be variable between lobes of the CIS. My pedological study of the McConnell and penultimate glacial surfaces within the study area was designed to elucidate relative weathering and thus the relative ages of these surfaces. Because no other soil studies have been conducted on glacial surfaces associated with the Cassiar lobe of the CIS, my research provides valuable information regarding the comparability of soil studies on till of different lithologies. The results will assist surficial geologists in regional mapping of these surfaces. In addition, I evaluate the usefulness of a variety of pedological analytical methods in characterizing central Yukon soils in both the field and the laboratory. This study provides the first analysis of soils derived from weathered bedrock in relict landscapes. These soils have possibly been preserved through glacial events of the Early and Middle Pleistocene. The specific objectives of my study are to: 1) characterize the morphology, chemical and physical properties, clay mineralogy, and degree of weathering of representative soils from McConnell, penultimate and pre-Reid surfaces; 2) assess standard methods for describing and quantifying soil weathering for their utility in other soil studies in the Yukon; 3) compare the results to those produced by researchers working at lower elevation in the central Yukon; and 4) relate results to the regional glacial and climate history.

2 GENESIS OF UPLAND SOILS ON PLEISTOCENE GLACIAL DEPOSITS, CENTRAL YUKON

2.1 Introduction

Jenny (1941) argued that soil is produced through the interaction of climate, biota, topography, parent material and time. In general, soil becomes thicker and shows increasing horizon differentiation with increasing age. As a result, differences in the degree of soil development can be used to differentiate surfaces of different ages, as long as other soilforming factors remain unchanged (Huggett 1998; Birkeland 1999). During the Pleistocene, climate has fluctuated markedly, thus separating the effects of climate and time can be challenging.

The central Yukon has been affected by repeated episodes of ice-sheet glaciation. The Cordilleran Ice Sheet (CIS) in the Yukon comprised a series of coalescent ice lobes flowing from source areas in the Selwyn, Pelly, Cassiar and Coast Mountains. This section of the CIS was contiguous with ice flowing from the St. Elias Mountains (Hughes *et al.* 1969; Jackson and Clague 1991; Jackson *et al.* 1991). The first CIS apparently was the largest of the past 2.6 million years (Jackson *et al.* 2003), and the youngest was the smallest of those for which there is evidence.

Glacial deposits of different ages support soils that have different properties. The glacial chronology upon which most of the early pedological work is based was first described by Bostock (1966). He recognized four advances of the CIS, from youngest and least extensive to oldest and most extensive, the McConnell, Reid, Klaza, and Nansen. The McConnell and, to a lesser extent, Reid limits are well defined by end moraines and other ice-marginal landforms (Bostock 1966; Hughes *et al.* 1969). In striking contrast, weathering and erosion have removed most ice-marginal features of the Nansen and Klaza glaciations,

thus most researchers after Bostock have grouped all events preceding the Reid glaciation into a single category known as pre-Reid (Figure 1.2).

The first studies of soil genesis on McConnell, Reid and pre-Reid surfaces were conducted in the 1970s and 1980s (Foscolos *et al.* 1977; Tarnocai *et al.* 1985; Smith *et al.* 1986; Tarnocai and Smith 1989) ("area of previous research" in Figure 1.2). These researchers described and sampled soils on stable (near level to very gently sloping) morainal and glaciofluvial surfaces at low elevation (450-1000 m asl, average ~650 m asl) in order to characterize soils where development and preservation were optimal. They named soils at their type sites: "Wounded Moose" for Early Pleistocene relict paleosols formed on pre-Reid deposits, "Diversion Creek" for Middle to Late Pleistocene relict paleosols formed on Reid deposits, and "Stewart" for Holocene soils formed on McConnell deposits (Table 2.1; Smith *et al.* 1986). Relict paleosols are not buried and are exposed to weathering at the surface.

Characteristic	Pre-Reid deposits	Reid deposit	McConnell deposit		
Soil name	Wounded Moose paleosol	Diversion Creek paleosol	Stewart neosol		
Soil type	Luvisol	Luvisol - Brunisol	Brunisol		
Solum depth	1-2 m	0.5-1 m	< 0.4 m		
	Strong red	Moderate red	Brown to grey (10YR)		
Solum colour	(5VR to 7.5VR)	to brown			
	(911 (10 7.511()	(7.5YR to 10 YR)			
Clay content	High	Moderate	Low		
Clay skins	Abundant	Uncommon	Absent		
Clay skins	(reddish-brown)	(brown)			
	Interstratified	No interstratified	No interstratified		
Clay mineralogy	phyllosilicates and	phyllosilicates or	phyllosilicates or		
	smectites	smectites	smectites		
Disintegration	Widespread alteration of	Partial alteration in less	Limited alteration		
of rock	most lithologies	resistant lithologies			
Periglacial features	Common and pronounced	Less frequent and			
	(thick sand wedges and	pronounced (occassional	Absent		
	involutions)	sand wedges and involutions)			

Table 2.1: Summary of soil characteristics in the central Yukon based on research by Foscolos *et al.* (1977), Tarnocai *et al.* (1985), and Smith *et al.* (1986).

Early researchers used differences in soil development in deposits of different age to infer climatic conditions during interglaciations, when the soils were assumed to have formed (Foscolos *et al.* 1977; Rutter *et al.* 1978; Tarnocai *et al.* 1985; Smith *et al.* 1986). They concluded that the deep weathering and pedogenic features in Wounded Moose relict paleosols resulted from pedogenesis over a long period of time under a relatively mild and humid climate of a late, pre-Reid interglaciation. Diversion Creek relict paleosols were thought to have formed during the interglaciation between the Reid and McConnell glaciations under a cool, sub-humid climate that was warmer and moister than the modern climate of central Yukon. This period was assumed to have been shorter than the pre-Reid interglaciation due to only moderate soil development. In addition, periglacial features in Diversion Creek relict paleosols are less developed and occur less frequently than those in Wounded Moose relict paleosols, suggesting that the McConnell glaciation was shorter than the reliant the Reid glaciation.

The only other study of soils of different ages in the central Yukon is that of Huscroft *et al.* (2006). They found that some soils formed on terraces of possibly younger pre-Reid age along the Yukon River had characteristics of the Diversion Creek relict paleosols, whereas other soils on higher, likely older terraces resembled Wounded Moose development. Smectite characteristic of Wounded Moose relict paleosols is present only in the older, higher terraces. Huscroft *et al.* (2006) inferred that the two groups of soils record two separate pre-Reid interglaciations. They suggested that the established soil-age relationships and, in turn, their relations to interglacial climates, are more complex than previously thought. It is clear that additional soil genesis studies in the central Yukon are required to clarify soil-age relationships.

Recent advances in dating ice-sheet glaciation in the central Yukon have further complicated the application of early studies of soil-age relationships in the region. The age of the McConnell glaciation is well constrained to MIS 2 (ca. 30-11 ka BP), based on radiocarbon ages (Matthews et al. 1990; Jackson and Harington 1991) and more recently terrestrial cosmogenic nuclide (TCN) dating (Bond and Lipovsky 2009). In contrast, the age of the Reid glaciation is unresolved. It has been broadly assigned to three glacial periods by different workers: MIS 4 (ca.75-58 ka BP), MIS 6 (ca. 195-127 ka BP), or MIS 8 (ca. 297-244 ka BP) (Hughes et al. 1989; Westgate et al. 2001; Huscroft et al. 2004). It is possible that landforms and other surfaces attributed to the Reid glaciation are, in fact, of different ages. Bostock (1966) thought that all Reid-age surfaces are correlative, but recent work raises the possibility that this inference is incorrect. Specifically, cosmogenic nuclide (TCN) dating of erratics on the southern Yukon Plateau near Aishihik Lake, a region affected by the St. Elias and Coast lobes of the CIS, suggests that the penultimate phase of ice-sheet glaciation in that area is MIS 4 (Ward et al. 2007). Dating of tephra associated with penultimate glacial deposits near Pelly Farm and Dawson City, region affected by the Selwyn lobe, suggests that 'Reid' deposits there date to MIS 6 (Ward et al. 2008; Westgate et al. 2008). Ward et al. (2007) proposed the name Gladstone for MIS 4 events near Aishihik Lake and argued that Reid should be reserved for MIS 6 events.

All previous soil genesis studies in the central Yukon were done on low-elevation soils in the Tintina Trench, which was glaciated by the Selwyn lobe of the CIS (Figures 1.1 and 1.2). In contrast, my study focuses on upland sites on the Lewes Plateau, which was glaciated by the Cassiar lobe. Although the term "Reid glaciation" has historically been applied to all penultimate ice-sheet glacial events in the Yukon, the more general term "penultimate" will be used in this paper, reflecting uncertainty about the age of the deposits.

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The terms McConnell and penultimate refer to glacial events. However, for ease of reference in this document, soils formed on deposits of these events are referred to as "McConnell soils" and "penultimate soils" respectively.

The chemical, mineralogical and micromorphological characteristics of soils developed on high-elevation tills of the McConnell and penultimate glaciations are described in this paper. My objectives are to (1) identify pedological tools that are useful in differentiating the soils and (2) assess the applicability of soil-geomorphic relationships developed for Diversion Creek relict paleosols and Stewart neosols, to McConnell and penultimate deposits on the Lewes Plateau.

2.2 Study area

The study area is on the Lewes Plateau, approximately 25 km southwest of Carmacks, and lies near the limit of the Cassiar lobe of the CIS during the McConnell and penultimate glaciations (Figure 2.1). The study area is located within Stikinia Terrane. The bedrock geology consists of Early Jurassic Long Lake Suite porphyritic plutonic rocks, which have intruded Triassic basalt (Tempelman-Kluit 1973; Gordey and Makepeace 2001). The porphyritic plutonic rock comprises massive to weakly foliated, fine to coarse-grained, biotite, biotite-muscovite and biotite-hornblende quartz monzonite to granite. Pegmatite and aplite phases are also abundant.

The study area is part of the Boreal Cordillera ecozone, within the Yukon Plateau-Central ecoregion (Smith *et al.* 2004). This ecoregion is characterized by a continental climate with low precipitation (mean annual precipitation (MAP) 250-300 mm/year) and cool temperatures (mean annual temperature (MAT) -4°C) (Smith *et al.* 2004), and is within the zone of discontinuous permafrost (Hegginbottom *et al.* 1995). Modelled site-specific MAT



Figure 2.1: Location of McConnell and penultimate till sample sites with respect to glacial limits. IRS image provided courtesy of Government of Yukon.

is -3.5 to -3.3°C and MAP is 320-346 mm at the four McConnell sampling locations; corresponding values at the six penultimate glaciation sample sites are -3.9 to -3.4°C and 325-365 mm (Wang *et al.* 2006). Vegetation communities range from open boreal forest to subalpine. The open boreal forest plant community is dominated by *Picea mariana* and a ground cover of shrubs *(Ledum groenlandicum, Vaccinium vitis-idaea* and *Betula glandulosa*), lichens (*Cladina rangiferina, Cladina mitis* and *Cladonia spp.*) and mosses. Treeline coincides with the boundary between the subalpine and alpine zones at about 1370 m asl.

Well preserved ground moraine and end moraines delineate the outer limit of the CIS during the McConnell glaciation; and more subdued and less continuous features delineate the penultimate glacial limit at higher elevation to the west (Hughes 1990; Jackson 2000). Soils were described and sampled at four sites on McConnell deposits between 1035 and 1100 m asl and at six sites between 1100 and 1250 m asl on penultimate deposits (Figure 2.1). The surficial material includes moraines and till blankets on rock. Till in these areas is commonly overlain by a veneer of loess thought to be of McConnell age (Foscolos *et al.* 1977). No loess dating to the penultimate event has been observed. A thin layer of the eastern lobe of the White River tephra (Lerbekmo and Campbell 1969) overlies the loess and has been dated at approximately 1150 yr BP (Clague *et al.* 1995).

2.3 Methods

2.3.1 Site selection and description

Stable sample sites were selected because they are most likely to preserve the longest record of soil formation. Flat to gently sloping sites (0 to 6°) were selected to limit influence of erosion and areas without permafrost were selected to facilitate pedon excavation. Six soil pits were excavated in penultimate till (Y08-15, Y08-16, Y08-21, Y08-22, Y08-23, and Y08-

36) and four sites were excavated in McConnell till (Y08-18, Y08-19, Y08-31, and Y08-33) (Figure 2.1). Horizon designations and soil descriptions were completed at each site according to the Canadian System of Soil Classification (Soil Classification Working Group 1998), the BC Field Manual for Describing Terrestrial Ecosystems (BC Ministry of Environment, Land and Parks 1998), and the taxonomic classification of humus forms (Green *et al.* 1993). Bulk samples were collected for physical and chemical characterization from each horizon. Samples were air-dried and sieved to < 2 mm.

2.3.2 Physical and chemical analyses

Analyses were conducted on the entire < 2 mm fraction unless otherwise noted. Particle-size analysis was done using the pipette technique (Gee and Bauder 1986) and sieving (Cantest Laboratories, Winnipeg, MB) following pre-treatment with hydrogen peroxide and citrate-dithionite-bicarbonate for removal of organic matter and iron respectively. For chemical analyses, duplicates were run on five percent of the samples. Soil pH was determined using both a 1:2 soil-to-water and a 1:2 soil-to-0.01 M CaCl₂ ratio (1:10 for organic samples) (Hendershot *et al.* 2008). All chemical concentrations are reported on an oven-dried basis. For total elemental analyses, samples were digested using lithium borate fusion (ALS Laboratories, Vancouver, BC). Concentrations of major elements were determined by ICP-atomic emission spectroscopy (AES), and those of trace elements were determined by inductively coupled argon plasma (ICP)-mass spectrometry (MS). A standard reference sample (TILL-C) from the Canadian Certified Reference Materials Project (Natural Resources Canada) was included in the total elemental analysis.

The following soil chemical analyses were performed at the BC Ministry of Forests and Range analytical chemistry laboratory in Victoria, BC. Total C and N were determined using a LECO CHN-600 Elemental Analyzer; total S was determined with a LECO SC-32

Analyzer. Cation exchange capacity (CEC) and exchangeable cations were determined using the BaCl₂ method (Hendershot and Duquette 1986) and ICP-AES, respectively. Soil weathering products were analyzed by selected dissolutions using sodium pyrophosphate, acid ammonium oxalate, and citrate-dithionite-bicarbonate extractions of Fe, Al and Si (Carter 1993), with elemental concentrations in the extracts measured by ICP-AES.

2.3.3 Weathering indices

Depletion/enrichment ratios of mobile major elements were determined using an immobile element as a reference (Taylor and Blum 1995). Ti was selected as the reference element due to its relative immobility in soils, especially poorly developed soils in temperate regions (April *et al.* 1986; Taylor and Blum 1995; Schaller *et al.* 2009). Zr was also used as a reference element, but its pattern mimicked that of Ti, thus only Ti values are presented here. The depletion/enrichment ratio is calculated as follows:

$$x_{i,j} = \frac{c_{i,j}/c_{i,p}}{\tau_{i_j}/\tau_{i_p}} \qquad \qquad Equation \ 1$$

where $C_{i,j}$ is the concentration of element i in horizon j, $C_{i,p}$ is the concentration of the same element in the parent material p, and Ti_j and Ti_p are the concentration of titanium in the same horizon j and the parent material p. A value lower than 1 indicates a depletion of the element, whereas a value greater than 1 indicates enrichment. The ratio $Ti_j:Ti_p$ is also plotted.

Major oxide concentrations were used to calculate the Chemical Index of Alteration (CIA), a widely used weathering index for feldspar-rich parent materials (Nesbitt and Young 1982). Calcium, sodium and potassium are released as feldspar weathers, whereas aluminum is relatively immobile during weathering. The CIA is calculated using molecular proportions as follows:

$$CIA = \left(\frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O}\right) \times 100 \qquad Equation 2$$

where CaO* is corrected for Ca in phosphates and carbonates. The CIA values of fresh albite, anorthite and potassium feldspar are approximately 50; the CIA of unaltered granites ranges from 45 to 55 (Nesbitt and Young 1982); and the maximum value of 100 occurs in aluminum oxides. I also calculated CIA values from data for two Stewart neosols (sites 4 and 6) and two Diversion Creek relict paleosols (sites 3 and 5) reported by Foscolos *et al.* (1977).

Extractions that separate different forms of Fe, Al and Si provide data on secondary weathering products that are diagnostic of processes of soil development. Pyrophosphate extractable Fe and Al (Fe_p, Al_p) are considered to be organically complexed forms (McKeague 1978), although Fe_p may overestimate the amount of organically complexed iron due to the presence of fine colloidal Fe oxides (Schuppli *et al.* 1983). Oxalate-extractable forms (Fe_o, Al_o, Si_o) represent the sum of short-range order (i.e. poorly crystalline or amourphous) minerals and organically complexed forms. Common short-range order phases of interest are ferrihydrite for iron and allophane and imogolite for aluminum and silicon (Borggaard 1982; Farmer *et al.* 1983; Parfitt and Wilson 1985; Parfitt and Childs 1988). Dithionite-citrate-bicarbonate extractable iron (Fe_d) represents the sum of all secondary Fe forms (Parfitt and Childs 1988). The ratio of Fe_d to total Fe provides a measure of the proportion of total iron that has been converted to secondary forms.

2.3.4 Micromorphological analysis

Intact soil samples were collected using Kubiëna boxes for micromorphological description of characteristic horizons in tephra and loess (Y08-23 Bmjy and IIAe) and till (Y08-15 IIIBm1; Y06-16 IIBm1 and IIBm3; Y08-18 IIIBm and IIIBC; Y08-21 IIIBm1 and

IIIBm2; Y08-23 IIIBm1; Y08-31 IIBm1 and IIBC; Y08-36 IIIBm and IIIC). Samples were oven-dried at 105°C for a minimum of two days and impregnated with epoxy resin in a vacuum chamber. Thin sections (30 µm thick) were examined with a petrographic microscope. Micromorphological descriptions use the terminology of Stoops (2003). The "c/f-related distribution" refers to the distribution of individual coarse fabric units in relation to smaller fabric units and associated pores; the b-fabric refers to the orientation of birefringent material under cross-polarized light; groundmass is a general term for the coarse and fine material that act as the base material of soil in thin section (Stoops 2003).

2.3.5 Mineralogical analysis

Sand and clay fractions of a subset of soil horizons were characterized for a range of parent materials from McConnell sites Y08-18 and Y08-31 and penultimate till sites Y08-15, Y08-21, Y08-23 and Y08-36. Sand, silt and clay fractions were separated by settling from suspension following removal of organic matter with hydrogen peroxide, and sesquioxides with a solution of citrate-bicarbonate-dithionite.

Clay fraction samples were prepared for K- and Ca-saturated treatments using the method of Theisen and Harward (1962). K-saturated samples were scanned at 0% relative humidity (RH), 54% RH, and after heating to 300°C and 550°C; Ca-saturated samples were scanned at 54% RH and solvated with ethylene glycol (EG) and glycerol (Gly). X-ray diffraction (XRD) patterns for clay minerals were obtained with Co-K α radiation (40 kV and 20 mA) over the range 2-36°2 θ . Clay minerals were identified based on their XRD patterns using standard criteria (Dixon and Weed 1989; Moore and Reynolds 1997; Arocena and Sanborn 1999).

The sand fractions were ground to ensure random orientation of grains, and the powder mount was scanned from 2-90°2θ under ambient temperature and humidity. XRD patterns were identified using Bruker EVATM diffraction software and its database of standard references. Qualitative description of sand grains and coarse fragments was completed using a petrographic microscope.

2.3.6 Statistics

I used the non-parametric Mann-Whitney test to evaluate the significance of difference in solum depth, pH, clay, silt and sand content, and CIA values between McConnell and penultimate soils. Differences between the two groups were determined using p-values between 0.10 and 0.05 to indicate marginal significance and values < 0.05 to be significant. All tests were one-tailed because the presumed direction of difference was known. The data were analyzed using Statistical Package for the Social Sciences version 16 (SPSS Inc. 2008). Mean CIA values, weighted for horizon thickness, were calculated for the till B horizon for each excavated soil pit. The till B horizon weighted means from penultimate and McConnell till were compared to determine differences in relative weathering.

2.4 Results

2.4.1 Pedon description

Organic horizons are similar at both McConnell and penultimate till sites. Thin (2-12 cm) hemimor humus consisting predominantly of Fm horizons, has loose to friable consistence, and weak to moderate, non-compact, matted structure (Appendix 1). Mycelia are common, and a few fecal pellets were noted. Colour ranges from black (10YR 2/1 m) to very dark brown (7.5YR 2.5/2 m, 10YR 2/2 m) and horizons that incorporate tephra are grayish brown (10YR 5/2). Organic horizons are extremely acidic (pH < 4.5 in CaCl₂), and

Horizon &	Parent	Sand	Silt	Clay	Tot C	Tot N	Tot S	pН	pН	CEC
depth (cm)	material			%	D			(H ₂ O)	(CaCl ₂)	cmol ⁽⁺⁾ /kg
McConnell till so	oils									
Orthic Dystric Br	unisol (Y0	8-18, 10	35 m asl	, 62°00'3	3.2"N, 13	36°34'39.	1"W)			
Fm (7-4)	Organic	-	-	-	39.02	1.07	0.09	4.33	3.86	32.08
Ah (0-4)	Organic	-	-	-	15.31	0.47	0.04	4.58	3.52	11.81
Bm (4-14)	Tephra	53.6	43.5	2.9	1.85	0.07	-	4.54	3.66	2.63
IIBm (14-23)	Loess	35.9	43.9	20.2	0.74	0.04	-	5.47	4.57	15.02
IIIBm (23-48)	Till	86 .1	9.3	4.6	0.21	0.02	-	6.34	5.39	7.30
IIIBC (48-82)	Till	85.2	11.5	3.4	0.16	0.01	-	6.67	5.94	6.87
IIIC (82-112+)	Till	83.5	12.6	3.9	0.16	0.01	-	7.12	6.28	7.49
Orthic Dystric Br	unisol (Y0	8-19, 10	40 m asl	, 62°00'2	2.9"N, 13	36°34'00.	7"W)			
Fmi (5-0)	Organic	-	-	-	18.04	0.69	0.09	5.24	4.32	24.06
Bm (0-9)	Tephra	48.5	47.6	4.0	1.07	0.05	-	6.05	5.16	3.07
IIBm (9-35)	Till	55.6	27.9	16.5	0.38	0.02	-	6.51	5.38	13.87
IIBC (35-56)	Till	61.2	27.0	11.8	0.18	0.01	-	6.92	5.83	11.85
IIC (56-100+)	Till	63.1	26.5	10.4	0.15	0.01	-	7.11	6.00	9.92
Orthic Dystric Br	unisol (Y0	8-31, 11	00 m asl	, 61°52'5	2.3"N, 13	36°34'20.	7"W)			
Fm (8-0)	Organic	-	-	-	45.21	1.44	0.13	4.58	3.87	25.97
Bm (0-8)	Tephra	36.8	59.5	3.7	0.72	0.03	-	5.63	4.71	1.72
IIBm1 (8-26)	Till	51.8	32.9	15.4	0.59	0.03	-	5.63	4.57	12.58
IIBm2 (26-42)	Till	57.5	29.0	13.6	0.23	0.02	-	6.80	5.63	9.87
IIBC (42-61)	Till	59.9	27.7	12.4	0.21	0.01	-	7.15	6.14	8.94
IICk (61-110+)	Till	73.1	20.8	6.1	0.23	0.01	-	8.62	7.32	5.70
Eluviated Dystric	c Brunisol	(Y08-33	, 1098 m	asl, 61°5	52'48.4"N	l, 136°34	'06.5"W	')		
Fm (4-0)	Organic	-	-	-	34.26	1.30	0.12	4.87	4.15	32.57
Ahey (0-3)	Tephra	58.8	36.6	4.6	1.81	0.07	-	4.87	3.92	3.00
Bmjy (3-19)	Tephra	25.7	70.6	3.7	1.12	0.06	-	5.20	4.19	2.05
IIAhb (19-22)	Till	-	-	-	1.05	0.04	-	5.29	4.30	5.19
IIBm1 (22-34)	Till	69.4	21.2	9.5	0.40	0.02	-	5.55	4.46	4.31
IIBm2 (34-48)	Till	77.8	15.7	6.6	0.35	0.02	-	5.79	4.67	3.13
IIC (48-107+)	Till	74.4	21.6	4.0	0.18	0.01	-	6.49	5.40	4.04
Penultimate till soils										
Orthic Dystric Br	unisol (Y0	8-15, 11	97 m asl	, 61°59'1	.9"N, 136	5°38'51.6'	"W)			
Fmi (2-0)	Organic	-	-	-	24.83	0.96	0.09	4.58	3.63	16.85
Bm (0-4)	Tephra	47.1	46.6	6.3	2.97	0.13	-	4.59	3.60	3.18
IIBm (4-10)	Loess	56.7	33.5	9.8	1.28	0.06	-	5.36	4.40	2.83
IIIBm1 (10-36)	Till	89.8	5.9	4.4	0.46	0.03	-	5.66	4.56	1.31
IIIBm2 (36-60)	Till	91.1	5.6	3.3	0.36	0.02	-	5.84	4.52	1.42
IIIBC (60-90)	Till	87.3	10.2	2.5	0.20	0.02	-	5.76	4.54	1.86
IIIC1 (90-119)	Till	86.1	11.3	2.5	0.15	0.01	-	6.03	4.85	3.95
IIIC2 (119-160+	-) Till	92.6	5.7	1.7	0.13	0.01	-	6.25	5.02	3.38

Table 2.2: Site descriptions and selected physical and chemical data for soils developed in McConnell and penultimate till.

Horizon &	Parent	Sand	Silt	Clay	Tot C	Tot N	<u>Tot S</u>	pН	pН	CEC
depth (cm)	material			%				(H ₂ O)	(CaCl ₂)	cmol(+)/kg
Penultimate till soils										
Orthic Dystric Brunisol (Y08-16, 1209 m asl, 61°59'1.1"N, 136°39'17.9"W)										
Fm (4-0)	Organic	-	-	-	38.08	1.21	0.11	4.13	3.34	16.80
Bm (0-10)	T & L*	39.7	57.7	2.6	1.28	0.06	-	4.62	3.68	1.61
IIBm1 (10-23)	Till	72.7	18.0	9.3	1.41	0.07	-	5.18	4.09	2.81
IIBm2 (23-45)	Till	83.2	11.7	5.1	0.69	0.05	-	5.64	4.44	1.55
IIBm3 (45-63)	Till	86.2	9.4	4.4	0.43	0.03	-	5.84	4.61	1.45
IIC (63-110+)	Till	83.0	13.9	3.1	0.22	0.02	-	6.07	4.88	1.91
Orthic Dystric Br	Orthic Dystric Brunisol (Y08-21, 1099 m asl, 62°00'31.4"N, 136°36'27.7"W)									
Fm (5-0)	Organic	-	-	-	39.10	0.95	0.08	3.85	2.96	12.77
Bm (0-10)	Tephra	48.3	46.0	5.7	1.46	0.06	-	4.71	3.86	2.03
IIBm1 (10-15)	Loess	21.2	64.4	14.4	1.42	0.07	-	5.43	4.40	6.74
IIBm2 (15-20)	Loess	32.8	49.4	17.9	0.65	0.03	-	5.73	4.58	7.30
IIIBm1 (20-40)	Till	65.1	25.7	9.2	0.25	0.02	-	5.91	4.69	4.24
IIIBm2 (40-70)	Till	67.2	23.1	9.8	0.21	0.02	-	6.04	4.76	5.26
Eluviated Dystric	Brunisol (Y08-22,	1092 m a	asl, 62°00)'30.6"N,	136°36'	33.9"W	')		
Fm (5-0)	Organic	-	-	-	40.98	1.35	0.12	5.08	4.28	32.03
Aej (0-2)	Tephra	41.2	55.5	3.4	1.08	0.05	-	4.77	3.80	1.29
Bm (2-9)	Tephra	51.4	42.1	6.5	1.18	0.05	-	5.18	4.20	1.71
IIBm (9-13)	Loess	26.5	58.6	14.9	0.82	0.04	-	5.42	4.42	5.57
IIIBm1 (13-36)	Till	70.1	19.5	10.3	0.36	0.02	-	5.59	4.51	5.94
IIIBm2 (36-72)	Till	74.1	19.5	6.5	0.19	0.01	-	5.97	4.67	4.37
IIIBC (72-102+)) Till	74.3	1 9.8	5.9	0.17	0.01	-	5.92	4.61	11.47
Eluviated Dystric	Brunisol (Y08-23,	1236 m a	asl, 61° 53	3' 50.64"	N, 136°	43' 19.0	5788"W)	
F (7+)	Organic	-	-	-	39.36	1.37	0.14	4.36	3.61	27.73
Fmi (7-0)	Organic	-	-	-	19.30	0.69	0.09	4.59	3.84	16.17
Bmjy (0-18)	Tephra	31.1	65.4	3.6	1.01	0.05	-	5.57	4.45	1.50
IIAe (18-20)	Loess	23.1	66.7	10.2	1.50	0.05	-	5.67	4.43	5.80
IIIBm1 (20-36)	Till	67.1	24.3	8.7	0.54	0.03	-	5.99	4.78	2.12
IIIBm2 (36-67)	Till	69.4	24.4	6.2	0.23	0.02	-	6.40	4.60	2.52
IIIBC (67-100)	Till	79.0	18.0	3.0	0.10	0.01	-	6.55	5.25	5.51
IIIC (100-110+)	Till	74.5	21.9	3.6	0.14	0.01	-	6.65	5.39	6.44
Orthic Dystric Brunisol (Y08-36, 1128 m asl, 61°52'45,4"N, 136°35'24.0"W)										
Fmi (4-0)	Organic	-	-	-	22.09	0.59	0.06	3.24	3.25	11.27
Bmy (0-8)	Tephra	29.5	67.0	3.5	0.63	0.03	_	5.43	4.42	0.94
IIBm (8-14)	Loess	47.5	41.2	11.3	0.79	0.03	-	5.72	4.70	3.99
IIIBm (14-30)	Till	66.8	27.0	6.2	0.25	0.02	-	6.07	4.97	3.27
IIIC (30-110+)	Till	74.7	21.6	3.8	0.15	0.01	-	6.92	5.99	4.67

Table 2.2 (continued): Site descriptions and selected physical and chemical data for soils developed in McConnell and penultimate till

* T & L indicates mixture of tephra and loess

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total carbon ranges from 18.0 to 45.2 % (Table 2.2). The lower boundary of the horizon is typically clear to abrupt and wavy to smooth.

The mineral horizons indicate that all ten pedons have formed in complex parent materials (Appendix 1). Uppermost is a thin veneer of tephra that ranges from 2 to 25 cm thick. Its structure ranges from weak and moderate subangular blocky to weak and moderate platy; vesicles are present at some sites. The dominant texture is silt loam, but some samples of tephra are sandy loam. Colour ranges from gray (10YR 6/1 m) and light gray (10YR 7/2) in unmodified tephra to grayish brown (10YR 5/2 m) and brown (10YR 4/3 m; 10YR 5/3 m) in oxidized mottles. The tephra is extremely acidic (pH < 4.5 in CaCl₂), with one exception, which is strongly acidic (pH 5.1-5.5 in CaCl₂) (Table 2.2, Appendix 2). Total carbon (mean 1.3%) and CEC (mean 2.06 cmol(+) kg⁻¹) are low. The lower boundary is abrupt and smooth to wavy. In the penultimate sites, cryoturbation is limited to tephra horizons at Y06-23 and Y08-36.

In most cases, a horizon of eolian material up to 15 cm thick directly underlies the tephra. This sediment is likely McConnell loess and is typically described as a Bm horizon. It ranges from sandy loam to loam. It occurs as a discrete layer at five of the six penultimate soil sites (Y08-15, -21, -22, -23, and 36) and is mixed with the tephra through colluviation at the sixth site (Y08-16). At McConnell sites, the eolian material appears as a discrete horizon at one site (Y08-18) and is incorporated into the upper portion of the underlying till at the other three sites (Y08-19, -31, -33). Structure ranges from weak and moderate subangular blocky to weak and moderate platy to granular. Colour is dominantly dark yellowish brown (10YR 3/4 m, 4/4 m, 3/6 m), with some brown horizons (7.5YR 4/4 m). The loess is very strongly to extremely acidic (pH in CaCl₂<5.0). Total carbon (mean 1.0%) and CEC (mean 6.75 cmol(+) kg⁻¹) are low. The lower boundary is either abrupt or clear and smooth to

wavy. Disrupted horizon boundaries indicative of cryoturbation were only observed at one McConnell site, and was restricted to the tephra and loess horizons (Y08-33; Figure 2.2).

Underlying the eolian material at Y08-18, -19, -31, -33 is McConnell till with a soil texture ranging from loamy sand to loam. Soils have a solum thickness of <50 cm and are classified as Orthic Dystric Brunisols or Eluviated Dystric Brunisols (Figure 2.2). Moderate colouration in the till B horizons range from brown (10YR 5/3) to olive brown (2.5Y 4/3); the colour of the till C horizon ranges from brown (10YR 5/3) to dark greyish brown (2.5Y 4/2). Development of pedogenic structure in the till-derived horizons is limited and ranges from weak subangular blocky to structureless. The pH of the upper solum (CaCl₂) is <5.5, but is slightly higher in the lower solum and parent material (>5.5) at three of four sites (Y08-18, -19 and -31). Secondary carbonate was observed on the underside of clasts at site Y08-19 and within the matrix at site Y08-31. Total carbon and CEC are low in both the B (mean 0.4%; 7.4 cmol(+) kg⁻¹) and combined BC and C (mean 0.2%; 7.4 cmol(+) kg⁻¹) horizons (Table 2.2). Silt caps were observed in lower horizons at some sites but no clay skins were found. *In situ* disintegration of granitic rock fragments was noted at Y08-31.

Pedons at the penultimate sites are classified as either Orthic or Eluviated Dystric Brunisols (Figure 2.3) and are developed on thick till or thin till over bedrock. The soil texture ranges from sand to sandy loam. Solum thickness ranges from 50 to 75 cm, except at site Y08-36 where the solum thickness is 36 cm. The B horizons range in colour from brown and strong brown (7.5YR 4/6 and 7.5YR 4/4) to olive brown (2.5Y 4/4), but are dominantly dark yellowish brown (10YR 3/4 to 4/6). Unweathered till ranges in colour from brown (10YR 5/3) to olive brown (2.5Y 4/4). Development of pedogenic structure is limited in the till horizons, ranging from weak subangular blocky to structureless. All soils are acidic throughout the solum, with pH (CaCl₂) <5.5. Total carbon and CEC are low in both the B

Figure 2.2: (A) McConnell landscape. Arrow shows location of pedon Y08-33. (B) Eluviated Dystric Brunisol formed in McConnell till at site Y08-33. Knife handle is 11 cm long.



Figure 2.3: (A) Penultimate landscape. Arrow shows location of pedon Y08-15. (B) Orthic Dystric Brunisol formed in penultimate till at site Y08-15. Knife handle is 11 cm long.



(mean 0.5%; 3.0 cmol(+) kg⁻¹) and combined BC and C (mean 0.2%; 4.9 cmol(+) kg⁻¹) horizons (Table 2.2). Silt caps were observed in lower horizons at some sites but no clay skins were found. *In situ* disintegration of granitic coarse fragments was commonly noted.

Textural differences (< 2mm) between McConnell and penultimate till exist. The C horizon of McConnell till has significantly more clay than the C horizon of penultimate till $(U=0, n_1=4, n_2=4, p<0.05)$ and marginally less sand $(U=3, n_1=4, n_2=4, p=0.10)$. Soils formed on penultimate till are marginally thicker than soils formed on McConnell till $(U=4, n_1=4, n_2=6, p<0.10)$. The pH is higher in the C horizon of McConnell till than that of penultimate till $(U=1, n_1=4, n_2=4, p<0.05)$.

2.4.2 Chemical weathering indices

Changes in base cation concentrations with depth at both the McConnell and penultimate sites are complicated by lithological discontinuities (Appendix 3). For this reason, calculation of depletion/enrichment factors is restricted to till-derived horizons only. Plots of depletion/enrichment index values (Equation 1) and reference element values (Ti_j/Ti_p) versus depth for McConnell and penultimate soils are shown in Figure 2.4. A greater depletion of base cations relative to Ti was expected for penultimate soils than McConnell soils. However, no clear difference is evident from the data in Figure 2.4. In McConnell soils the depletion of base cations relative to Ti is observed at Y08-19 and Y08-31 (Figure 2.4 b, c), but not at Y08-18 or Y08-33 (Figure 2.4 a,d). The depletion of base cations at Y08-31 is much greater than observed at any of the penultimate soil sites. The four penultimate soil profiles (Y08-15, -16, -21, -36) show a mild depletion of base cations with depth (Figure 2.4 e,f,g,j), but an enrichment in cations is evident in profile Y08-22 (Figure 2.4 h).

Figure 2.4: Depth profiles of depletion and enrichment factors of base cations in < 2mm fraction of soils developed on McConnell (A-D) and penultimate (E-J) tills. Concentrations are shown relative to C horizons and Ti (Equation 1). Ti is shown relative to C horizon only.



CIA values show consistent changes with depth (Figure 2.5), with the lowest values in tephra and the highest values in loess; values decrease with depth in till horizons. CIA values for tephra horizons at penultimate and McConnell sites are similar and range from 48.8 to 50.4. Values in the underlying loess range from 54.6 to 58.6 across all sites. The high CIA values in loess are likely due in part to its fine texture and in part to incorporation of inherited weathering products. CIA values in both McConnell and penultimate tills decrease with depth, but weighted mean values for B horizons show the two groups are not significantly different (U=11, n_1 =4, n_2 =6, p>0.10), indicating there is no significant difference in feldspar weathering between them. CIA values range from 50.8 and 55.4 in McConnell B horizons and from 50.3 to 55.9 in penultimate till B horizons. McConnell soils have profiles CIA profiles similar to soils formed on McConnell deposits described by Foscolos *et al.* (1977), whereas penultimate soils generally have lower values than the Diversion Creek soils (Figure 2.5).

Mean values of Fe_p and Al_p are low in both McConnell (0.11%, 0.12%) and penultimate (0.16%, 0.07%) B horizons, suggesting that organically bound forms of these elements are not actively being translocated through the profile (Appendix 2). Mean values of Fe_o are also very low in the B horizons (0.46% in McConnell and 0.51% in penultimate soils), indicating that short-range order forms of Fe are also not actively being produced. Mean values of Al_o and Si_o are very low (0.25% and 0.14% in McConnell B horizons and 0.35% and 0.13% in penultimate B horizons), indicating that no allophanic materials have been produced. Mean values of Fe_d are low for both McConnell (0.81%) and penultimate (0.63%) B horizons. The ratio of Fe_d to total Fe (Fe_d:Fe_t) decreases with depth in all pedons (Figure 2.6), indicating that alteration to secondary products of iron decreases with depth.

However, overall alteration of Fe and Al in the till horizons is limited and the values in

McConnell and penultimate soils are similar.

Figure 2.5: Depth profiles of CIA values (Equation 2) in < 2mm fraction of soils developed on McConnell (A) and penultimate (B) tills. Profiles at sites 3-6 based on data in Foscolos *et al.* (1977).





Figure 2.6: Depth profiles of Fe_d/Fe_t in < 2mm fraction of soils developed on McConnell (A) and penultimate (B) tills. Fe_t was determined by ICP-AES.

2.4.3 Soil micromorphology

The tephra shows little evidence of weathering. Grains of plagioclase, hornblende and pyroxene appear unweathered; few are pitted. Red-brown amorphous material, likely Fe-oxide associated with weathering of volcanic glass, is present within the matrix and attached to coarse grains as coatings. The tephra exhibits a single grain microstructure and a coarse monic (only large fabric units) c/f-related distribution (Appendix 5).

Pedogenic features are more common in the loess. Soil horizons have granular to weak platy microstructure (Figure 2.7a). In cold environments, this structure is associated with frost activity (van Vliet-Lanoë 1985). The c/f-related distribution is double-spaced coarse enaulic (smaller units form aggregates between coarse units). Pores are primarily compound packing voids (voids formed through loose packing of soil components) and vughs (irregular voids not interconnected with other voids). Loess in McConnell soils is generally incorporated into the upper portion of the till; the groundmass comprises both coarse particles with thick coatings and unsorted aggregates of fine particles. Very thin (~10µm) grain argillans (clay coatings) and embedded grain argillans are present in the loess, but are discontinuous. Cappings are thick (up to 1 cm), range from unsorted to slightly inversely graded, and may occur in all orientations.

Micromorphological features in till soil horizons of both age groups are similar, but are generally less developed in McConnell pedons. There is significant variability in features both within thin sections and in soil material within each horizon thus this comparison is reliant on a limited number of observations. Recognizable particulate organic matter is limited to the near-surface horizons where roots and plant litter are incorporated. B horizons in till are made up primarily of loosely packed, coarse material with coatings of unsorted to poorly inversely sorted clay, silt and sand grains and amorphous material. The c/f-related

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distribution within the groundmass ranges from coarse monic (Figure 2.7b) to chitonic (Figure 2.7c), and in cappings from enaulic (Figure 2.7f) to porphyric (larger units in dense groundmass of fine units). Many cappings have poorly developed platy microstructure. Cappings are generally thinner in McConnell till (~300 μ m) than in penultimate till (~600 μ m), but occur in all orientations in both. Reddish-brown material, likely Fe oxides, fills cracks and occurs within cappings and local aggregates (Figure 2.7c). B-fabric is speckled to crystallitic with granostriations (Figure 2.7g) from oriented clay. Grain argillans are uncommon and very thin (~10 μ m) in McConnell till (Figure 2.7d). Similarly sized grain argillans (~10-20 μ m) are more common in penultimate till, and some embedded grain argillans occur within aggregates and cappings. Argillans, like cappings, occur in all possible orientations, although they may not cover the entire circumference of an individual grain. Argillans and cappings become less common with depth.

McConnell and penultimate tills contain a variety of minerals and rock fragments. Significant alteration is limited, but is more developed in the penultimate till. Nearly all large clasts are entirely unaltered, except for thin weathering rinds. Alteration of primary minerals is limited but is most common in plagioclase and biotite (Figure 2.7h). More resistant grains, such as quartz, show little or no alteration. Some elongated grains, are oriented vertically.

Figure 2.7 (next page): (A) Loess horizon (IIAe Y08-23) with granular microstructure showing weak development of platy microstructure. (B) McConnell till (IIIBm Y08-18) with coarse monic c/f related distribution. (C) Iron oxides (o) and staining of coarse fragment edges and cracks; very weak development of coatings (IIIBm Y08-18). (D) Very weak birefringence along edges of coarse fragments with very weak development of granostriated clay argillans (a) (IIIBm Y08-18). (E) Penultimate till (IIIBm1 Y08-21) showing cappings on several grain faces indicating rotation. (F) Capping showing internal sorting with fine grains at base of cap (IIIBm1 Y08-21). (G) Penultimate till (IIIBm2 Y08-21) showing birefringence of granostriated clay argillan (a) on bottom surface of grain. (H) Penultimate till (IIIBm1 Y08-23) showing alteration of biotite (b) and development of chlorite (c).


2.4.4 Mineralogy

The sand-size fraction of the tephra is composed primarily of volcanic glass, plagioclase, hornblende, pyroxene and magnetite. The sand-size fraction of the loess is dominated by quartz, plagioclase, chlorite and chlorite intergrades, with some alkali feldspar, pyroxene and amphibole. The sand-size mineral fraction of McConnell till is dominated by quartz and plagioclase with some pyroxene and chlorite intergrades. The sand-size mineral fraction of the penultimate till is also dominated by quartz and plagioclase, with some chlorite, chlorite intergrades, pyroxene and olivine. Biotite is a common mineral in loess and both McConnell and penultimate tills. It was observed in thin sections, but was not evident in X-ray diffractograms.

Table 2.3: Summary of results of semiquantitative X-ray diffraction of the 2- μ m fraction of selected samples. **XXX** = dominant component, XX = common component, x = minor component.

Horizon	Quartz	Feldspar	Mica	Chlorite	Vermiculite	Smectite	Kaolinite	intergrades
Loess	х	х	х	XX	XXX	-	X	XXX
McConnell B	x	х	х	XX	XXX	x	x	XX
McConnell C	x	Х	x	XX	XX	XXX	?	XX - x
Penultimate B	х	х	x	XXX	х	-	?	XXX
Penultimate BC/C	х	x	х	XXX	XX	х	?	XX

The clay mineralogy of the loess and till is summarized in Table 2.3. An example of XRD patterns for till-based horizons is provided in Figure 2.8 (Appendix 4). The clay fraction of all parent material types contains small amounts of primary quartz, feldspar and mica. The clay fraction of loess is dominated by vermiculite and intergrades of chlorite, with smaller concentrations of chlorite and kaolinite. The clay fraction of the B horizons of McConnell till is dominated by vermiculite, chlorite and chlorite intergrades with minor amounts of kaolinite and smectite. The C horizons of the McConnell till are dominated by

01.1

smectite with smaller amounts of chlorite, chlorite intergrades and vermiculite. B horizons in penultimate till are dominated by chlorite and chlorite intergrades, with small amounts of vermiculite. The BC and C horizon of the penultimate till also have chlorite, chlorite intergrades, and vermiculite with only a small amount of smectite. Although primary chlorite occurs in the sand-size fraction, pedogenic chlorite may also be present in the clay size fraction at McConnell and penultimate sites.

Figure 2.8 (next page): X-ray diffraction patterns for the clay fractions of McConnell (Y08-31) IIBm1 and IIC horizons, and penultimate (Y08-23) IIIBm1 and IIIC horizons. Treatment designations refer to different K and Ca saturations: ethylene (EG) and glycerol (Gly) solvations, heat treatment and relative humidity. Annotations indicate examples of diagnostic peaks and major clay mineral types. d-spacings shown in nanometers.



2.5 Discussion

2.5.1 Site variability

Stable landscape positions were chosen to reduce pedon variability between sites of the same age. All McConnell soils show similar soil development. Only one profile in the penultimate group (Y08-36) shows weaker development than the others, as indicated by its thinner solum (< 50 cm). Although this pedon is located on what has been mapped as hummocky Reid moraine (Hughes 1990), it is located less than 1 km from the McConnell limit and this landform could have been misclassified. It may have formed or been modified during the McConnell advance, although there is no independent evidence to test this possibility.

2.5.2 Comparison of soils developed on McConnell and penultimate tills

All of the pedons studied which were derived from McConnell and penultimate till at high elevation on the Lewes Plateau are Brunisols. These soils share features indicative of only weak development, yet differ in age by at least 50 ka. Although the thickness of the McConnell soils is < 50 cm and that of the penultimate soils is 50-75 cm, other criteria used in past studies were not found to be reliable field indicators of soil age in this study. Clay skins were not observed, and solum colour was not markedly different between the groups. Although disintegrated coarse fragments of granite appear to be more common in soils on older deposits, their presence or absence cannot be reliably used to distinguish between surfaces of differing age because they were present in pedons of both groups. Chemical indexes such as depletion/enrichment ratios, CIA values, and extractions of secondary forms of iron and aluminum do not discriminate between soils formed on McConnell and penultimate tills. McConnell till appears to be less acidic than its penultimate counterpart, but it is unclear if this difference is the result of the duration or intensity of weathering or lithological discontinuity.

There are several possible reasons for the lack of significantly greater morphological development of the older till-derived soils on the Lewes Plateau. First, in spite of efforts to select stable landscape positions, the sites may be sufficiently geomorphically active that episodic or continuous removal of soil material occurs before pedogenic features can develop. Denudation of the solum, addition of fresh parent material, and soil production occur simultaneously in soil. Because of this, the concept of soil "age" (i.e. the time that has elapsed since a parent material has been incorporated into the soil mantle), becomes less relevant when the soil consists of particles of different ages (Almond *et al.* 2007). If the study sites were unstable, removal of particles through erosion would delay soil development.

Second, differences in site factors, such as texture, may result in different rates of soil development and lessen the differences between McConnell and penultimate soils. Important indicators of soil development, such as soil structure, aggregate formation, water-holding capacity and surface area available for weathering are impacted by soil texture. In fine-textured soils, greater surface area, higher water-holding capacity and improved aggregate stability result in more rapid soil development. McConnell soils are finer-textured and may have developed more quickly than their penultimate counterparts.

Third, climate at these high-elevation sites is not conducive to strong morphological development. Estimated MAT range from -3.3 to -3.9°C; the temperature range of the mean warmest month is 11.0-12.6°C (Wang *et al.* 2006). Estimated MAP is also low (325-365 mm). Despite the at least 50 ka difference in time available for soil development between the

McConnell and penultimate sites, climatic conditions may simply be too harsh to establish significant differences between soil development on these surfaces.

Not only are the macroscopic and chemical differences in McConnell and penultimate soil development minor, there is also little difference in the micromorphology of the two groups of soils (Appendix 5). Both display features characteristic of frost-affected soils, such as silt caps with internal sorting, fine coatings on coarse grains and rotation of coarse grains (Corte 1966; Harris and Ellis 1980; Harris 1985; van Vliet-Lanoë 1985), but in all cases these features are sparse and poorly expressed. Clay accumulation is minor; embedded grain argillans are rare in penultimate till and are most likely relicts of former grain argillans that have been destroyed by cryoturbation and subsequently redeposited in aggregates. The lack of differentiation of micromorphological features in penultimate and McConnell soils is likely due, at least in part, to the coarse texture of both groups. In cold environments, texture and drainage are the main drivers of frost dynamics in soil because they impact the retention of capillary and adsorbed water (van Vliet-Lanoë 1985). Fine-textured sediments and soils are more susceptible to frost activity and show stronger development of frost features, as observed in some loess horizons at the study sites.

Despite the similarities between McConnell and penultimate soils, the clay mineralogy of both the C and till-derived B horizons are different. Significantly, smectite is most abundant in McConnell C horizons, followed by McConnell till-derived B horizons. In contrast, smectite is only sporadically present in penultimate C horizons and is absent in penultimate till-derived B horizons (Appendix 4). Although comparative clay mineralogical data are sparse, no differences were noted between soils on Reid and McConnell surfaces in the Tintina Trench (Foscolos *et al.* 1977). The presence of smectite was considered diagnostic of older pre-Reid relict paleosols by Foscolos *et al.* (1977) and Huscroft *et al.*

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(2006). Its presence was attributed to temperate interglacial climates during the Late Tertiary or Early Pleistocene. Recent research has shown that smectite can form in cool environments within Holocene time frames (Egli *et al.* 2001), but its presence in young McConnell soils is likely due to inheritance from parent material. It is also possible that smectite is inherited from more developed soils but the lack of this clay mineral in penultimate soil suggests that this is unlikely.

The lower concentration of smectite in the B horizons compared to the C horizons of McConnell soils suggests that smectite may be unstable in the weathering environment. Because the Lewes Plateau was affected by the Cassiar lobe of the CIS and the area of previous research in the Tintina Trench was affected by the Selwyn lobe, the absence of smectite in McConnell and Reid soils from earlier studies may indicate differences in clay mineralogy of the source areas. The presence of smectite in Quaternary deposits in the Yukon should not necessarily be interpreted as an indicator of past temperate climatic conditions.

2.5.3 Comparison of soil on penultimate till and Diversion Creek soil

Soils developed on penultimate till in the study area show much weaker morphological development than Diversion Creek relict paleosols in the Tintina Trench. Except for solum depth, no field characteristics are similar between the penultimate soils of this study and the Diversion Creek relict paleosols. There are several possible reasons for the weaker morphological development.

First, as mentioned previously, the Lewes Plateau and the area of previous research in the Tintina Trench were affected by different lobes of the CIS, thus the respective tills may differ in lithology. Differences in clay concentration between penultimate soils and Diversion Creek relict paleosols as well as the presence of smectite in till derived from the Cassiar lobe but not the Selwyn lobe, suggest that lithological differences in parent material could result in variable soil development.

Second, flat, well-drained locations lacking permafrost were difficult to find for this study. At most, only a small fraction of the landscape can be considered stable over long periods of time (Almond *et al.* 2007), and even a slight slope may result in a sustained erosion of material and slowing of soil development. The Diversion Creek soils are located on low-elevation, flat outwash terraces and till surfaces that are likely more stable than the locations selected for this study, and may have acted as areas of accumulation instead of erosion. The apparent absence of two loess sequences (i.e. one for each of the penultimate and McConnell glaciations) in the penultimate pedons provides negative evidence of erosion. Due to active geomorphic processes, the penultimate sites may not truly represent soils that have been exposed to continuous weathering since the mid-Pleistocene.

Third, the decreasing rate of weathering associated with more severe climates at higher elevation may be sufficient to reduce the morphological expression of soil development. Elevation-related differences in climate in the central Yukon are complicated by winter temperature inversions that can result in little difference in mean annual air temperatures between summits and valley bottoms (Côté *et al.* 2008). However, soil formation is most rapid in the spring and summer when water is available and temperatures favour greater rates of chemical weathering. Temperatures during the warmest month are higher (15.0-15.4°C) at the low-elevation Diversion Creek sites studied by Smith *et al.* (1986) than at the high-elevation penultimate sites in this study (11.0-12.4°C) (Wang *et al.* 2006). Microclimate may also play a role through its impacts on incoming solar radiation and water infiltration, but insufficient site information is available to assess this factor.

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Fourth, the glacial chronology in the study area has not been re-evaluated since Ward *et al.* (2007) obtained an MIS 4 age for the penultimate glacial advance of the CIS in the Aishikik Lake area. The Diversion Creek relict paleosol occurs on deposits of the Selwyn lobe thought to date to MIS 6 (Westgate *et al.* 2008; Ward *et al.* 2008). Further study of this chronology is necessary to confirm the age of the penultimate event at the study sites and thus the time of formation available for penultimate till-derived soils.

Evidence of periglacial activity is more significant in Diversion Creek relict paleosols than in penultimate soils of this study. Sand wedges in Diversion Creek relict paleosols were largely formed on large, broad, flat, glaciofluvial deposits in valley bottoms. These sites may have been subject to more extreme cold events due to temperature inversions during winter, leading to thermal cracking. The glaciofluvial deposits would also have provided an abundant source of sand for filling the cracks. The penultimate soils of this study show no significant evidence of periglacial activity. A flat landscape, ideal for the formation of sand wedges, and a local source of sand required for infilling cracks, are absent. The apparent absence of significant cryogenic features at these sites may also be due to erosion of the upland landscapes.

Micromorphological differences between the soils are largely related to differences in clay content. Micromorphological features such as brown void and grain argillans, and cryogenic features such as papules and oriented fabrics are present in the Diversion Creek relict paleosols (Fox and Protz 1981; Tarnocai and Smith 1989; Tarnocai and Valentine 1989; Fox 1994). Papules are interpreted as being inherited from pre-Reid Wounded Moose relict paleosols. In the penultimate till soils of this study, only weak grain argillans were observed and there is no clear evidence of inherited features. Cryogenic features are limited

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to rotation of coarse grains and particle sorting in silt caps. These differences may be due in part to the differences in clay content of the local parent materials.

2.6 Conclusions

Soils in the glaciated region of central Yukon are more complex and diverse than previously thought. Early researchers noted major morphological differences between Diversion Creek relict paleosols formed on Reid deposits and Stewart neosols formed on McConnell deposits at low elevation in the Tintina Trench. In contrast, I found that soils formed on penultimate and McConnell tills at high elevation on the Lewes Plateau differ little in morphology and chemistry. Aside from solum depth and clay mineralogy, traditional tools for evaluating weathering, such as bulk elemental chemistry and iron and aluminum alterations, were not useful in differentiating between McConnell and penultimate soils. Soil pH was different between McConnell and penultimate till-derived soils but it is unclear whether this difference is due to weathering or inherited differences in parent material.

The contrast between the Diversion Creek relict paleosol and the comparatively poorly developed penultimate soils is likely due to differences in elevation, landscape position, and provenance of the parent materials. The more severe climate at higher elevations leads to slower pedogenesis at upland sites. Although the study sites were selected for their stability in the landscape, they were likely not as stable as the flat moraine and outwash terraces previously studied in the Tintina Trench. Textural differences between the Diversion Creek relict paleosol and the penultimate till soils in this study may be inherited from parent materials, or may be due to differences in accumulation or erosion of fine materials due to landscape position or stronger pedogenic development of secondary minerals. The lack of periglacial features may be a result of the coarse texture of the till matrix, lack of a local source of sand or erosion of upland sites.

Smectite has, in the past, been attributed to soil formation on glacial deposits that are much older than the penultimate glaciation. It was assumed to be a relic of a temperate interglacial climate preceding the Reid glaciation. The presence of smectite in McConnell deposits in this study and the decrease in smectite towards the surface suggest that the mineral is inherited from parent material. The Lewes Plateau and area of previous research in the Tintina Trench were affected, respectively, by the Cassiar and Selwyn lobes. Differences in parent material suggest that the presence of smectite cannot be used as an indicator of very old relict paleosols on surfaces affected by the Cassiar lobe. A more thorough analysis of clay mineralogy of McConnell and penultimate till-derived soils at a wider range of sites influenced by these lobes of the CIS is warranted.

The Reid advance of the Selwyn lobe likely dates to MIS 6 age (Westgate *et al.* 2001; Ward *et al.* 2008). The penultimate (Gladstone) advance from the Coast and St Elias Mountains has been dated to MIS 4 age (Ward *et al.* 2007). In contrast, the age of the penultimate advance of the Cassiar lobe is uncertain. The presence of weak morphological development in the soils characterized in this study provides circumstantial evidence that the time separating the McConnell and penultimate advances of the Cassiar lobe may be shorter than that separating the last two advances of the Selwyn lobe. Caution is required, however, because this lack of differentiation of the two soils could be a result of other factors, including elevation. Further refinement of the glacial chronology in this region is necessary to resolve this issue.

3 GENESIS OF HIGH-ELEVATION GRANITIC SOILS, CENTRAL YUKON

3.1 Introduction

The Cordilleran Ice Sheet (CIS) repeatedly covered southern and central Yukon during the Pleistocene. The Yukon sector of the CIS was nourished by glaciers flowing from the Selwyn, Pelly, Cassiar and Coast Mountains (Jackson *et al.* 1991). Bostock (1966) described four, successively less extensive advances of the CIS based on geomorphological evidence – from youngest to oldest the McConnell, Reid, Klaza and Nansen glaciations. The McConnell glaciation has been correlated with Marine Isotope Stage (MIS) 2 (Matthews *et al.* 1990; Jackson and Harington 1991); its lobes are considered to be synchronous across the central Yukon. The penultimate advance has been assigned to MIS 6 by some researchers (Westgate *et al.* 2008) and MIS 4 by others (Ward *et al.* 2007).

Few landforms produced by the Klaza and Nansen advances remain because they have been removed by weathering and erosion. Thus glacial events prior to the Reid glaciation are simply termed pre-Reid advances (Westgate *et al.* 2001). Although the extent, number and ages of pre-Reid advances are poorly constrained (Huscroft *et al.* 2004), the oldest is likely about 2.6 Ma (Froese *et al.* 2000) and there have been at least seven glacial advances in the central and southern Yukon since that time (Duk-Rodkin *et al.* 2001).

Extensive areas beyond the limit of Reid glaciation has been mapped as glaciated by pre-Reid ice (Figure 1.1; Duk-Rodkin 1999). Limited ground-checking of this limit has shown that pre-Reid ice may not be as extensive as previously thought in the Aishihik (Hughes 1990) and McQuesten (Bond and Lipovsky 2010) map sheets. Geomorphic evidence of pre-Reid events on the Lewes Plateau of central Yukon (Figure 1.1) is limited to local patches of till, scattered glaciofluvial landforms, glacial erosional landforms and

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drainage anomalies (Hughes 1990; Jackson 2000). Parts of the Yukon beyond the limit of pre-Reid glaciation have remained ice-free throughout the Pleistocene (Figure 1.2).

Beyond the penultimate glacial limit, the Lewes Plateau is underlain primarily by granitic bedrock and regolith. The most striking features beyond the Reid limit in the Carmacks (NTS 115I) and Ashihik Lake (NTS 115H) map sheets are tors bordered by grus (Bostock 1966; Hughes 1990; Jackson 2000). There are competing definitions of "tor" (Migoń 2006), but a useful definition for this study is "an exposure of rock *in situ* upstanding on all sides from the surrounding slopes and it is formed by the differential weathering of a rock bed and the removal of debris by mass movement" (Pullan 1959 *quoted in* Hughes 1990). The grus is composed of sand and gravel-size particles derived by mechanical and chemical weathering of the tors (Migoń and Lidmar-Bergstrom 2001).

Tors are readily modified or destroyed by glacial erosion (Hattestrand and Stroeven 2002), thus their presence was formerly used to indicate areas that were ice-free (Linton 1955). Subsequent research, however, documented erratics in close association with tors, showing that these features can survive glaciation (Sugden 1968; Sugden and Watts 1977). Many tors, blockfields, and felsenmeer in glaciated regions in Fennoscandinavia and Canada have been only partially modified by ice and have survived as relict features (Linton 1955; Sugden and Watts 1977; Kleman and Stroeven 1997; Hattestrand and Stroeven 2002; André 2004). The antiquity of tors has been confirmed through terrestrial cosmogenic nuclide (TCN) dating (Stroeven *et al.* 2002; Briner *et al.* 2003; Marquette *et al.* 2004; Miller *et al.* 2006; Darmody *et al.* 2008). Preservation of these features has been explained by their being covered by cold-based ice that was frozen to its bed. Within the Carmacks and Aishihik Lake map sheets, tors are restricted to pre-Reid glaciated surfaces and unglaciated areas,

suggesting that the environmental conditions and time required for tor formation may not have been present since the close of the penultimate glaciation (Hughes 1990).

Relict land surfaces have features that are inherited from past environments and are being modified by modern processes (Goodfellow 2007). Pedological features observed in deep weathering profiles can be used to interpret conditions of soil formation. Interpretation must consider, however, that climate, time or a combination of the two can be responsible for specific pedological features. In arctic and sub-arctic Canada, relict soil features have been used to infer warm temperate conditions in the Tertiary and glacial and interglacial climates of the Quaternary (Foscolos *et al.* 1977; Rutter *et al.* 1978; Smith *et al.* 1986; Tarnocai and Smith 1989; Tarnocai and Valentine 1989; Tarnocai and Schweger 1991; Duk-Rodkin *et al.* 1996; Jackson *et al.* 1999). Relict soil features indicative of climates warmer than today include rubification of horizons, development of Podzolic Bf and Luvisolic Bt horizons, and deep sola. Relict soil features indicative of periglacial environments include cryoturbated soil horizons, vesicles, and rotated sand grains.

Early soil genesis studies in the central Yukon focussed on stable low-elevation (<1000 m asl) surfaces of McConnell, Reid and pre-Reid outwash or till (Foscolos *et al.* 1977; Rutter *et al.* 1978; Tarnocai *et al.* 1985; Smith *et al.* 1986; Tarnocai and Smith 1989). Soils formed on these surface were named the Stewart neosols, Diversion Creek paleosols, and the Wounded Moose paleosols, respectively. Researchers found that weathering increased with age and the formation of soil characteristics was used to develop the following paleoclimatic model: a) an interglacial event that was warmer and more humid than today followed the last pre-Reid glaciation; b) subsequent cooling culminated in the Reid glaciation; c) the Reid-McConnell interglaciation was more temperate than today but cooler and drier than the previous interglaciation; and d) subsequent cooling culminated in the

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McConnell glaciation, which was not as cold as the Reid glaciation. This paleoclimate model is a simplification as there were many pre-Reid glaciations.

Soil evidence of warm, humid Late Tertiary and Early Pleistocene interglacial climates in unglaciated northern Yukon has been provided by Tarnocai and Valentine (1989) and Tarnocai and Schweger (1991). They documented Tertiary-age Podzols and Luvisols with significant soil development (the Burnt Hill and Bluefish River paleosols) near the community of Old Crow, suggesting formation at a time that was warmer and more humid than today. A drill core collected from a former meltwater channel at 1250 m asl in the Dawson Range contained four, Podzolic paleosols separated by colluvium that represent at least two Middle Pleistocene glacial and interglacial periods (Jackson *et al.* 1999). Modern analogues of these Podzolic soils are found much farther south, in the wettest regions of the British Columbia interior. The exact ages of the paleosols are unknown, but they likely date to the Middle Pleistocene. Whatever their age, they indicate that at least one of the pre-Reid interglacials was sufficiently warm for podzolization to occur.

Relict soil properties have been used in paleoenvironmental reconstructions in the central Yukon. Other than the study by Jackson *et al.* (1999), however, the reconstructions are based on studies at low-elevation sites. The general objective of my study is to describe and characterize bedrock-derived soils at high elevations in central Yukon beyond the Reid limit in order to better understand Middle and Early Pleistocene environmental conditions. My specific objectives are to: (1) describe weathering of bedrock-derived soils in high-elevation, pre-Reid landscapes through mineralogical, chemical and micromorphological analyses; (2) assess whether pedologic features formed under past or modern climates; and (3) propose plausible scenarios for landscape and soil evolution.

3.2 Study sites

Four study sites above 1250 m asl were selected on the Lewes Plateau (Figure 1.1) in the northeast corner of the Aishihik Lake map sheet (NTS 115H), beyond the limit of the penultimate advance of the CIS (Figure 3.1). The four sites are within the region of pre-Reid glaciation mapped by Hughes (1990). Till and erratics were not observed in the vicinity of the study sites. The dominant surface material in this upland rolling landscape is weathered bedrock-derived colluvium; bedrock outcrops, including tors, are common. The study area is located within Stikinia Terrane. The bedrock geology consists of Early Jurassic Long Lake Suite porphyritic plutonic rocks, which have intruded Triassic basalt (Tempelman-Kluit 1973; Gordey and Makepeace 2001). The porphyritic plutonic rock comprises massive to weakly foliated, fine to coarse-grained, biotite, biotite-muscovite and biotite-hornblende quartz monzonite to granite. Pegmatite and aplite phases are also abundant. Grant Abbott of the Yukon Geological Survey (personal communication 2009) confirmed that samples of bedrock collected from tors adjacent to the four study sites were Long Lake Suite, hornblende quartz monzonite and aplite. Bedrock and colluvium are locally veneered by loess, likely of McConnell age (Jackson 2000), and the eastern lobe of the White River tephra (~1150 ybp) (Clague et al. 1995).

The study sites are within the Boreal Cordilleran ecozone of the Yukon Plateau – Central ecoregion (Smith *et al.* 2004). The region lies within the zone of discontinuous permafrost (Hegginbottom *et al.* 1995) and the lower elevations of the ecoregion are characterized by a continental climate with low precipitation and cool temperatures. Modelled estimates of mean annual temperature range from -3.9 to -3.4°C; estimates of mean annual precipitation range from 343 to 367 mm (Wang *et al.* 2006).



Figure 3.1: Location of sample sites and glacial limits. IRS image provided by Government of Yukon.

Three of the four pedons (Y08-10, Y08-13 and Y08-28) are located in the subalpinealpine transition (1200 – 1370 m asl); one (Y08-24) is located above treeline in the alpine zone (> 1370 m asl) (Figure 3.1). *Picea mariana* is the only tree species at the subalpine sites, and the dominant shrubs are *Salix* spp. and *Betula glandulosa*. The groundcover includes *Vaccinium vitis idaea*, *Vaccinium uliginosum*, *Empetrum nigrum*, *Arctostaphylos* spp., *Pedicularis labradorica*, grass, and lichens, including *Cladina* spp., *Cladina rangifera*, *Cladonia* spp., *Cetraria* spp., *Cetraria icelandica*, *Flavocetraria*, *Stereocaulon* spp., and *Thamnolia vermicularis*. The groundcover at the alpine site is dominated by *Dryas integrifolia*, *Salix* spp., *Arctostaphylous rubra*, *Saxifraga* spp., grasses, and lichens (*Cladonia* spp., *Cetraria* spp., *Cetraria icelandica*, *Flavocetraria*, *Stereocaulon* spp., *Thamnolia vermicularis*, *Alectoria ochroleuca*).

3.3 Methods

3.3.1 Site selection and description

Stable sampling sites were selected to favour long-term preservation of profiles. Nearly flat surfaces (0-4°) were selected to limit the influence of erosion. Permafrost was absent in the top 100 cm of the soil and no patterned ground was absent within the study area. Horizon designations and soil descriptions were completed at each site according to the Canadian System of Soil Classification (Soil Classification Working Group 1998), the BC Field Manual for Describing Terrestrial Ecosystems (BC Ministry of Environment, Land and Parks 1998), and the taxonomic classification of humus forms (Green *et al.* 1993). Bulk samples were collected for physical and chemical characterization from each horizon. Samples were air-dried and sieved to < 2 mm.

3.3.2 Physical and chemical analyses

Analyses were conducted on the entire < 2 mm fraction unless otherwise noted. Particle-size analysis was done using the pipette technique (Gee and Bauder 1986) and sieving (Cantest Laboratories, Winnipeg, MB) following pre-treatment with hydrogen peroxide and citrate-dithionite-bicarbonate for removal of organic matter and iron respectively. For chemical analyses, duplicates were run on five percent of the samples. Soil pH was determined using both a 1:2 soil-to-water and a 1:2 soil-to-0.01 M CaCl₂ ratio (1:10 for organic samples) (Hendershot *et al.* 2008). All chemical concentrations are reported on an oven-dried basis. For total analyses, samples were digested using lithium borate fusion (ALS Laboratories, Vancouver, BC). Concentrations of major elements were determined by ICP-atomic emission spectroscopy (AES), and those of trace elements were determined by inductively coupled argon plasma (ICP)-mass spectrometry (MS). A standard reference sample (TILL-C) from the Canadian Certified Reference Materials Project (Natural Resources Canada) was included in the total elemental analysis.

The following soil chemical analyses were performed at the BC Ministry of Forests and Range analytical chemistry laboratory in Victoria, BC. Total C and N were determined using a LECO CHN-600 Elemental Analyzer; total S was determined with a LECO SC-32 Analyzer. Cation exchange capacity (CEC) and exchangeable cations were determined using the BaCl₂ method (Hendershot and Duquette 1986) and ICP-AES, respectively. Soil weathering products were analyzed by selected dissolutions using sodium pyrophosphate, acid ammonium oxalate, and citrate-dithionite-bicarbonate extractions of Fe, Al and Si (Carter 1993), with elemental concentrations in the extracts measured by ICP-AES.

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3.3.3 Weathering indices

Depletion/enrichment ratios of mobile major elements were determined using an immobile element as a reference (Taylor and Blum 1995). Ti was selected as the reference element due to its relative immobility in soils, especially weakly developed soils in temperate regions (April *et al.* 1986; Taylor and Blum 1995; Schaller *et al.* 2009). Zr was also used as a reference element, but its pattern mimicked that of Ti, thus only Ti values are presented here. The depletion/enrichment ratio is calculated as follows:

$$x_{i,j} = \frac{C_{i,j}/C_{i,p}}{T_{ij}/T_{ip}}$$
 Equation 1

where $C_{i,j}$ is the concentration of element i in horizon j, $C_{i,p}$ is the concentration of the same element in the parent material p, and Ti_j and Ti_p are the concentration of titanium in the same horizon j and the parent material p. Where the parent material was not encountered within the pedon, the lowest mineral horizon is used as a substitute. A value lower than 1 indicates a depletion of the element, whereas a value greater than 1 indicates enrichment. The ratio $Ti_i:Ti_p$ is also plotted.

Major oxide concentrations were used to calculate the Chemical Index of Alteration (CIA), a widely used weathering index for feldspar-rich parent materials (Nesbitt and Young 1982). Calcium, sodium and potassium are released as feldspar weathers, whereas aluminum is relatively immobile during weathering. The CIA is calculated using molecular proportions as follows:

$$CIA = \left(\frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O}\right) \times 100 \qquad Equation 2$$

where CaO* is corrected for Ca in phosphates and carbonates. The CIA values of fresh albite, anorthite and potassium feldspar are approximately 50; the CIA of unaltered granites ranges from 45 to 55 (Nesbitt and Young 1982); and the maximum value of 100 occurs in

aluminum oxides. I also calculated CIA values from data for two Stewart neosols (sites 4 and 6) and two Diversion Creek paleosols (sites 3 and 5) reported by Foscolos *et al.* (1977).

Extractions that separate different forms of Fe, Al and Si provide data on secondary weathering products that are diagnostic of processes of soil development. Pyrophosphate extractable Fe and Al (Fe_p, Al_p) are considered to be organically complexed forms (McKeague 1978), although Fe_p may overestimate the amount of organically complexed iron due to the presence of fine colloidal Fe oxides (Schuppli *et al.* 1983). Oxalate-extractable forms (Fe_o, Al_o, Si_o) represent the sum of short-range order (i.e. poorly crystalline or amourphous) minerals and organically complexed forms. Common short-range order phases of interest are ferrihydrite for iron and allophane and imogolite for aluminum and silicon (Borggaard 1982; Farmer *et al.* 1983; Parfitt and Wilson 1985; Parfitt and Childs 1988). Dithionite-citrate-bicarbonate extractable iron (Fe_d) represents the sum of all secondary Fe forms (Parfitt and Childs 1988). The ratio of Fe_d to total Fe provides a measure of the proportion of total iron that has been converted to secondary forms.

3.3.4 Micromorphological analysis

Intact samples were collected using Kubiëna boxes for micromorphological description of characteristic horizons in tephra (Y08-10 Bmjy; Y08-13 Bmy) loess (Y08-13 IIBm1; Y08-28 IIAey) and colluvium or residuum (Y08-10 IIIBmy1, IIIBmy3, IVBmy; Y08-13 IIIBmy1, silt cap; Y08-24 IIBmy1, IIIBC; Y08-28 IIIBmy3). Samples were ovendried at 105°C for a minimum of two days and impregnated with epoxy resin in a vacuum chamber. Thin sections (30 µm thick) were examined with a petrographic microscope. Micromorphological descriptions use the terminology of Stoops (2003). The "c/f-related distribution" refers to the distribution of individual coarse fabric units in relation to smaller fabric units and associated pores; the b-fabric refers to the orientation of birefringent material under cross-polarized light; the groundmass is a general term that refers to the coarse and fine material that forms the base material of soil in thin section (Stoops 2003).

3.3.5 Mineralogical analysis

Sand and clay fractions of a subset of soil horizons were characterized for a range of parent materials in Y08-10 and Y08-13. Sand, silt and clay fractions were separated by settling from suspension following removal of organic matter with hydrogen peroxide, and sesquioxides with a solution of citrate-bicarbonate-dithionite.

Clay fraction samples were prepared for K- and Ca-saturated treatments using the method of Theisen and Harward (1962). K-saturated samples were scanned at 0% relative humidity (RH), 54% RH, and after heating to 300°C and 550°C; Ca-saturated samples were scanned at 54% RH and solvated with ethylene glycol (EG) and glycerol (Gly). X-ray diffraction (XRD) patterns for clay minerals were obtained with Co-K α radiation (40 kV and 20 mA) over the range 2-36°2 θ . Clay minerals were identified based on their XRD patterns using standard criteria (Dixon and Weed 1989; Moore and Reynolds 1997; Arocena and Sanborn 1999).

The sand fractions were ground to ensure random orientation of grains, and the powder mount was scanned from 2-90°2θ under ambient temperature and humidity. XRD patterns were identified using Bruker EVATM diffraction software and its database of standard references. Qualitative description of sand grains and coarse fragments was completed using a petrographic microscope

3.3.6 Statistics

I used the non-parametric Mann-Whitney test to evaluate the significance of difference in CIA values between horizons of colluvium and residuum. Differences between

the two groups were determined using p-values between 0.10 and 0.05 to indicate marginal significance and p-values < 0.05 to be significant. All tests were one-tailed because the presumed direction of difference was known. The data were analyzed using Statistical Package for the Social Sciences version 16 (SPSS Inc. 2008).

3.4 Results

3.4.1 Pedon descriptions

All soil pits were excavated adjacent to granitic tors (Figure 3.2). The soils at the subalpine sites (Figure 3.3) are Eluviated Dystric Brunisols (Y08-13 and Y08-28) (Figure 3.4) and Brunisolic Dystric Turbic Cryosol (Y08-10); the soil at the alpine site is an Orthic Dystric Brunisol (Y08-24). Pedons are classified as Cryosols based on the presence of permafrost within either a) 1 m of the surface, or b) 2 m of the surface if the solum is strongly cryoturbated (Soil Classification Working Group 1998). Sites Y08-13 and Y08-28 are strongly cryoturbated but were excavated only to a maximum depth of 1.1 m. Although these soils have been designated as Brunisols, they may be Cryosols if permafrost is encountered within the top 2 m of the surface.

These pedons formed on complex parent materials: bedrock residuum that weathered *in situ*, colluvium, loess, and tephra. Residuum and colluvium were differentiated in the field on the basis of differences in texture, colour and internal structure (Appendix 1). All pedons have a thin (1-10 cm), dark brown (10YR 2/2) to black (10YR 2/1 m) hemimor humus form at the surface. This horizon has an average carbon content of 20.8% (Table 3.1) with differences in carbon content between sites likely due to incorporation of tephra. Horizon structure at all sites is non-compact matted, with either a firm (Y08-10, Y08-13) or loose (Y08-24, Y08-28) consistence. All horizons are extremely acidic (pH <4.5 in CaCl₂). Mycelia are few to common, and fecal pellets are absent to common.



Figure 3.2: Tor adjacent to sample sites Y08-10 and Y08-13.

Figure 3.3: Pre-Reid landscape at site Y08-13. Arrow indicates location of soil pit.



Figure 3.4: Eluviated Dystric Brunisol formed in weathered bedrock at site Y08-13. Knife handle is 11 cm long.



Tephra-derived horizons are <1 to 10 cm thick and have a sandy loam texture. They range from light grey (10YR 7/1 m) to pale brown (10YR 6/3 m), depending on the degree of weathering and staining by organic matter. Structure ranges from single grain to weak fine or coarse subangular blocky; the consistence ranges from friable to firm. The lower boundary of the tephra is clear to abrupt and is typically wavy or broken. Tephra horizons are extremely acidic (pH <4.5 in CaCl₂). Contemporary freeze-thaw activity in the tephra is suggested by the presence of small hummocks approximately 10 cm in diameter, by the vertical orientation of some coarse fragments at Y08-24, and by blocky structure.

Loess is up to 19 cm thick and is present near the top of the subalpine pedons. At the alpine site, loess appears to have moved downward through the profile, as evidenced by accumulations of silt within the underlying fragmented bedrock. Texture ranges from silt loam to loam, and colour ranges from dark yellowish brown (10YR 4/4 m) to dark brown (10YR 3/3 m), including brown (10YR 5/3 m). Localized, light gray (10YR 7/2 m) patches in the loess horizons are evidence of limited eluviation. Structure is typically weak fine platy to fine to very fine, weak, subangular blocky, but includes some moderate, medium, subangular blocky structure. Consistence ranges from firm to friable. The loess is very strongly acid to extremely acidic (pH <5.0 in CaCl₂). The lower boundary of loess horizons is clear to abrupt and typically wavy.

The main parent material at the study sites is colluviated weathered granitic bedrock that has moved downslope due to frost action and creep. Underlying residuum is interpreted to have formed by *in situ* disintegration. The study area has been mapped as glaciated during the Middle or Early Pleistocene, but no till, moraines, or erratics were observed at or near the study sites. **Table 3.1:** Site descriptions and selected physical and chemical data for pedons developed in colluvium and weathered bedrock beyond the penultimate glacial limit.

Sample / Horizon and depth (cm)	Parent material	Sand	Silt	Clay	Total C	Total N	Total S	pH (H ₂ O)	pH (CaCl₂)	CEC cmol ⁽⁺⁾
				9	6	-				kg ⁻¹
Y08-10 Brunisolic Dy	stric Turbic	c Cryosc	ol (129-	4 m asl	, 61°58	8'45.5"1	N, 136°	39'57.4'	'W)	
Ah (0-7)	tephra	-	-	-	15.62	0.53	0.064	4.51	3.45	7.86
Bmjy (7-17)	tephra	68.0	28.9	3.1	1.62	0.07	-	5.02	4.02	1.50
IIBm (17-22)	loess	28.6	56.9	14.5	2.05	0.11	-	5.58	4.60	2.80
IIIBmy1 (22-47)	colluvium	72.5	17.0	10.5	0.42	0.03	-	5.58	4.41	3.89
IIIBmy2 (47-62)	colluvium	68.2	20.0	11.8	0.18	0.01	-	5.68	4.43	11.74
IIIBmy3 (62-97)	colluvium	74.4	15.7	9.9	0.19	0.01	-	5.67	4.43	9.03
IVBmy (97-110+)	residuum	64.2	23.2	12.6	0.14	0.01	-	6.03	4.79	15.32
Y08-13 Eluviated Dys	stric Brunise	ol (1281	m asl,	61°58	'58.7"N	I, 136°₄	40'14.9	"W)		
Fm (6-0)	organic	-	-	-	30.56	1.04	0.093	4.64	3.77	19.57
Aey (0-3)	tephra	58.3	39.3	2.4	1.32	0.06	-	4.58	3.64	1.45
Bmy (3-8)	tephra	55.5	38.4	6.1	1.29	0.06	-	4.99	4.14	1.77
IIBmy1 (8-13)	loess	21.4	63.1	15.6	1.40	0.07	-	5.47	4.37	3.30
IIBmy2 (13-20)	loess	39.1	45.1	15.8	0.83	0.05	-	5.74	4.8 1	2.26
IIIBmy1 (20-66)	colluvium	80.1	12.4	7.5	0.24	0.02	-	5.90	4.74	2.24
IIIBmy2 (20-90)	colluvium	87.6	7.5	4.9	0.15	0.01	-	5.90	4.73	1.88
IVBmy1 (23-110+)	residuum	71.5	19.4	9.1	0.15	0.01	-	5.90	4.65	8.72
IVBmy2 (83-110+)	residuum	75.3	17.4	7.3	0.12	0.01	-	6.13	5.08	8.59
Y08-24: Orthic Dystr	ic Brunisol ((13 8 7 m	, 61°54	4'7.9"N	l, 136°4	42'13.0'	"W)			
Fm (2-0)	organic	-	-	-	19.55	0.79	0.093	5.13	4.30	24.53
Bmy (0-5)	tephra	43.3	52.9	3.8	1.80	0.09	-	5.30	4.38	2.19
IIBmy1 (5-23)	colluvium	70.8	22.4	6.8	0.97	0.06	-	5.49	4.47	1 .8 7
IIBmy2 (23-85+)	colluvium	80.1	15.6	4.4	0.28	0.02	-	5.88	4.71	1.33
IIIBCy (39-85+)	loess and	51.3	44.0	4.7	0.34	0.02	-	5.66	4.51	2.96
	bedrock									
Y08-28 Eluviated Dys	stric Brunise	ol (1300	m, 61°	°54'17.	6"N , 13	36°42'8	.0"W)			
Fmi (1-0)	organic	-	-	-	17.42	0.66	0.064	4.36	3.36	9.54
Bm1 (0-4)	tephra	77.2	1 8 .4	4.4	4.36	0.18	-	4.53	3.68	3.86
Bm2 (4-7)	tephra	72.5	23.7	3.8	2.08	0.08	-	4.97	4.03	1.60
IIAey (7-9)	loess	36.0	55.5	8.6	1.32	0.05	-	5.12	4.13	3.10
IIIBmy1 (9-20)	colluvium	46.3	42.4	11.3	1.46	0.07	-	5.45	4.53	1.17
IIIBmy3 (20-33)	colluvium	48.1	43.5	8.4	0.52	0.03	-	5.76	4.63	5.15
IIIBmy2 (33-40)	colluvium	71.2	21.1	7.7	0.29	0.02	-	5.58	4.32	11.40
IIIBmy4 (40-110+)	colluvium	81.3	12.7	6.0	0.20	0.01	-	5.71	4.39	11.19
IIIC (110+)	colluvium	75.2	19.0	5.8	0.20	0.01	-	5.87	4.63	13.41

Grus weathered from tors is the source of colluvium at all sites. The texture of the colluvial horizons ranges from sand to loam, but is dominantly sandy loam. Coarse fragments in the heavily cryoturbated pedons (Y08-10, -13, and -28) are angular and range from 25 to 80% by volume. The colour of colluvial B horizons ranges from reddish yellow (5YR 6/8 m) to olive brown (2.5Y 4/4 m), but is dominantly dark yellowish brown (10YR 3/6, 4/4 and 4/6 m), and yellowish brown (10YR 5/5, 5/6 and 5/8 m), with only single examples of each of the extreme hues. Structure is very weakly developed and includes single grain, very fine, and medium weak subangular blocky. Consistence is loose to very friable. Silt caps are common on coarse fragments and are formed by translocation of silt and fine sand. These caps are easily visible in the field and can be > 1.0 cm thick. All colluvial horizons are very strongly acidic (pH <5.0 in CaCl₂). Boundaries are clear, but are commonly broken due to cryoturbation.

All residuum is sandy loam in texture and coarse fragments range from 20 to 95% by volume. Colour ranges from reddish yellow (7.5YR 6/8 m) to olive brown (2.5Y 4/4 m), but is dominantly yellowish brown (10YR 5/8 m) and brownish yellow (10YR 6/8 m). The residuum is largely structureless and loose; it is strongly to very strongly acid (pH <5.5 in CaCl₂). Residuum horizons are heavily cryoturbated; involutions appear up into the overlying colluvial horizons (Figure 3.4). The alpine pedon (Y08-24) has weaker morphological soil development than the subalpine soils – rubification is less pronounced at this site and the soil is skeletal.

3.4.2 Chemical properties

Total carbon concentrations are very low in all mineral horizons (Table 3.1). Because carbonates are not present in these soils, total carbon can be taken as equivalent to organic carbon. Cation exchange capacity (CEC) is low in colluvium $(1.2-11.4 \text{ cmol}^{(+)} \text{kg}^{-1})$ and

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only slightly higher in residuum (8.6-15.3 cmol (+) kg⁻¹). The dominant exchangeable cation in all mineral horizons is Ca^{2+} (Appendix 2).

Figure 3.5: Depth profiles of base cation depletion and enrichment in < 2 mm fraction relative to C horizon and immobile reference element (Equation 1). Titanium is plotted as the ratio relative to the C horizon.



Depletion/enrichment ratios were calculated for the bedrock-derived horizons and plotted as a function of depth. No clear trends are evident across the sites (Figure 3.5). CIA values were calculated from major oxide data (Appendix 3) and plotted as a function of depth. Values are lowest in tephra horizons and highest in loess horizons. Trends within the weathered bedrock horizons at sites Y08-10 and -13 are similar, increasing with depth (Figure 3.6a). In contrast, values decrease slightly with depth or remain constant at sites Y08-24 and -28 (Figure 3.6b). There is no statistically significant difference between the CIA values of colluvium and residuum at the four study sites (U=5, n_1 =4, n_2 =4, p>0.10).

However, Y08-24 has lower CIA values throughout the solum, consistent with its weak morphological soil development and alpine location. A sample of granitic rock was collected from a tor adjacent to sites Y08-10 and -13, and a second sample was collected adjacent to site Y08-28. The CIA values for the two rock samples are 47.6 and 51.8, respectively. These values are lower than the CIA for weathered bedrock (residuum) in the associated pedons (Figure 3.6). CIA values were calculated from Foscolos *et al.* (1977) for pre-Reid Wounded Moose paleosols (Sites 1 and 2) to compare to pre-Reid soils in this study. Values for Site 1 are comparable to those obtained in this study, while values calculated Site 2 are higher (Figure 3.6), indicating a greater degree of weathering.

Sodium pyrophosphate and oxalate extractable Fe, Al and Si are low in all pedons, with maximum values in loess (Figure 3.7; Appendix 2). Values range from 0.03 to 0.47% for Fe_p, 0.09 to 1.12% for Fe_o, 0.03 to 1.71% for Al_p, 0.07 to 0.98% for Al_o and 0.02 to 0.34% for Si_o. Concentrations of Al_o and Si_o are so low that no calculation was made for allophanic materials. Dithionite-extractable Fe ranges from 0.12 to 2.12%, and is higher at sites Y08-10 and Y08-13 than at sites Y08-24 and Y08-28. Secondary iron is mostly crystalline in form at the first two sites, comprising 80 to 91% of all secondary Fe in the colluvium and 90-92% of all secondary Fe in the residuum. At Y08-23 and Y08-28, only 20-51% of the secondary Fe in the colluvium and 33-69% of the secondary Fe in the residuum is crystalline in form. In spite of peaks of Fe_d at Y08-10 and Y08-13, most iron remains in primary form, with less than 50% pedogenic iron in most horizons at these sites. Secondary iron is especially low at Y08-24 and Y08-28 (< 35% in all horizons).

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Figure 3.6: Depth profiles of CIA values in < 2mm fraction for (a) Y08-10, Y08-13 and bedrock in adjacent tor and (b) Y08-24, Y08-28 and bedrock in adjacent tor. Data for Wounded Moose (WM) sites 1 and 2 are from Foscolos *et al.* (1977).





Figure 3.7: Depth profiles of Fe_p and Al_p (pyrophosphate), Fe_0 , Al_0 and Fe_0 (oxalate), Fe_d (dithionite) and Fe_t (total).

3.4.3 Soil micromorphology

In thin section, colluvial and residual horizons exhibit microfabrics where coarse fragments are dominant (Figure 3.8a) and where fine particles are dominant and arranged as aggregates or thick coatings (Figure 3.8d). Coarse fragments are loosely packed (Figure 3.8a), with thin argillans (Figure 3.8h) that are generally approximately 5 μ m thick, but are observed up to 50 μ m. The thickness of caps is limited by the size of the coarse fragments on which they have formed (0.5 mm to 2 cm). Caps thicker than 1 cm were commonly observed in the field, and some were as thick as 2 cm. The caps are a mixture of clay, silt, and sand, probably with sesquioxides, as indicated by reddish-brown colouration (Figure 3.8b).

The c/f-related distribution ranges from chito-gefuric (larger fabric units with some fine units occurring as covers or links) (Figure 3.8a) and enaulic (smaller units form aggregates) in the main groundmass of the thin section to enaulic and porphyric (larger units occur in matrix of finer units) in aggregates and coatings. Microstructure is dominantly pellicular (most coarse grains coated by fine material) (Figure 3.8e), but is granular in those parts of thin sections dominated by small aggregates. B-fabric is dominantly crystallitic (primary grains) and granostriated (oriented clay along surfaces of coarse fragments). Embedded grain argillans occur within some small aggregates, but no void argillans or papules were observed. Simple and complex packing voids are dominant except in fine-grained illuvial material at the highest site (Y08-24) where vesicles have formed (Figure 3.8g). Bridges between coarse fragments are uncommon (Figure 3.8c). Thick caps are common on the upper surface of coarse grains, but also occur in other orientations. Some of these caps are inversely graded from coarse at the top to fine at the bottom (Figure 3.8b). Rotated grains are common and have likely formed from repeated illuvial deposition on coarse fragments followed by rotation due to frost heave.

Primary grains are angular (Figure 3.8a, e), suggesting they have been weathered in place or transported only a short distance (Stoops 2003). The faces of quartz grains are largely unaltered except for some minor pitting (Figure 3.8f) and fracturing, but alteration products of other primary minerals are common. Feldspar grains are highly weathered and seriticized. Biotite is strongly weathered, with formation of secondary minerals including chlorite (Appendix 5). Fissures, cleavage planes and fractures in primary minerals are commonly filled with reddish-brown oxides and oriented clay material (Figure 3.8f).

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Figure 3.8 (next page): (A) Micromorphology of colluvium collected at ~ 20 cm (IIIBmy1; Y08-10B) showing dominance of coarse fragments and silt caps on large grains. (B) An enlarged view of a silt cap, showing fines at the boundary with the coarse fragment gradually coarsening to sand at the periphery (Y08-10B). (C) Oxide and mineral bridges in the colluvial horizon (Y08-10B). (D) Upward involution of colluvium enriched with fine material at 55 cm (IIIBmy3; Y08-10D). (E) Residuum at ~95 cm (IVBmy; Y08-10D), showing pellicular microstructure with angular coarse fragments. (F) Quartz grain with minor pitting (XPL) and a coating of brown oxides (Y08-10D). (G) Vesicles in silt caps (XPL) at ~65 cm in alpine site (IIIBCy; Y08-24A). (H) Thin granostriated cutans at ~40 cm within an aggregate (XPL) (IIIBmy; Y08-28B).



3.4.4 Soil mineralogy

The sand-size fraction of the tephra is composed of glass, plagioclase, hornblende, pyroxene and magnetite. No identifiable XRD peaks were observed in the clay-size fraction. The sand-size fraction of the loess is dominated by quartz, plagioclase, chlorite and chlorite intergrades, with some alkali feldspar, pyroxene, biotite and amphibole. The clay fraction of the loess is dominated by chlorite and chlorite intergrades, with mica, vermiculite, and minor quartz and feldspar (Table 3.2).

Table 3.2: Summary of results of semiquantitative X-ray diffraction of the 2- μ m fraction of selected samples. **XXX** = dominant component, XX = common component, x = minor component. Mixed layers include chloritic intergrades (a) and other mixed layer (b).

	Pri	nary mine	erals	cals Clay minerals							
Horizon	Quartz	Feldspar	Mica	Chlorite	Vermiculite	Smectite	Kaolinite	Mixed layer			
Loess	x	х	XX	XXX	XX-x	-	-	XXX(a)			
Silt cap	x	х	X	Х	XX	XX	XXX	XX (a/b)			
Colluvium	x	_	x	XX	XXX	-	XXX	XX(a)			
Residuum	_	-	x	-	XXX-XX	XXX-XX	XXX-XX	XX(b)			

The mineralogy of the sand-size fraction of colluvium is dominated by quartz, plagioclase feldspar, chlorite, chlorite intergrades, biotite, hornblende and minor pyroxene and zircon. The clay fraction is made up mainly of vermiculite, with lesser amounts of chlorite and chlorite intergrades, and trace amounts of primary mica and quartz (Figure 3.9; Appendix 4). Kaolinite is likely an important mineral, but its presence is difficult to confirm due to the presence of chlorite. Where both kaolinite and chlorite are present, a doublet peak in the XRD pattern at the second-order kaolinite and fourth-order chlorite (0.358 and 0.355 nm, respectively) indicates that both minerals are present. There is no doublet in the XRD patterns of colluvium, but both minerals are thought to be present due to a small first-order
peak for chlorite (1.4 nm) and large peaks at 0.714 nm and 0.358 nm. Large amounts of kaolinite may be masking weak second- and fourth-order chlorite peaks.

The mineralogy of the sand-size fraction of residuum is similar to that of colluvium. The clay fraction of the residuum contains vermiculite, smectite and kaolinite, as well as a mixed-layer phyllosilicate and minor mica (Figure 3.9; Appendix 4). The mixed-layer phyllosilicate is not a chlorite intergrade because the K-saturated samples lack a broad diffraction peak between 1.40 and 1.02 nm. A mixed-layer kaolinite-montmorillonite clay is found in soils near Dawson City (Kodama *et al.* 1976; Foscolos *et al.* 1977), but none of the samples of the residuum has its characteristic broad peak between 0.7 and 0.8 nm. It is likely a smectite-mica intergrade due to its broad peak around 2.5 nm and weak peak at 1.2 nm (Allen *et al.* 2001).

Kaolinite dominates the clay fraction separated from a silt cap at 90 cm at site Y08-13. Smectite, vermiculite and small amounts of chlorite, mixed-layer phyllosilicates, primary mica, feldspar and quartz are also present. No doublet was observed in the second-order peak of kaolinite and fourth-order peak of chlorite, but the values are closer to kaolinite.

Figure 3.9 (next page): X-ray diffraction patterns for clay fractions at sites Y08-10 and Y08-13. Treatment designations refer to different K and Ca saturations, ethylene glycol (EG) and glycerol (Gly) solvations, heat treatments and relative humidity. D-spacing is in nanometers.



3.5 Discussion

3.5.1 Evidence of periglacial activity

Many of the features in the soils of this study are a result of frost processes; some are relict and others are contemporary. Development of frost features depends largely on soil temperature, soil texture and water availability. It is favoured in fine-textured horizons within the active layer, which are affected by repeated freeze and thaw, and in areas of poor drainage (van Vliet-Lanoë 1998). Frost features form when ice segregates in the soil (Harris 1985; van Vliet-Lanoë 1985). As the soil freezes, water migrates toward the freezing plane from unfrozen soil below, forming ice lenses and dehydrating the area below the freezing plane (Harris 1985).

The most impressive evidence of periglacial activity in the subalpine soils is extensive cryoturbation of bedrock-derived horizons (colluvium and residuum). Sites were chosen where permafrost is deep or absent, but the weathered bedrock is severely cryoturbated. Some mixing of tephra and loess has occurred, but neither has been incorporated into the underlying weathered bedrock. The lower boundaries of these two deposits in the subalpine soils are approximately horizontal, supporting the interpretation that the cryoturbation is relict. Preservation of relict cryoturbation features and subsequent overlay of horizontal horizons have been observed in other subarctic soils in the Yukon (Tarnocai and Valentine 1989). The relict cryoturbation could have occurred due to exposure to periglacial environments during glacial periods with subsequent horizontal deposition of parent material under non-permafrost conditions.

The absence of patterned ground in the study area provides additional, albeit negative, evidence that the cryoturbation of the subalpine soils is likely a relict feature. Additionally, modern soils with active cryoturbation typically have organic matter incorporated deep into

the solum (Tarnocai *et al.* 1993; Ping *et al.* 2008). The absence of organic matter in the cryoturbated horizons indicate that either none has been incorporated or that it has decomposed following changes to the permafrost table. If organic matter had been present, a lowering of the permafrost table would improve soil aeration and it is foreseeable that organic matter would rapidly decompose.

Micromorphological evidence of frost activity is not as dramatic. Frost features are best developed in fine-textured soils, thus the coarse colluvial and residual horizons may simply be poor recorders of frost activity. Definitive evidence of frost activity in these horizons is limited to rotated coarse grains. Vesicles that have likely formed from frost activity (Harris 1985) occur in fine caps on cobbles and boulders at the alpine site (Y08-24). Inverse grading in caps and weak granular and platy microstructure is observed in fine caps and aggregates at the subalpine sites. Such features (Locke 1986), and granular (Pawluk 1988) and platy (Harris 1985) structure have been described in frost-affected soils. However, these features can form by other processes and thus are not diagnostic of frost action.

Micromorphological evidence of frost activity in weathered bedrock horizons is subtle, and it was not possible to determine with certainty whether it is relict or modern. Furthermore, features developed in tephra and loess suggest that some frost activity affects at least the upper part of the solum. Contemporary climate is suitable for frost activity but evidence does not suggest it occurs to great depth.

3.5.2 Soil weathering and evidence of paleo-pedogenesis

Most of the data obtained in this study suggest that there is limited weathering and soil development at all sites. The alpine soil (site Y08-24) shows the least amount of soil development based on horizonation, rubification, and chemical analyses and has likely experienced a different genetic pathway than the soils at the other sites. Although thick sola have developed at the subalpine sites (Y08-10, Y08-13, Y08-28), there is little rubification. No clay skins are sufficiently thick to be visible in the field, and only thin grain argillans were found in thin section. Depletion/enrichment ratios for base cations show no depthrelated trends, and CIA values indicate only moderate weathering of primary minerals. Although CIA values in all weathered bedrock horizons are higher than those in local bedrock outcrops, there is no significant difference between CIA values of colluvium and residuum horizons. Iron and aluminum extractions indicate that production of secondary weathering products of these two elements is limited in all pedons, but particularly at Y08-28. The lack of chemical change with depth is likely due to intense cryoturbation of colluvium and residuum.

The results contrast with those obtained by previous researchers on Early to Middle Pleistocene paleosols in the Yukon. Low-elevation (< 1000 m asl) Wounded Moose soils developed on pre-Reid till and outwash are Luvisols with rubified B horizons, common thick clay skins, well developed papules and argillans, and significant chemical alteration (Smith *et al.* 1986; Tarnocai and Smith 1989). The stronger soil development is likely related to the stability of the flat low-elevation sites and higher summer temperature related to the lower elevations of the sites. Both the Wounded Moose paleosols and the soils of this study, however, show evidence of relict periglacial conditions in the development of sand wedges and cryoturbation.

The only other high-elevation soils (1250 m asl) reported in the Yukon that are possibly of the same age formed in colluvium near Pony Creek (Jackson *et al.* 1999). These buried, well-developed Podzolic paleosols, however, lack evidence of periglacial activity. Although they are situated in a similarly exposed, high-elevation landscape, the paleosols were buried intact by colluvium and did not experience subsequent periglacial activity or erosion. If the study area was ice-covered in the Early Pleistocene, the lack of till at the pre-Reid sites in this study indicates that soil material has moved off site and that significant erosion of soil may have occurred over long periods of time. Only one loessal deposit, likely of McConnell age, is present. Loess is typically associated with glaciation and if erosion was minimal we might expect several loess deposits representative of the penultimate and pre-Reid glaciations to be present at my sites. Its absence provides some indication of the possibility of profile truncation through wind erosion. The lack of soil development at my study sites may be an indication of the mobility of material and not an absence of a favourable soil-forming environment.

Although field observations and chemical analyses indicate that little soil development has occurred in pedons at the study sites, evidence of alteration of primary minerals viewed in thin section and formation of secondary clay minerals of the colluvium and residuum horizons suggests there has been some chemical weathering. Kaolinite, a common weathering product of granite (Tardy *et al.* 1973), and vermiculite, a common alteration product of plagioclase and mica, are found in the weathered bedrock horizons. The presence of smectite in the residuum but not in the colluvium, and the presence of chlorite and its intergrades in the colluvium but not in the residuum, suggest a complex history of weathering.

Other researchers (Foscolos *et al.* 1977; Huscroft *et al.* 2006) have suggested that the presence of smectites in Pleistocene soils in the Yukon indicate weathering under temperate conditions during interglaciations prior to the penultimate glaciation. Smectites in the residuum in this study likewise may be a relict feature from warmer interglaciations, having formed *in situ* or translocated from higher in the profile. For example, translocation of fine particles from early loess deposits into the lower pedon may have introduced inherited fine

particles that were highly weathered. Early loess deposits and residuum have likely been truncated due to erosion, and the existing pedon may be a remnant of a former thicker pedon. The overlying colluvium originated largely from grus produced by weathering of adjacent tors and moved downslope to form a veneer over the residuum. The clay mineral assemblage of the colluvium differs from that of the residuum and appears to be indicative of less weathered primary mineral material. However, the colluvium is probably a combination of fresh grus and recycled residuum from farther upslope, thus we would expect to find inherited smectite within it.

An alternative hypothesis for the occurrence of smectites in the residuum is that drainage in the residuum was more restricted in the past. Smectites may form from many minerals, including other 2:1 phyllosilicates such as mica, chlorite and vermiculite (Jackson 1965; Arocena and Sanborn 1999; Birkeland 1999; Bonifacio *et al.* 2009). They require soil conditions in which bases are readily available, such as in poorly drained soils (Schaetzl and Anderson 2005). The pedons are generally well to moderately-well drained today, but a shallower permafrost table during glaciations may have caused poor drainage conditions, allowing weathering products to accumulate in the active layer. Although smectite formation has typically been ascribed to warm environments, it has been reported to form in perennially frozen soils (Vogt and Larque 1998). A study of smectites in Holocene deposits in the Swiss Alps suggests that extended warm periods may not be necessary for the production of this mineral (Egli *et al.* 2003).

Chlorite and chloritic intergrades are common early weathering products in the western Cordillera of Canada (Kodama 1979). At my sites, they occur in the clay fraction of the colluvium, but not the residuum. Advanced podzolization can lead to a decrease in chlorite in soil horizons and a concomitant increase in expandable clay minerals (Kodama

1979). The absence of chlorite and chlorite intergrades in the residuum may be due to their complete alteration to expanding clays. However, chlorite and its intergrades are present in the sand-size fraction of the residuum, thus one might expect that weathering and comminution should add these minerals to the clay fraction of the same horizon. However, if the clay assemblage and weathering observed in residuum are indeed relict, the horizons may be relatively inactive today and weathering of sand-size chlorites may be exceedingly slow, or even not occurring, under modern conditions.

3.5.3 Landscape and soil evolution

Chemical analyses, clay mineralogy, and the presence of periglacial features indicate that the subalpine soils investigated in this study have a complex pedogenic history. The soils have been impacted through many Quaternary glacial-interglacial cycles by: 1) periods of significant weathering; 2) cryoturbation and other periglacial activity; 3) solum truncation through erosion; and 4) rejuvenation through colluvial and eolian inputs.

While the lack of glacial landforms and deposits such as erratics do not show conclusively that the study area was ice free in the Early Pleistocene, it is possible that the penultimate glaciation represents the maximum extent of ice locally. Here, I suggest three plausible scenarios for soil formation preceding the penultimate glaciation that can account for the observed soil properties (Figure 3.10). In Scenario A, I assume that the area was icefree during the most recent pre-Reid glaciation; in scenario B, I assume the area was covered by cold-based ice; and in scenario C, I assume the area was covered by warm-based ice.

In scenario A, a weathering mantle of granitic bedrock forms during a pre-Reid interglaciation (stage A1). The area remains ice-free during the most recent pre-Reid glaciation but is affected by periglacial processes (stage A2). During deglaciation, some

surface erosion would have occurred (stage A3). Soils continued to develop during the following interglaciation, producing deep sola and secondary clay (stage A4).

In scenario B, a weathering mantle of granitic bedrock forms during a pre-Reid interglaciation (stage B1). Cold-based ice covered the study area during the most recent pre-Reid glaciation of unknown age (stage B2), accompanied by limited erosion and deposition of till. Tors, residuum, and soils were preserved beneath the cold-based ice (stage B3). During deglaciation, some surface erosion would have occurred. Soils continued to develop during the following interglaciation, producing deep sola and secondary clay (stage B4). This interglaciation was either long or more temperate than most. Colluvium slowly moved downslope and the soil mantle was slowly eroded during this period.

In scenario C, warm-based ice overrode the study area during a pre-Reid glaciation of unknown age (stage C1), eroding underlying sola and depositing till (stage C2). The till was removed by erosion and its weathering products redistributed downslope during deglaciation and the following interglaciation (stage C3). Granitic bedrock was weathered, producing tor outcrops and soil (stage C4).

In all scenarios, the study sites were near the margin of the CIS during the penultimate glaciation and would have experienced periglacial conditions that cryoturbated the soils (stage 5). During deglaciation of the penultimate event and the interglaciation that followed, soils continued to developed, tempered, however, by concomitant erosion of the soil mantle with additions of colluvium from upslope landscape positions (stage 6). Periglacial conditions would have returned during the McConnell glaciation, although cryoturbation seems to have been limited during this event (stage 7). During the Holocene, loess and tephra have been deposited, but not incorporated into underlying weathered bedrock, suggesting that severe cryoturbation no longer occurs at the study sites (stage 8).



discussion in text for details. Figure 3.10: Schematic diagram showing landscape evolution scenarios A, B and C. See

The absence of till suggests that these sites were either unglaciated, were covered by cold-based ice which deposited little till during the last pre-Reid glaciation, or have been sufficiently geomorphically active in the past to erode all evidence of till. In Scenario A and B, the tors formed prior to glaciation, whereas scenario C supposes that they formed following the most recent pre-Reid glaciation. The last scenario requires a lengthy period of time between the last pre-Reid CIS and the penultimate event to form the tors. The presence of loess near the surface suggests that the sites are reasonably stable for thousands or tens of thousands of years during interglaciations and that interglacial environments may have been insufficiently geomorphically active for widespread erosion of till. In addition, if the penultimate CIS dates to MIS 6, as apparently is the case in the Klondike Plateau, and the youngest pre-Reid event dates to MIS 8, insufficient time is available for scenario B to be correct. The lack of erratics, the apparent contemporary stability of the sites, and the likely timeline suggest that scenario C is not likely.

The study area in located in the Aishihik map sheet and has been contradictorily mapped as covered by pre-Reid ice (Duk-Rodkin 1999) and beyond the maximum extent of ice locally (Hughes 1990). In addition, the pre-Reid and penultimate glaciations on the Lewes Plateau have not been dated, thus the duration of time for tor formation and soil development is unknown. It is not possible to further test these scenarios or propose other pathways for landscape evolution without age control. A possible way of resolving these questions would be to date the tors using terrestrial cosmogenic nuclide exposure (TCN) techniques. Such ages would show whether these are surfaces have survived a pre-Reid interglacial period or formed more recently. TCN dating has been used to derive exposure ages, determine erosion histories and elucidate glacial chronologies elsewhere in North America (Briner *et al.* 2003; Marquette *et al.* 2004; Miller *et al.* 2006; Ward *et al.* 2007;

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Schaller et al. 2009), in Fennoscandinavia (Darmody et al. 2008; Stroeven et al. 2002; Stroeven et al. 2006), and in Norway (Paasche et al. 2006).

3.6 Conclusion

This study assessed soil weathering and development at four upland sites beyond the penultimate glacial limit on the Lewes Plateau. Parts of the Lewes Plateau were glaciated at least once, and probably many times, before the penultimate glaciation. However, no till or erratics were found in the vicinity of the study sites; if such deposits did exist, they were destroyed by erosion prior to the penultimate glaciation or the area was not ice-covered.

The primary parent material at the four study sites is weathered granitic bedrock, but loess and tephra are also present. The polygenetic soils developed on these materials have complex weathering histories that include episodic soil formation, removal, and rejuvenation through addition of colluvium and loess. Some properties, such as mild chemical alteration, mild rubification, and limited clay enrichment, are characteristic of youthful soils. Other properties, such as deep sola, presence of smectite clay in the deepest horizons, and cryoturbation, require longer periods of soil formation or possibly a climate different from that of today. The balance between soil formation and soil erosion has resulted in a mix of relict and youthful features. Although some frost activity is likely in the modern environment, features indicative of severe cryoturbation in these pedons are relict, having been produced under periglacial conditions during one or more pre-McConnell glaciations.

The polygenetic origin of these soils and periodic removal of material make interpretation of their features challenging. Three scenarios are presented for the formation of the soils in the case of ice-cover. In the first scenario, the study area was not glaciated during the most recent pre-Reid glaciation and the landscape represents long-term weathering since at least the mid-Pleistocene. In the second scenario, the landscape and its weathering mantle

were preserved beneath cold-based ice during the most recent pre-Reid glaciation, and soil development continued following deglaciation. In the third scenario, erosive warm-based ice covered the study area during the last pre-Reid glaciation and deposited till. This scenario demands a much longer, subsequent interglacial period to remove all evidence of till and erratics and to subsequently form tors. The soil developed during this interglaciation was later cryoturbated during the penultimate glaciation. The absence of till and erratic as well as the likely duration of weathering suggest the first two scenarios are more likely than the last. Elucidation of these or other potential landscape evolutionary pathways is not possible without age control for pre-Reid and penultimate glacial advances on the Lewes Plateau.

4 SYNTHESIS AND APPLICATION OF RESEARCH

This study is the first to describe and interpret high-elevation soils developed in granitic bedrock and colluvium and in tills deposited by the two most recent advances of the Cordilleran Ice Sheet (CIS) in central Yukon. A range of pedological methods was utilized in this study to describe the soils and infer their genesis. This chapter considers the utility of these methods and their potential application for pedological research elsewhere in the region. Previous studies of soil genesis in the central Yukon have focussed on either different parent materials or different landscape positions. This chapter also discusses how the results of this study can help elucidate regional glacial history and landscape evolution.

4.1 Usefulness of selected pedological analyses

This study has shown that field criteria alone cannot discriminate soils formed on McConnell and penultimate-age glacial deposits at high elevation on the Yukon Plateau. Although these deposits differ in age by at least 50 ka, soil development and morphological expression are similar. The only useful field indicator found in this study is solum depth, which is <50 cm for McConnell soils and 50-75 cm for penultimate glacial soils. Sites for this study were selected from the most stable positions in the landscape, thus this difference in depth may not exist in other, more geomorphically active parts of the landscape. The inability of field criteria to discriminate soils of different ages may be due to the periglacial activity, slow weathering at high elevations, and the coarse texture of the parent material. The lithology and degree of weathering of coarse fragments may be useful metrics for differentiating McConnell and penultimate soils, however detailed observations required for quantitative comparison were not collected in this study. Collection of data of this type is recommended for future study of till deposits at high elevation.

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Evidence of major relict frost activity was found on weathered bedrock surfaces glaciated prior to the Reid glaciation. Permafrost in the study area today is discontinuous. I selected sample sites that had no permafrost within the upper metre of the pedon. The presence of severe cryoturbation in the sola at these study sites, coupled with the lack of patterned ground in the vicinity of the excavations and horizontal orientation of modern deposits of loess and tephra, indicate that the cryoturbation is relict and related to a past glacial climate. Observations on the distribution of permafrost, patterned ground and other periglacial features are helpful for establishing whether pedon-scale cryoturbation is a relict or contemporary feature. These observations in turn provide useful insight into the periglacial environment to which these soils were exposed.

Chemical and physical analyses of samples can be expensive and time-consuming, thus researchers must make choices about the analyses that will be done. In general, laboratory analyses performed in this study did not reveal many differences in weathering between soils of different age. Identification and quantification of secondary weathering products of iron and aluminum did not yield any major trends or reveal significant alteration in any of the soils. Pyrophosphate extraction is an important tool for identifying modern Podzolic B horizons, but dithionite and oxalate extractions are not likely to yield much useful information in weakly weathered soils. Although the depletion/enrichment ratios showed no significant trends, major and trace element analyses were useful for calculating the Chemical Index of Alteration (CIA). The values can be compared to those of unaltered local bedrock and show depth-related changes in non-cryoturbated pedons. Thus pyrophosphate extraction and major and trace element analyses are recommended for use in future studies.

The clay mineralogical data show that our understanding of the mineralogical composition of Yukon soils and parent materials is incomplete. Past studies of clay minerals

in central Yukon paleosols are based on a limited number of samples, and interpretation of clay assemblages relied heavily on paleoenvironmental explanations. Prior to this study, smectite had only been identified in soils on pre-Reid moraine or outwash deposits; its presence was attributed to a warm, humid climate during an early pre-Reid interglaciation. In this study, however, smectite was found in soils and unweathered till of McConnell age, suggesting that parent material has a strong influence on soil clay mineral assemblages. At weathered bedrock sites, the presence of smectite in residuum but not colluvium, and the presence of chlorite and its intergrades in colluvium but not residuum suggest that mineralogy may be used to identify horizons that have experienced different weathering histories. Determination of clay mineralogy in future pedological studies on a variety of landscapes and parent materials in central Yukon would provide much-needed insight into the complex patterns of inheritance, formation and distribution of clay minerals. Other techniques for clay mineralogical analyses, such as scanning electron microscopy, may be useful techniques but were not used in this study.

Micromorphology was used in this study to identify periglacial features that were not evident in the field and to locate and identify clay-size particles. A diverse range of soil microenvironments was observed in thin section. The heterogeneity of mineral assemblages observed in this study may be due in part to the diversity of soil microenvironments. Analysis of thin sections in conjunction with X-ray diffraction may help determine which clay minerals have been inherited from parent material and which have formed *in situ* by weathering.

4.2 Regional glacial history

Since Bostock (1966) first proposed a chronology of glacial advances, our understanding of the behaviour and chronology of the CIS has changed dramatically. Early

researchers assumed that glacial advances in central Yukon were synchronous, but it now appears that the deposits of the penultimate glaciation differ in age, from MIS 4 to MIS 6. Additionally, differences in parent material imposed by the multiple sources of the CIS suggest that differences in weathering across the central Yukon may not solely be a result of paleoenvironmental conditions.

Morphological and chemical differences in soils formed on McConnell and penultimate tills at high elevation in central Yukon are minor. In contrast, previous studies showed significant differences in soil development on glacial deposits of McConnell and Reid age at low elevation sites. The early pedological studies were conducted in the Tintina Trench, which was glaciated by the Selwyn lobe of the CIS. The penultimate glaciation in that area has been reliably assigned to MIS 6. My study was done on the Lewes Plateau, which was glaciated by the Cassiar lobe of the CIS and where the age of the penultimate advance remains uncertain. Differences in clay mineralogy suggest that the tills deposited by the two lobes, and thus soil parent materials, are different. Further differentiation of lithology, and mineralogy of the Cassiar and Selwyn lobes would require more detailed study. Because the age of the penultimate advance of the Cassiar lobe is not known with certainty, the contribution of time to soil formation in this region is not known. To better understand the contribution of pedogenic time to these soils, it is imperative to correctly ascertain the age of the penultimate advance of the Cassiar lobe, possibly through terrestrial cosmogenic nuclide (TCN) dating.

The lack of morphological development in high-elevation pedons in this study may be due to factors other than age. Weathering at high elevations is less intense than at lowelevation sites due to cooler summer temperatures. Exposed high-elevation sites may also be

more geomorphically active than low-elevation sites, resulting in greater loss of soil products through erosion.

Study of soils developed in weathered bedrock beyond the limit of the penultimate glaciation yielded little insight into pre-Reid CIS behaviour. These soils were severely cryoturbated during the penultimate and McConnell glaciations. These soils, however, show contradictory evidence of limited (modest chemical alteration and rubification) and extensive (deep sola, distinct clay mineralogy) weathering.

The balance between soil production and soil removal in central Yukon is unknown, but it depends in part on past ice-sheet behaviour. Three hypothetical scenarios have been proposed to explain soil development and landscape evolution on the Yukon Plateau. The first two assume that the study area was overridden by ice during the latest pre-Reid advance but differ in the timing of the glaciation and the basal thermal regime of the CIS. In the first hyposthesis, the plateau was covered by cold-based ice, thus preserving deep weathering profiles and tors. In the second scenario, warm-based ice eroded soils and tors, and that today's solum formed over a long period of time following erosion of till. Alternatively, the third scenario suggests that the study area remained ice-free during the most recent pre-Reid glaciation and the landscape is a function of long-term weathering throughout the Pleistocene. No erratics were observed in the area directly surrounding sampling locations in the pre-Reid landscape. If the area was glaciated, the lack of erratic would more closely support the scenario of cold-based ice. However, without age control on the pre-Reid advance in this region, we cannot discern whether the warm-based ice scenario is impossible, although it is less likely.

4.3 Future research directions

Pedological and paleoclimatic interpretations in the study area depend considerably on the ages of the surfaces on which the soils formed. McConnell glacial deposits have been dated with certainty to MIS 2, but penultimate deposits may be MIS 4 or MIS 6, and the ages of pre-Reid events on Lewes Plateau are unknown. The age of the penultimate glaciation must be established to determine whether the lack of morphological differences between soils in deposits of the two most recent advances of the CIS are related to a short duration of weathering or other soil-forming factors. Determining the exposure ages of local tors at pre-Reid sites through terrestrial cosmogenic nuclide (TCN) dating will help determine whether the tors are relict features that survived cover by non-erosive cold-based ice or whether they formed during a particularly long interglaciation following the youngest pre-Reid advance. TCN dating of horizons within individual pedons may provide information on erosion rates, which could help determine the balance between soil genesis and soil erosion. Additional age control may be provided through tephrochronology or other dating techniques.

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Appendix 1: Site and pedon descriptions

Site No: **Y08-18**

Soil Classification: Orthic Dystric Brunisol

Site Description

Location: McConnell moraine

Latitude:	62°00'33.2"	Longitude:	136°34'39.1"	Elevation:	1035 m
Aspect:	SE	Slope:	3°	Slope Position:	Low ridge top

Parent Material:

Thin veneer of White River Tephra (I) draped over thin veneer of eolian material (II), described as loess. These in turn overlie McConnell age till (III).

Vegetation:

Open Boreal forest. Picea mariana with groundcover including Betula pumila var. Glandulifera, Vaccinium uliginosum, Lupinus arcticus, Empetrum nigrum, Oxycoccus spp., grass, moss and lichens (Cladina spp., Cladonia spp., Cetraria spp., Cetraria icelandica, Flavocetraria, Peltigera spp., Stereocaulon spp.)

Comments:

The site is located on a McConnell moraine on a low ridge adjacent to a wetland. Permafrost is common throughout the surrounding landscape. Silt caps are common on clasts throughout the profile and organic staining is also observed on the underside of some clasts.

Thin Sections:

Sample ID	Horizon	Depth (cm)	Notes
Y08-18-A	Bm / IIBm	10-17	Tephra / loess boundary.
Y08-18-B	IIIBm	27-33	Weathered till horizon.
Y08-18-C	IIIBC	64-70	
Y08-18-D	Fm / Ah	7-0	

Horizon Sample #	Depth (cm)	Description
Fm Y08-18-01	3-0	organic; very dark brown (7.5YR 2.5/2 m); weak non-compact matted; friable; common mycelia; few fecal pellets; plentiful fine and medium roots; clear smooth boundary; 2-4 cm thick; extremely acid
Ah Y08-18-02	0-4	organic; very dark grayish brown (10YR 3/2 m), and grayish brown (10YR 5/2 m); moderate non-compact matted; friable; common mycelia; plentiful fine roots; clear wavy boundary; 4-10 cm thick; extremely acid; classified as a mineral horizon (<17% C), description is based on field classification as organic.
Bm Y08-18-03	4-14	tephra; light gray (10YR 7/2 m), and brown (10YR 5/3 m); sandy loam; fine to medium weak subangular blocky; very friable; plentiful very fine roots; abrupt wavy boundary; 4-7 cm thick; extremely acid
IIBm Y08-18-04	14-23	loess; dark yellowish brown (10YR 3/6 m); loam; very fine to medium weak subangular blocky to very fine weak granular; friable; plentiful very fine roots; 3% gravel; clear smooth boundary; 6-12 cm thick; very strongly acid
IIIBm Y08-18-05	23-48	till; dark yellowish brown (10YR 4/6 m); loamy sand; very fine to fine weak subangular blocky; very friable; plentiful very fine roots; 30% gravel and 10% cobbles; gradual smooth boundary; 24-29 cm thick; strongly acid
IIIBC Y08-18-06	48-82	till; dark yellowish brown (10YR 4/4 m); loamy sand; fine weak subangular blocky to single grain; very friable; few fine roots; 45% gravel and 10% cobbles; diffuse smooth boundary; 33-39 cm thick; medium acid
IIIC Y08-18-07	82-112+	till; dark grayish brown (2.5Y 4/2 m); loamy sand; fine weak subangular blocky to single grain; loose; 45% gravel and 15% cobbles; slightly acid

 Table A1-1: Pedon description of Y08-18.

Note: Texture and reaction classes are derived from laboratory data. pH was determined in 0.01M CaCl₂.



Figure A1-1: Pedon with horizon designations Y08-18. Knife handle is 11 cm long.

Site No: Y08-19

Soil Classification: Orthic Dystric Brunisol

Site Description

Location:	McConnell moraine				
Latitude:	62°00'22.9"	Longitude:	136°34'00.7"	Elevation:	1040 m
Aspect:	neutral	Slope:	0°	Slope Position:	Upland

Parent Material:

Thin veneer of White River Tephra (I) draped over McConnell age till (II). Some eolian material (loess) incorporated into upper till horizons.

Vegetation:

Dry area in open Boreal forest that is dominated by *Populus tremuloides* and *Betula* papyrifera with groundcover including Arctostaphylos uva-ursi, Vaccinium uliginosum, Vaccinium vitis-idaea, Ledum groenlandicum, Lupinus arcticus, Saxifrage spp., Geocaulon spp., Betula pumila var. Glandulifera, Empetrum nigrum, grass and lichen (Cladina spp., Cladina rangifera, Cladina mitis, Cladonia spp., Flavocetraria, Stereocaulon spp.).

Comments:

The site is located on a ridge top of McConnell moraine. The area is well drained and dominated by drier vegetation. A very thin discontinuous layer of loess can be seen at the upper boundary of the till but is insufficient to assign as a separate horizon. Some calcareous deposits were observed on the underside of large clasts in the BC or C horizon, however not sufficiently common to label as a Ck horizon.

Thin Sections:

Sample ID	Horizon	Depth (cm)	Notes
Y08-19-A	IIBm	18-25	Weathered till.
Y08-19-B	IIBC	45-52	Transition between weathered till and parent material.
Y08-19-C	IIC	80-87	
Horizon Sample #	Depth (cm)	Description	
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Fmi Y08-19-01	5-0	organic; very dark brown (10YR 2/2 m), and grayish brown (10YR 5/2 m); moderate non-compact matted; friable; common mycelia; few fecal pellets; plentiful medium to few fine roots; abrupt smooth boundary; 2-8 cm thick; extremely acid	
Bm Y08-19-02	0-9	tephra; light brownish gray (10YR 6/2 m), and brown (10YR 5/3 m); sandy loam; fine to medium weak subangular blocky to fine weak platy; very friable; plentiful very fine roots; abrupt smooth boundary; 4-13 cm thick; strongly acid	
IIBm Y08-19-03	9-35	till; dark yellowish brown (10YR 4/4 m); sandy loam; fine to medium weak subangular blocky; friable; few very fine roots; 25% gravel and 10% cobbles; gradual smooth boundary; 25-29 cm thick; strongly acid	
IIBC Y08-19-04	35-56	till; brown (10YR 5/3 m); sandy loam; very fine to medium weak subangular blocky; friable; few very fine roots; 25% gravel and 10% cobbles; diffuse smooth boundary; 19-21 cm thick; medium acid	
IIC Y08-19-05	56-100+	till; brown (10YR 5/3 m); sandy loam; fine to medium weak subangular blocky; friable; few very fine roots; 30% gravel and 10% cobbles; medium acid (few carbonate accumulations on underside of coarse fragments)	

 Table A1-2: Pedon description of Y08-19.



Figure A1-2: Pedon with horizon designations Y08-19. Knife handle is 11 cm long.

Soil Classification: Orthic Dystric Brunisol

Site Description

Location:	McConnell moraine							
Latitude:	61°52'52.3"	Longitude:	136°34'20.7"	Elevation:	1100 m			
Aspect:	neutral	Slope:	0°	Slope Position:	Ridge top			
D .14								

Parent Material:

Thin veneer of White River Tephra (I) draped over McConnell age till (II). Some eolian material (loess) incorporated into upper till horizons.

Vegetation:

Open Boreal forest. Dominated by *Picea mariana* with groundcover including *Betula pumila* var. *Glandulifera, Salix* spp., *Empetrum nigrum, Vaccinium* spp., and several lichens (*Cladina* spp., *Cladonia* spp., *Cetraria* spp., *Cetraria icelandica, Flavocetraria, Peltigera* spp., *Masonhalea richardsonii*).

Comments:

The site is located on a McConnell moraine. A discrete horizon of loess is not evident but may be incorporated into the upper till horizons. The pedon was wet near the base (110 cm) thus permafrost is likely below. Silt caps are found throughout the profile as well as some frost shattered stones.

Sample ID	Horizon	Depth (cm)	Notes	
Y08-31-A	IIBm1	10-15		
Y08-31-B	BC	55-62		

Horizon Sample #	Depth (cm)	Description
Fm Y08-31-01	8-0	organic; very dark brown (7.5YR 2.5/2 m); weak non-compact matted; friable; common mycelia; few fecal pellets; plentiful medium and fine roots; abrupt smooth boundary; 4-8 cm thick; extremely acid
Bm Y08-31-02	0-8	tephra; light gray (10YR 7/2 m); silty loam; massive to very coarse weak platy; friable; plentiful very fine to few fine roots; abrupt smooth boundary; 2-15 cm thick; very strongly acid
IIBm1 Y08-31-03	8-26	till; light olive brown (2.5Y 5/4 m), and yellowish brown (10YR 5/4 m); loam; fine to medium weak subangular blocky to very fine weak platy; friable; plentiful very fine to few fine roots; 5% gravel, 15% cobbles and 10% stones; gradual smooth boundary; 14-19 cm thick; very strongly acid
IIBm2 Y08-31-04	26-42	till; olive brown (2.5Y 4/3 m); sandy loam; fine to medium moderate subangular blocky; friable; few fine roots; 5% gravel, 15% cobbles and 10% stones; gradual smooth boundary; 15-18 cm thick; medium acid
IIBC Y08-31-05	42-61	till; olive brown (2.5Y 4/3 m); sandy loam; fine to medium weak subangular blocky; friable; few fine roots; 5% gravel, 15% cobbles and 10% stones; diffuse smooth boundary; 19-21 cm thick; slightly acid
IICk Y08-31-06	61-110+	till; light olive brown (2.5Y 5/3 m); sandy loam; fine to medium weak subangular blocky to massive; friable; 5% gravel, 15% cobbles and 10% stones; carbonates present; neutral

Table A1-3: Pedon description of Y08-31.



Figure A1-3: Pedon with horizon designations Y08-31. Knife handle is 11 cm long.

Soil Classification: Orthic Dystric Brunisol

Site Description

Location:	McConnell moraine						
Latitude:	61°52'48.4"	Longitude:	136°34'06.5"	Elevation:	1098 m		
Aspect:	N (350°)	Slope:	2.5°	Slope Position:	Ridge top		
D . 17							

Parent Material:

Thin veneer of White River Tephra (I) draped over McConnell age till (II). Some eolian material (loess) incorporated into upper till horizons.

Vegetation:

Open Boreal forest. Dominated by *Picea mariana* with groundcover including *Betula pumila* var. *Glandulifera, Salix* spp., *Empetrum nigrum, Vaccinium* spp., and several lichens (*Cladina* spp., *Cladonia* spp., *Cetraria* spp., *Cetraria icelandica, Flavocetraria, Peltigera* spp.).

Comments:

The site is located on a McConnell moraine. A discrete horizon of loess is not evident but may be incorporated into the upper till horizons. Cryoturbation is evident only in upper horizons. Silt caps are observed throughout the profile.

Sample ID	Horizon	Depth (cm)	Notes
Y08-33-A	IIBm1	25-32	Weathered till.

Horizon Sample #	Depth (cm)	Description
Fm Y08-33-01	4-0	organic; black (10YR 2/1 m); weak non-compact matted; friable; common mycelia; few fecal pellets; plentiful medium to fine roots; abrupt wavy boundary; 2-5 cm thick; extremely acid
Ahey Y08-33-02	0-3	tephra; light gray (10YR 7/1 m), and brown (10YR 5/3 m); sandy loam; fine to medium weak subangular blocky; very friable; plentiful fine and very fine roots; abrupt broken boundary; 0-14 cm thick; extremely acid
Bmjy Y08-33-03	3-19	tephra; light gray (10YR 7/2 m), and brown (10YR 5/3 m); silty loam; fine to coarse weak subangular blocky; friable; plentiful very fine roots; abrupt irregular boundary; 4-23 cm thick; extremely acid
IIAhb Y08-33-04	19-22	till; dark brown (10YR 3/3 m); fine to very fine weak subangular blocky; friable; plentiful very fine roots; 5% gravel; abrupt broken boundary; 0-3 cm thick; extremely acid
IIBm1 Y08-33-05	22-34	till; dark yellowish brown (10YR 4/6 m); sandy loam; fine weak subangular blocky to single grain; friable; plentiful very fine roots; 15% gravel, 15% cobbles and 10% stones; diffuse smooth boundary; combined thickness of IIBm1 and IIBm2 is 24-37 cm; extremely acid
IIBm2 Y08-33-06	34-48	till; dark yellowish brown (10YR 3/6 m); loamy sand; fine weak subangular blocky to single grain; friable; few very fine roots; 15% gravel, 15% cobbles and 10% stones; abrupt wavy boundary; very strongly acid
IIC Y08-33-07	48-107+	till; light olive brown (2.5Y 5/3 m); loamy sand; fine weak subangular blocky; friable; few very fine roots; 20% gravel, 30% cobbles and 10% stones; strongly acid

 Table A1-4: Pedon description of Y08-33.



Figure A1-4: Pedon with horizon designations Y08-33. Knife handle is 11 cm long.

Soil Classification: Orthic Dystric Brunisol

Site Description

Location:	Penultimate mo	oraine complex	•		
Latitude:	61°59'1.9"	Longitude:	136°38'51.6"	Elevation:	1197 m
Aspect:	SW	Slope:	6°	Slope Position:	Moraine ridge

Parent Material:

Thin veneer of White River Tephra (I) draped over thin veneer of eolian material (II), described as loess. These in turn overlie penultimate age till (III).

Vegetation:

Lower end of transition from open Boreal forest to subalpine. Groundcover dominated by *Betula glandulosa*, with other species including *Vaccinium vitis idaea*, *Empetrum nigrum*, *salix* spp., grass, moss and lichen (*Cladina* spp., *Cladina rangifera*, *Cladonia* spp., *Cetraria* spp., *Flavocetraria*, *Peltigera* spp., *Masonhalea richardsonii*, *Stereocaulon* spp., *Thamnolia vermicularis*).

Comments:

The site is located within a moraine complex near the penultimate limit. Test holes dug on flatter surfaces adjacent to pit had more prominent ash and loess deposition. The pedon was excavated on an exposure with a minor slope. Some decomposed granite clasts are evident throughout the profile. Organic acid staining is evident on clasts in the lower portion of the profile. Occasional silt caps are found in the IIIBC and IIIC1 horizons.

Sample ID	Horizon	Depth (cm)	Notes
Y08-15-A	IIIBm1	~15	Uppermost weathered till horizon.

Horizon Sample #	Depth (cm)	Description
Fmi Y08-15-01	2-0	organic; very dark brown (10YR 2/2 m); medium non-compact matted; friable; common mycelia; plentiful fine and medium roots; abrupt smooth boundary; 2-4 cm thick; extremely acid
Bm Y08-15-02	0-4	tephra; brown (10YR 4/3 m), and light gray (10YR 7/2 m); sandy loam; medium to coarse moderate subangular blocky; friable; plentiful fine roots; abrupt smooth boundary; 3-6 cm thick; extremely acid
IIBm Y08-15-03	4-10	loess; dark yellowish brown (10YR 3/4 m); sandy loam; medium to coarse moderate subangular blocky; friable; plentiful fine roots; abrupt smooth boundary; 4-11 cm thick; extremely acid
IIIBm1 Y08-15-04	10-36	till; strong brown (7.5YR 4/6 m); sand; fine to medium weak subangular blocky; very friable; plentiful very fine roots; 50% gravel and 10% cobbles; gradual smooth boundary; 17-27 cm thick; very strongly acid
IIIBm2 Y08-15-05	36-60	till; dark yellowish brown (10YR 4/6 m); sand; fine to medium weak subangular blocky; very friable; plentiful very fine roots; 60% gravel and 15% cobbles; gradual wavy boundary; 16-25 cm thick; very strongly acid
IIIBC Y08-15-06	60-90	till; yellowish brown (10YR 5/4 m); sand; fine weak subangular blocky; very friable; plentiful very fine roots; 60% gravel and 20% cobbles; gradual wavy boundary; 20-37 cm thick; very strongly acid
IIIC1 Y08-15-07	90-119	till; dark yellowish brown (10YR 4/4 m); loamy sand; medium weak subangular blocky; very friable; few very fine roots; 55% gravel and 15% cobbles; clear wavy boundary; 18-31 cm thick; very strongly acid
IIIC2 Y08-15-08	119- 160+	till; brown (10YR 4/3 m); sand; single grain; loose; few very fine roots; 50% gravel; strongly acid

 Table A1-5: Pedon description of Y08-15.

Figure A1-5: Pedon with horizon designations Y08-15. Knife handle is 11 cm long.



Soil Classification: Orthic Dystric Brunisol

Site Description

<i>Location:</i> Penultimate moraine complex	
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Latitude:	61°59'1.1"	Longitude:	136°39'17.9"	Elevation:	1209 m
Aspect:	NE (10°)	Slope:	3.5°	Slope Position:	Moraine

Parent Material:

A thin veneer of mixed White River Tephra and eolian material (loess) (I) overlies penultimate age till (II).

Vegetation:

Lower end of transition from open Boreal forest to subalpine. Groundcover dominated by *Betula glandulosa*, with other species including *Vaccinium vitis idaea*, *Empetrum nigrum*, *Salix* spp., grass, moss and lichen.

Comments:

The sampling site is located in an undulating penultimate moraine complex with permafrost common in hollows. Standing water is common in hollows but hillocks are well drained. Organic acid staining is found on the bottom of many clasts.

Sample ID	Horizon	Depth (cm)	Notes
Y08-16-A	IIBm1	10-17	Uppermost weathered till horizon.
Y08-16-B	IIBm3	55-62	Lowermost weathered till horizon.

Horizon Sample #	Depth (cm)	Description
Fm Y08-16-01	4-0	organic; very dark brown (7.5YR 2.5/2 m); medium non-compact matted; friable; common mycelia; few fecal pellets; abundant very fine and plentiful medium roots; 2-6 cm thick; extremely acid
Bm Y08-16-02	0-10	mixed tephra and loess; light yellowish brown (10YR 6/4 m), and light gray (10YR 7/2 m); silty loam; fine moderate subangular blocky; very friable; plentiful medium and fine roots; abrupt smooth boundary; 5-17 cm thick; extremely acid
IIBm1 Y08-16-03	10-23	till; brown (7.5YR 4/4 m); sandy loam; medium weak subangular blocky; friable; plentiful fine and very fine roots; 30% gravel, 20% cobbles and 5% stones; abrupt wavy boundary; 10-14 cm thick; extremely acid
IIBm2 Y08-16-04	23-45	till; dark yellowish brown (10YR 3/6 m); loamy sand; single grain; very friable; few fine and very fine roots; 30% gravel, 20% cobbles and 5% stones; gradual wavy boundary; 17-22 cm thick; extremely acid
IIBm3 Y08-16-05	45-63	till; dark yellowish brown (10YR 3/4 m); loamy sand; single grain; 30% gravel, 10% cobbles and 5% stones; gradual wavy boundary; 12- 20 cm thick; very strongly acid
IIC Y08-16-06	63-110	till; brown (10YR 5/3 m); loamy sand; single grain; 40% gravel and 20% cobbles; very strongly acid

 Table A1-6: Pedon description of Y08-16.



Figure A1-6: Pedon with horizon designations Y08-16. Knife handle is 11 cm long.

Soil Classification: Orthic Dystric Brunisol

Site Description

Location:	Penultimate till over bedrock							
Latitude:	62°00'31.4"	Longitude:	136°36'27.7"	Elevation:	1099 m			
Aspect:	neutral	Slope:	2.5°	Slope Position:	Ridge top			

Parent Material:

Thin veneer of White River Tephra (I) draped over thin veneer of eolian material (II), described as loess. These in turn overlie veneer of penultimate age till (III) over granitic bedrock (R).

Vegetation:

Open boreal forest. *Picea mariana* with ground cover that includes *Salix* spp., *Vaccinium vitis idaea*, *Vaccinium uliginosum*, *Geocaulon* spp., moss and lichen (*Cladina* spp., *Cladonia* spp., *Flavocetraria*, *Peltigera* spp., *Stereocaulon* spp.).

Comments:

Permafrost is common within the sampling area. In this ridge top location, till is very thin with bedrock close to the surface. Rotten granite clasts and silt caps are observed within the profile and organic acid staining is common on the base of clasts.

Sample ID	Horizon	Depth (cm)	Notes
Y08-21-A	IIIBm1	22-29	Weathered till horizon.
Y08-21-B	IIIBm2	41-48	Weathered till horizon.
Y08-21-C	Bm/IIBm1	2-9	Boundary between tephra and loess horizon.

Horizon Sample #	Depth (cm)	Description
Fm Y08-21-01	5-0	organic; very dark brown (7.5YR 2.5/2 m); moderate non-compact matted; firm; common mycelia; few fecal pellets; few medium and few fine roots; abrupt and smooth boundary; 4-9 cm thick; extremely acid
Bm Y08-21-02	0-10	tephra; brownish yellow (10YR 6/6 m), and gray (10YR 6/1 m); sandy loam; weak fine to medium subangular blocky; very friable; few very fine roots; abrupt and wavy boundary; 6-15 cm thick; extremely acid
IIBm1 Y08-21-03	10-15	loess; dark yellowish brown (10YR 4/4 m); silty loam; moderate fine platy to weak fine to medium subangular blocky; friable; few very fine roots; abrupt and wavy boundary; 2-9 cm thick; extremely acid
IIBm2 Y08-21-04	15-20	loess; dark yellowish brown (10YR 3/4 m); loam; moderate fine platy to weak fine to moderate subangular blocky; friable; very few fine roots; clear and wavy boundary; 3-10 cm thick; very strongly acid
IIIBm1 Y08-21-05	20-40	till and weathered bedrock; dark yellowish brown (10YR 3/6 m); sandy loam; weak medium to coarse subangular blocky; very friable; few very fine roots; 40% gravel and 20% cobbles; clear and irregular boundary; 7-36 cm thick; very strongly acid
IIIBm2 Y08-21-06	40-70	till and weathered bedrock; dark yellowish brown (10YR 4/4 m); sandy loam; weak fine to medium subangular blocky; very friable; 25% gravel, 25% cobbles and 25% stones; 18-32 cm thick; very strongly acid
R	70+	

 Table A1-7: Pedon description of Y08-21.



Figure A1-7: Pedon with horizon designations Y08-21. Knife handle is 11 cm long.

Soil Classification: Eluviated Dystric Brunisol

Site Description

Location:	Penultimate till over bedrock							
Latitude:	62°00'30.6"	Longitude:	136°36'33.9"	Elevation:	1092 m			
Aspect:	W (270°)	Slope:	4.5°	Slope Position:	Ridge top			

Parent Material:

Thin veneer of White River Tephra (I) draped over thin veneer of eolian material (II), described as loess. These in turn overlie veneer of penultimate age till (III) over granitic bedrock (R).

Vegetation:

Open boreal forest. Picea mariana with groundcover including Empetrum nigrum, Betula pumila var. Glandulifera, Ledum groenlandicum, Oxycoccus spp., Vaccinium vitis-idaea, Vaccinium uliginosum, Rosa acicularis and lichens (Cladina spp., Cladonia spp., Peltigera spp, Masonhalea richardsonii, Stereocaulon spp.).

Comments:

Permafrost is common in the surrounding landscape. Till is very thin with bedrock close to the surface in this ridge top location. Rotten granite clasts and silt caps are observed within the profile.

Sample ID	Horizon	Depth (cm)	Notes
Y08-22-A	IIIBm2	~60-67	Weathered clast within horizon.
Y08-22-B	Bm/IIBm	~1-8	Tephra / loess boundary.
Y08-22-C	IIIBm1	~20-27	Weathered till.
Y08-22-D	IIIBm2	~40-47	Weathered till.

Horizon Sample #	Depth (cm)	Description
Fm Y08-22-01	5-0	organic; very dark brown (10YR 2/2 m); weak non-compact matted; loose; few mycelia; plentiful medium and fine roots; abrupt wavy boundary; 2-9 cm thick; extremely acid
Aej Y08-22-02	0-2	tephra; gray (10YR 6/1 m); silty loam; fine to medium weak subangular blocky; friable; few very fine roots; clear smooth boundary; 2-10 cm thick; extremely acid
Bm Y08-22-03	2-9	tephra; yellowish brown (10YR 5/6 m); sandy loam; fine to medium weak subangular blocky; very friable; plentiful very fine roots; abrupt wavy boundary; 3-8 cm thick; extremely acid
IIBm Y08-22-04	9-13	loess; brown (7.5YR 4/4 m); silty loam; fine to medium weak platy to medium weak subangular blocky; friable; plentiful very fine roots; clear smooth boundary; 3-7 cm thick; extremely acid
IIIBm1 Y08-22-05	13-36	till; dark yellowish brown (10YR 4/6 m); sandy loam; medium weak subangular blocky; friable; plentiful very fine roots; 30% gravel and 20% cobbles; diffuse wavy boundary; 16-19 cm thick; extremely acid
IIIBm2 Y08-22-06	36-72	till; brown (10YR 5/3 m); sandy loam; fine weak subangular blocky; loose; 40% gravel, 10% stones and 20% cobbles; diffuse wavy boundary; 22-29 cm thick; very strongly acid
IIIBC Y08-22-07	72-102+	till; light olive brown (2.5Y 5/3 m); sandy loam; single grain; loose; 30% gravel, 20% stones and 30% cobbles; very strongly acid

 Table A1-8: Pedon description of Y08-22.



Figure A1-8: Pedon with horizon designations Y08-22. Knife handle is 11 cm long.

Soil Classification: Eluviated Dystric Brunisol

Site Description

Location:	Penultimate moraine							
Latitude:	61°53'50.6"	Longitude:	136°43'19.7"	Elevation:	1236 m			
Aspect:	neutral	Slope:	0°	Slope Position:	Moraine ridge top			
D (17	, • I							

Parent Material:

Thin veneer of White River Tephra (I) draped over thin veneer of eolian material (II), described as loess. These in turn overlie penultimate age till (III).

Vegetation:

Subalpine. Dominated by *Betula pumila* var. *Glandulifera* and *Salix* spp. with other groundcover including *Pedicularis labradorica*, *Oxycoccus* spp., grass, and lichens (*Cladina* spp., *Cladonia* spp., *Cetraria* spp., *Flavocetraria*, *Peltigera* spp., *Masonhalea richardsonii*, *Stereocaulon* spp., *Thamnolia vermicularis*)

Comments:

Frost boils are common seasonal freeze/thaw features observed in the tephra horizon. Nonsorted, patterned ground is common in area surrounding the pedon. The sampling area is very open and exposed. Snow is not likely to accumulate in the winter, resulting in poor insulation and colder ground conditions than other penultimate age sites. Fungal mycelia are noted in a portion of discontinuous buried organic layer beneath Bmjy.

Sample ID	Horizon	Depth (cm)	Notes
Y08-23-A	Bmjy/IIAe/ IIIBm1	17-24	Boundary between tephra, loess and weathered penultimate till.
Y08-23-B	IIIBm1	17-24	

Horizon Sample #	Depth (cm)	Description
F Y08-23-01	10-7	organic; very dark brown (7.5YR 2.5/2 m); weak non-compact matted; loose; few mycelia; plentiful medium to very fine roots; abrupt broken boundary; 0-7 cm thick; extremely acid
Fmi Y08-23-02	7-0	organic; very dark brown (7.5YR 2.5/2 m); moderate non-compact matted; friable; few mycelia; few fecal pellets; plentiful very fine and few fine roots; abrupt irregular boundary; 2-12 cm thick; extremely acid
Bmjy Y08-23-03	0-18	tephra; pale brown (10YR 6/3 m); silty loam; coarse weak subangular blocky; firm; plentiful fine roots; abrupt smooth boundary; 6-25 cm thick; extremely acid
IIAe Y08-23-04	18-20	loess; grayish brown (10YR 5/2 m); silty loam; fine to very fine weak subangular blocky to coarse moderate granular; friable; plentiful very fine roots; 10% gravel; abrupt smooth boundary; 1-6 cm thick; extremely acid
IIIBm1 Y08-23-05	20-36	till; dark yellowish brown (10YR 4/6 m); sandy loam; fine to coarse weak subangular blocky; very friable; plentiful very fine roots; 40% gravel and 10% cobbles; clear smooth boundary; 13-20 cm thick; very strongly acid
IIIBm2 Y08-23-06	36-67	till; olive brown (2.5Y 4/4 m); sandy loam; medium to coarse weak subangular blocky; friable; few very fine roots; 35% gravel and 25% cobbles; gradual smooth boundary; 22-31 cm thick; very strongly acid
IIIBC Y08-23-07	67-100	till; olive brown (2.5Y 4/3 m); loamy sand; fine to coarse weak subangular blocky to single grain; friable; 40% gravel and 30% cobbles; diffuse smooth boundary; 33-36 cm thick; strongly acid
IIIC Y08-23-08	100- 110+	till; olive brown (2.5Y 4/4 m); loamy sand; fine weak subangular blocky to single grain; very friable; 40% gravel and 30% cobbles; strongly acid

Table A1-9: Pedon description of Y08-23.



Figure A1-9: Pedon with horizon designations Y08-23. Knife handle is 11 cm long.

Soil Classification: Orthic Dystric Brunisol

Site Description

Location:	Penultimate moraine								
Latitude:	61°52'45.4"	Longitude:	136°35'24.0"	Elevation:	1128 m				
Aspect:	neutral	Slope:	0°	Slope Position:	Ridge top				
Parent Ma	terial:								

Thin veneer of White River Tephra (I) draped over thin veneer of eolian material (II), described as loess. These in turn overlie penultimate age till (III).

Vegetation:

Open Boreal forest. *Picea mariana* with groundcover including *Betula pumila* var. *glandulifera, Ledum groenlandicum, Salix* spp., moss and lichens (*Cladina* spp., *Cladonia* spp., *Flavocetraria, Peltigera* spp.).

Comments:

Shallow weathering is observed although the area is mapped as penultimate aged moraine. Silt coatings are observed on clasts and fines accumulate in voids found in the IIIC horizon.

Sample ID	Horizon	Depth (cm)	Notes
Y08-36-A	IIIBm	16-23	
Y08-36-B	IIIC	38-45	

Horizon Sample #	Depth (cm)	Description
Fmi Y08-36-01	4-0	organic; very dark grayish brown (10YR 3/2 m), and very dark brown (10YR 2/2 m); weak non-compact matted; friable; common mycelia; few fecal pellets; plentiful coarse and medium roots; clear and wavy boundary; 3-8 cm thick; extremely acid
Bmy Y08-36-02	0-8	tephra; light gray (10YR 7/2 m); silty loam; weak fine to medium platy to moderate fine subangular blocky; friable; plentiful fine and few medium roots; abrupt irregular boundary; 2-18 cm thick; extremely acid
IIBm Y08-36-03	8-14	loess; dark yellowish brown (10YR 4/6 m); loam; moderate fine subangular blocky; friable; few very fine roots; few gravel; clear wavy boundary; 4-12 cm thick; very strongly acid
IIIBm Y08-36-04	14-30	till; light olive brown (2.5Y 5/4 m); sandy loam; massive; very friable; very few very fine roots; 15% gravel and 20% cobbles; clear wavy boundary; 11-18 cm thick; very strongly acid
IIIC Y08-36-05	30-110+	till; olive brown (2.5Y 4/4 m); loamy sand; massive; very friable; very few very fine roots; 20% gravel and 35% cobbles; medium acid

 Table A1-10: Pedon description of Y08-36.



Figure A1-10: Pedon with horizon designations Y08-36. Knife handle is 11 cm long.

Soil Classification: Brunisolic Dystric Turbic Cryosol

Site Description

Location:	Pre-Reid platea	u beyond penultimate terminal moraine				
Latitude:	61°58'45.5"	Longitude:	136°39'57.4"	Elevation:	1294 m	
Aspect:	neutral	Slope:	0°	Slope Position:	Plateau	
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Parent Material:

Thin veneer of White River Tephra (I) draped over thin veneer of eolian material (II), described as loess. These in turn overlie highly cryoturbated horizons of colluvium (III) and residuum (IV) derived from granitic bedrock.

Vegetation:

Upper end of transition from open Boreal forest to subalpine. *Picea mariana* is the only tree species, shrubs are *Salix* spp. and *Betula glandulosa*. Groundcover includes *Vaccinium vitis idaea*, *Vaccinium uliginosum*, *Empetrum nigrum*, *Arctostaphylos* spp., grass, moss, and lichen.

Comments:

The site is located in a landscape with several granitic tor outcrops. These outcrops are highly exposed and immediately surrounded by bare grus, or grus with thin cryptogamic crusts developing. The tors have subangular edges. The sample site is located adjacent to two tors, in an area with vegetation cover, including *Picea mariana* which provide additional stability to this active landscape. Water seepage was encountered at 120cm; it is assumed that the permafrost table is likely located within 2m of the surface, thus this soil is within the Cryosolic order.

Thin section:

Sample ID	Horizon	Depth (cm)	Notes
Y08-10-A	Bmjy/IIBm	~ 10	Includes volcanic ash, buried organics and underlying loess
Y08-10-B	IIIBmy1	~ 20	
Y08-10-C	IVBmy	~ 95	Predominantly yellow coloured residuum with some darker adjacent residuum
Y08-10-D	IIIBmy3	~ 55	IIIBmy3 in upward involution, also captured IIIBmy2 material. IIIBmy3 is a vertical streak through the profile.

Horizon Sample #	Depth (cm)	Description
Ah Y08-10-07	0-7	organic and tephra; very dark brown (10YR 2/2 m); weak non-compact matted; firm; few mycelia; few fecal pellets; abundant fine roots, plentiful medium roots; clear, smooth boundary; 4-8 cm thick; extremely acid; classified as a mineral horizon due to <17% C but large amount of organic matter incorporated
Bmjy Y08-10-01	7-17	tephra; pale brown (10YR 6/3 m); sandy loam; weak fine subangular blocky; friable; plentiful medium roots; abrupt, wavy boundary; extremely acid
IIBm Y08-10-02	17-22	loess; dark brown (10YR 3/3 m); silty loam; weak fine platy; friable; few fine roots; clear, wavy boundary; very strongly acid
IIIBmy1 Y08-10-03	22-47	colluvium; dark yellowish brown (10YR 3/6 m); sandy loam; weak fine subangular blocky; friable; few fine roots, very few fine roots; 50% gravel and 5% cobbles; clear, broken boundary; extremely acid
IIIBmy2 Y08-10-04	47-62	colluvium; yellowish brown (10YR 5/8 m); sandy loam; weak fine to medium subangular blocky; friable; few very fine roots; 40% gravel; clear, broken boundary; extremely acid
IIIBmy3 Y08-10-05	62-97	colluvium; yellowish brown (10YR 5/6 m); sandy loam; weak fine to medium subangular blocky; friable; 40% gravel and 5% cobbles; clear, broken boundary; extremely acid
IVBmy Y08-10-06	97-110+	residuum; yellowish brown (10YR 5/8 m); sandy loam; weak fine to medium subangular blocky; friable; 20% gravel; very strongly acid

 Table A1-11: Pedon description of Y08-10.



Figure A1-11: Pedon with horizon designations Y08-10. Knife handle is 11cm long.

Soil Classification: Eluviated Dystric Brunisol

Site Description

Location:	Pre-Reid plateau beyond penultimate terminal moraine	
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Latitude:	61°58'58.7"	Longitude:	136°40'14.9"	Elevation:	1281 m
Aspect:	neutral	Slope:	0-2°	Slope Position:	Plateau

Parent Material:

Thin veneer of White River Tephra (I) draped over thin veneer of eolian material (II), described as loess. These in turn overlie highly cryoturbated horizons of colluvium (III) and residuum (IV) derived from granitic bedrock.

Vegetation:

Upper end of transition from open Boreal forest to subalpine. *Picea mariana* is the only tree species, shrubs are *Salix* spp. and *Betula glandulosa*. Groundcover includes *Vaccinium vitis idaea*, *Vaccinium uliginosum*, *Empetrum nigrum*, *Arctostaphylos* spp., grass, moss, and lichen.

Comments:

Silt cappings are present through most of the profile and vary from thin to thick (>1 cm). Weathered coarse fragments include decomposing granite that are easily broken apart by hand. No permafrost was observed but soil is strongly cryoturbated. It was not possible to excavate the pit to 2 m, however if permafrost is present between the base of the pit (110 cm) and 200 cm the soil would belong to the Cryosolic order.

Sample ID	Horizon	Depth (cm)	Notes
Y08-13-A	Bmy/IIBm1	3-10	Ash / loess boundary
Y08-13-B	IIIBmy1	40-46	
Y08-13-C	Decomposed granite	~90	Silt coating

Horizon Sample #	Depth (cm)	Description
Fm Y08-13-01	6-0	organic; very dark brown (10YR 2/2 m); strong non-compact matted; firm; mycelia common; plentiful moderate and fine roots; abrupt and smooth boundary; 4-10 cm thick; extremely acid
Aey Y08-13-02	0-3	tephra; pale brown (10YR 6/3 m); sandy loam; single grain; friable; plentiful very fine roots and few fine roots; clear and irregular boundary; 2-4 cm thick; extremely acid
Bmy Y08-13-03	3-8	tephra; pale brown (10YR 6/3 m) and yellowish brown (10YR 5/6 m); sandy loam; single grain; friable; plentiful very fine roots and few fine roots; abrupt and wavy boundary; 2-6 cm thick; extremely acid
IIBmy1 Y08-13-04	8-13	loess; dark yellowish brown (10YR 4/4 m); silty loam; moderate medium subangular blocky; friable; plentiful very fine and fine roots; 5% gravel; clear and wavy boundary; 5-9 cm thick; extremely acid
IIBmy2 Y08-13-05	13-20	loess; dark yellowish brown (10YR 3/6 m); loam; moderate fine to medium subangular blocky; friable; plentiful very fine and fine roots; 5% gravel; clear and wavy boundary; 6-10 cm thick; very strongly acid
IIIBmy1 Y08-13-06	20-66	colluvium; dark yellowish brown (10YR 4/6 m); loamy sand; single grain; loose; plentiful very fine roots; 65% gravel and 15% cobbles; clear and broken boundary; very strongly acid
IIIBmy2 Y08-13-07	20-90	colluvium; dark yellowish brown (10YR 4/6 m); sand; single grain; loose; plentiful very fine roots; 65% gravel and 25% cobbles; clear and broken boundary; very strongly acid
IVBmy1 Y08-13-08	23- 110+	residuum; yellowish brown (10YR 5/8 m) and strong brown (7.5YR 5/8 m); sandy loam; single grain; loose; few very fine roots; 75% gravel and 5% cobbles; very strongly acid
IVBmy2 Y08-13-09	83- 110+	residuum; brownish yellow (10YR 6/8 m) and reddish yellow (7.5YR 6/8 m); sandy loam; single grain; loose; discontinuous; few very fine roots; 75% gravel and 5% cobbles; strongly acid

 Table A1-12: Pedon description of Y08-13.



Figure A1-12: Pedon with horizon designations Y08-13. Knife handle is 11cm long.

Soil Classification: Orthic Dystric Brunisol

Site Description

Location: Pre-Reid ridgetop beyond penultimate terminal moraine

Latitude:	61°54'7.9"	Longitude:	136°42'13.0"	Elevation:	1387 m
Aspect:	SW	Slope:	3°	Slope Position:	Ridge top

Parent Material:

Thin veneer of White River Tephra (I) draped over colluviated granitic bedrock (II). Translocated fine material, possibly eolian in origin, surrounding boulders (III).

Vegetation:

Open alpine. Groundcover is dominated by *Dryas integrifolia, salix* spp., *Arctostaphylous rubra, Saxifraga* spp., grass and lichens (*Cladonia* spp., *Cetraria* spp., *Cetraria icelandica, Flavocetraria, Stereocaulon* spp., *Thamnolia vermicularis, Alectoria ochroleuca*). Beyond pedon there are islands of *Betula* spp. communities.

Comments:

This site is an exposed ridgetop adjacent to tors with rounded edges. This landscape appears more sculpted than Y08-10 and is approximately 100m higher. Frost action is evident with frost boils pervasive within the landscape. The pedon is less weathered than other pre-Reid sites, with a skeletal macrostructure to 85cm, and fragmental macrostructure below with interlocking angular blocks. Grey matrix (fine textured with some coarse fragments) that surrounds clasts throughout the profile is pervasive and may be largely translocated eolian material. Organic acid staining is observed on the bottom of some clasts.

Sample ID	Horizon	Depth (cm)	Notes
Y08-24-A	IIIBCy	65-72	IIIBC collected from the top of a clast.
Y08-24-B	IIBmy1	12-19	
Y08-24-C	IIBmy1 in Aey	12-19	Colluviated bedrock upwelling into ash in a frost boil.

Horizon Sample #	Depth (cm)	Description
Fm Y08-24-01	2-0	organic; black (10YR 2/1 m); weak non-compact matted; loose; few mycelia; few fecal pellets; plentiful medium and very fine roots; clear wavy boundary; 1-6 cm thick; extremely acid
Bmy Y08-24-02	0-5	tephra; pale brown (10YR 6/3 m); silty loam; weak coarse subangular blocky; friable; plentiful medium and very fine roots; few gravel; clear broken boundary; 0-7 cm thick; extremely acid
IIBmy1 Y08-24-03	5-23	colluvium; dark yellowish brown (10YR 4/4 m); sandy loam; weak fine to medium subangular blocky; very friable; plentiful very fine and few fine roots; 10% gravel, 25% cobbles and 25% stones; gradual smooth boundary; 18-29 cm thick; extremely acid
IIBmy2 Y08-24-04	23-85+	colluvium; dark yellowish brown (10YR 3/6 m); loamy sand; weak fine to medium subangular blocky to single grain; very friable; plentiful very fine roots; 10% gravel, 25% cobbles and 45% stones; clear broken boundary; very strongly acid
IIIBCy Y08-24-05	39-85+	loess and bedrock; dark yellowish brown (10YR 3/5 m); sandy loam; weak fine to medium subangular blocky; friable; plentiful very fine roots; very strongly acid

 Table A1-13: Pedon description of Y08-24.



Figure A1-13: Pedon with horizon designations Y08-24. Knife handle is 11 cm long.

Soil Classification: Eluviated Dystric Brunisol

Site Description

Location:	Pre-Reid ridgetop beyond penultimate terminal moraine					
Latitude:	61°54'17.6"	Longitude:	136°44'8.0"	Elevation:	1300 m	
Aspect:	NE	Slope:	4°	Slope Position:	Ridge top	

Parent Material:

Thin veneer of White River Tephra (I) draped over thin veneer of eolian material (II), described as loess. These in turn overlie highly cryoturbated horizons of colluvium / residuum (III) derived from granitic bedrock.

Vegetation:

Subalpine. Groundcover includes Salix spp., Pedicularis labradorica, grass and lichen (Cladina spp., Cladina rangifera, Cladonia spp., Cetraria spp., Cetraria icelandica, Flavocetraria, Stereocaulon spp., Thamnolia vermicularis).

Comments:

Site is located on ridge top mapped as penultimate moraine but appears to be pre-Reid weathered bedrock. The pedon is located in the lee of a tor. No till found and solum is in grus type material. Fractured bedrock was encountered at 110cm. Discontinuous, buried sections of an H horizon with fecal matter and mycelia are present below the tephra.

Sample ID	Horizon	Depth (cm)	Notes
Y08-28A	IIAey- IIIBmy1	8-15	Loess incorporated into weathered bedrock.
Y08-28B	IIIBmy3	40-47	
Horizon Sample #	Depth (cm)	Description	
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Fmi Y08-28-01	1-0	organic; very dark brown (10YR 2/2 m); weak non-compact matted; loose; common fecal pellets; few mycelia; plentiful medium to very fine roots; clear smooth boundary; 1-3 cm thick; extremely acid	
Bm1 Y08-28-02	0-4	tephra; grayish brown (10YR 5/2 m); loamy sand; fine to very fine weak subangular blocky; very friable; plentiful fine and very fine roots; abrupt wavy boundary; 2-8 cm thick; extremely acid	
Bm2 Y08-28-03	4-7	tephra; light brownish gray (10YR 6/2 m); sandy loam; medium to fine weak subangular blocky; friable; plentiful fine and very fine roots; abrupt wavy boundary;3-11 cm thick; extremely acid	
IIAey Y08-28-04	7-9	loess; light gray (10YR 7/2 m), and brown (10YR 5/3 m); silty loam; fine to very fine weak subangular blocky; friable; plentiful fine and very fine roots; 5% gravel; abrupt broken boundary; 2-10 cm thick; extremely acid	
IIIBmy1 Y08-28-05	9-20	colluvium; dark yellowish brown (10YR 4/6 m); loam; medium to very fine weak subangular blocky; very friable; plentiful fine and medium roots; 20% gravel and 15% stone; clear broken boundary; 9-16 cm thick; extremely acid	
IIIBmy3 Y08-28-07	20-33	colluvium; dark yellowish brown (10YR 4/6 m); sandy loam; very fine weak subangular blocky; very friable; few very fine roots; 40% gravel, 15% cobbles and 15% stones; diffuse broken boundary; 15-40 cm thick; extremely acid	
IIIBmy2 Y08-28-06	33-40	colluvium; light olive brown (2.5Y 5/4 m); loam; fine weak subangular blocky; very friable; few very fine roots; 25% gravel; clear broken boundary; 0-19 cm thick; very strongly acid	
IIIBmy4 Y08-28-08	40-110+	colluvium; yellowish brown (10YR 5/5 m), and reddish yellow (5YR 6/8 m); loamy sand; very fine to medium weak subangular blocky to single grain; loose; 40% gravel, 20% cobbles and 20% stones; extremely acid	
IIIC Y08-28-09	110+	residuum; olive brown (2.5Y 4/4 m); sandy loam; loose; 40% gravel, 15% cobbles and 40% stones; very strongly acid	

 Table A1-14: Pedon description of Y08-28.

Note: Texture and reaction classes are derived from laboratory data. pH was determined in 0.01M CaCl₂.

Figure A1-14: Pedon with horizon designations Y08-28. Knife handle is 11 cm long.



Appendix 2: Selected physical and chemical properties of <2mm fractions

	Depth			pН	pН				
Horizon	(cm)	Sand	Silt	Clay	С	Ν	S	(H ₂ O)	(CaCl ₂)
Fm	3-0	-	-	_	39.02	1.07	0.09	4.33	3.86
Ah	0-4	-	-	-	15.31	0.47	0.04	4.58	3.52
Bm	4-14	53.6	43.5	2.9	1.85	0.07	-	4.54	3.66
IIBm	14-23	35.9	43.9	20.2	0.74	0.04	-	5.47	4.57
IIIBm	23-48	86.1	9.3	4.6	0.21	0.02	-	6.34	5.39
IIIBC	48-82	85.2	11.5	3.4	0.16	0.01	-	6.67	5.94
IIIC	82-112+	83.5	12.6	3.9	0.16	0.01	-	7.12	6.28

Table A2-1: Selected physical and chemical properties, pedon Y08-18, McConnell moraine.

	Depth		cmol (+) / kg								
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	\mathbf{K}^{+}	Mg ²⁺	Mn ²⁺	Na ⁺	CEC		
Fm	3-0	0.40	22.94	0.05	3.22	3.84	1.44	0.19	32.08		
Ah	0-4	3.19	5.97	0.54	0.85	0.96	0.19	0.09	11.81		
Bm	4-14	1.63	0.62	0.14	0.09	0.09	0.01	0.05	2.63		
IIBm	14-23	0.66	9.96	0.02	0.12	4.16	0.00	0.10	15.02		
IIIBm	23-48	0.05	5.24	0.00	0.09	1.85	0.01	0.05	7.30		
IIIBC	48-82	0.02	5.23	0.00	0.12	1.45	0.01	0.05	6.87		
IIIC	82-112+	< 0.001	5.92	< 0.001	0.14	1.35	0.01	0.06	7.49		

	Depth				Fe _o /	Fe _d /			
<u>Horizon</u>	(cm)	Alp	Alo	<u> </u>	Feo	Fed	Sio	Fed	Fe _{Tot}
Ah	0-4	-	-	-	-	-	-	-	-
Bm	4-14	0.08	0.13	0.05	0.31	0.12	0.04	2.54	0.04
IIBm	14-23	0.75	0.34	0.52	0.40	1.13	0.13	0.36	0.31
IIIBm	23-48	0.04	0.23	0.05	0.50	0.70	0.18	0.71	0.24
IIIBC	48-82	0.03	0.14	0.04	0.34	0.59	0.15	0.57	0.19
IIIC	82-112+	0.02	0.17	0.04	0.43	0.69	0.19	0.62	0.23

Subscripts: p = pyrophosphate; o = oxalate; d = dithionite-citrate-bicarbonate; Tot = total.

	Depth			pH	pН				
<u>H</u> orizon	(cm)	Sand	Silt	Clay	С	Ν	S	(H ₂ O)	(CaCl ₂)
Fmi	5-0	-	-	-	18.04	0.69	0.09	5.24	4.32
Bm	0-9	48.5	47.6	4.0	1.07	0.05	-	6.05	5.16
IIBm	9-35	55.6	27.9	16.5	0.38	0.02	-	6.51	5.38
IIBC	35-56	61.2	27.0	11.8	0.18	0.01	-	6.92	5.83
IIC	56-100+	63.1	26.5	10.4	0.15	0.01		7.11	6.00

 Table A2-2: Selected physical and chemical properties, pedon Y08-19, McConnell moraine.

	Depth cmol (+) / kg									
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	K ⁺	Mg ²⁺	Mn ²⁺	Na ⁺	CEC	
Fmi	5-0	0.39	19.75	0.02	0.86	2.60	0.36	0.09	24.06	
Bm	0-9	0.21	2.45	0.02	0.07	0.26	0.01	0.06	3.07	
IIBm	9-35	0.04	9.16	0.00	0.10	4.40	0.01	0.15	13.87	
IIBC	35-56	0.02	8.10	< 0.001	0.10	3.47	0.01	0.15	11.85	
IIC	56-100+	0.00	7.18	< 0.001	0.09	2.51	0.01	0.12	9.92	
	Depth			%		:		Fe _o /	Fe _d /	
Horizon	(cm)	Alp	Alo	Fep	Feo	Fed	Sio	Fed	Fe _{Tot}	
Bm	0-9	0.08	0.19	0.04	0.42	0.16	0.09	2.62	0.06	
IIBm	9-35	0.05	0.28	0.04	0.34	0.90	0.15	0.37	0.30	
IIBC	35-56	0.03	0.20	0.04	0.28	0.69	0.19	0.40	0.23	
IIC	56-100+	0.28	0.14	0.23	0.21	0.60	0.15	0.35	0.22	

Subscripts: p = pyrophosphate; o = oxalate; d = dithionite-citrate-bicarbonate; Tot = total. * Data are reported on an oven-dry basis.

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	Depth				pH	pН			
Horizon	(cm)	Sand	Silt	Clay	С	N	S	(H ₂ O)	(CaCl ₂)
Fm	8-0				45.21	1.44	0.13	4.58	3.87
Bm	0-8	36.8	59.5	3.7	0.72	0.03		5.63	4.71
IIBml	8-26	51.8	32.9	15.4	0.59	0.03		5.63	4.57
IIBm2	26-42	57.5	29.0	13.6	0.23	0.02		6.80	5.63
IIBC	42-61	59.9	27.7	12.4	0.21	0.01		7.15	6.14
IICk	61-110+	73.1	20.8	6.1	0.23	0.01		8.62	7.32

 Table A2-3: Selected physical and chemical properties, pedon Y08-31, McConnell moraine.

	Depth								
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	K	Mg ²⁺	Mn ²⁺	Na ⁺	CEC
Fm	8-0	0.37	15.65	0.07	3.76	4.45	1.47	0.20	25.97
Bm	0-8	0.44	1.05	0.05	0.05	0.08	0.00	0.05	1.72
IIBml	8-26	0.41	9.02	0.01	0.11	2.94	0.01	0.07	12.58
IIBm2	26-42	0.02	6.87	< 0.001	0.10	2.78	0.02	0.09	9.87
IIBC	42-61	0.02	6.42	0.00	0.12	2.29	0.01	0.09	8.94
IICk	61-110+	0.01	4.87	< 0.001	0.14	0.64	< 0.001	0.04	5.70

	Depth			Fe _o /	Fe _d /					
Horizon	(cm)	Alp	Alo	Fep	Feo	Fe _d	Sio	Fed	Fe _{Tot}	_
Bm	0-8	0.09	0.17	0.05	0.34	0.12	0.07	2.70	0.05	
IIBm1	8-26	0.08	0.28	0.09	0.54	0.99	0.15	0.55	0.23	
IIBm2	26-42	0.03	0.15	0.05	0.31	0.70	0.13	0.44	0.20	
IIBC	42-61	0.02	0.11	0.03	0.26	0.61	0.11	0.42	0.20	
IICk	61-110+	0.02	0.11	0.03	0.43	0.48	0.12	0.90	0.18	

	Depth			pH	pН				
Horizon	(cm)	Sand	Silt	Clay	С	Ν	S	(H ₂ O)	(CaCl ₂)
Fm	4-0	-	-	-	34.26	1.30	0.12	4.87	4.15
Ahey	0-3	58.8	36.6	4.6	1.81	0.07	-	4.87	3.92
Bmjy	3-19	25.7	70.6	3.7	1.12	0.06	-	5.20	4.19
IIAhb	19-22	-	-	-	1.05	0.04	-	5.29	4.30
IIBm1	22-34	69.4	21.2	9.5	0.40	0.02	-	5.55	4.46
IIBm2	34-48	77.8	15.7	6.6	0.35	0.02	-	5.79	4.67
IIC	48-107+	74.4	21.6	4.0	0.18	0.01		6.49	5.40

Table A2-4: Selected physical and chemical properties, pedon Y08-33, McConnell moraine.

	Depth		cmol (+) / kg								
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	\mathbf{K}^{+}	Mg ²⁺	Mn ²⁺	Na ⁺	CEC		
Fm	4-0	0.62	23.22	0.12	2.30	4.22	1.95	0.14	32.57		
Ahey	0-3	1.20	1.20	0.15	0.13	0.25	0.01	0.06	3.00		
Bmjy	3-19	0.79	0.89	0.08	0.09	0.15	0.00	0.04	2.05		
IIAhb	19-22	1.26	2.75	0.10	0.10	0.83	0.03	0.12	5.19		
IIBm1	22-34	0.51	2.76	0.02	0.08	0.88	0.01	0.06	4.31		
IIBm2	34-48	0.38	2.05	0.01	0.06	0.59	0.01	0.04	3.13		
IIC	48-107+	0.04	2.83	0.00	0.07	1.05	0.01	0.05	4.04		

	Depth				Fe _o /	Fe _d /			
Horizon	(cm)	$\mathbf{Al}_{\mathbf{p}}$	Alo	Fep	Feo	Fed	Sio	Fed	Fe _{Tot}
Ahey	0-3	0.04	0.09	0.06	0.39	0.17	0.03	2.26	0.06
Bmjy	3-19	0.04	0.09	0.03	0.17	0.07	0.03	2.38	0.03
IIAhb	19-22	0.10	0.23	0.12	0.58	0.79	0.10	0.74	-
IIBm1	22-34	0.32	0.29	0.33	0.75	0.95	0.13	0.79	0.30
IIBm2	34-48	0.16	0.27	0.15	0.53	0.59	0.13	0.90	0.22
IIC	48-107+	0.03	0.12	0.04	0.28	0.39	0.10	0.72	0.14

	Depth				%			pH	pН
Horizon	(cm)	Sand	Silt	Clay	С	Ν	S	(H ₂ O)	(CaCl ₂)
Fmi	2-0	-	-	-	24.83	0.96	0.09	4.58	3.63
Bm	0-4	47.1	46.6	6.3	2.97	0.13	-	4.59	3.60
IIBm	4-10	56.7	33.5	9.8	1.28	0.06	-	5.36	4.40
IIIBm1	10-36	89.8	5.9	4.4	0.46	0.03	-	5.66	4.56
IIIBm2	36-60	91.1	5.6	3.3	0.36	0.02	-	5.84	4.52
IIIBC	60-90	87.3	10.2	2.5	0.20	0.02	-	5.76	4.54
IIIC1	90-119	86.1	11.3	2.5	0.15	0.01	-	6.03	4.85
IIIC2	119-160+	92.6	5.7	1.7	0.13	0.01		6.25	5.02

Table A2-5: Selected physical and chemical properties, pedon Y08-15, penultimate moraine.

	Depth _		cmol (+) / kg								
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	K	Mg ²⁺	<u>M</u> n ²⁺	Na ⁺	CEC		
Fmi	2-0	2.87	8.43	0.33	0.97	2.49	1.64	0.12	16.85		
Bm	0-4	2.13	0.40	0.16	0.16	0.19	0.07	0.06	3.18		
IIBm	4-10	1.25	1.16	0.02	0.08	0.26	0.02	0.04	2.83		
IIIBm1	10-36	0.47	0.61	0.01	0.07	0.14	0.00	0.02	1.31		
IIIBm2	36-60	0.50	0.65	0.01	0.06	0.19	< 0.001	0.02	1.42		
IIIBC	60-90	0.43	1.06	0.00	0.07	0.27	0.00	0.02	1.86		
IIIC1	90-119	0.19	2.87	0.00	0.10	0.76	0.01	0.03	3.95		
IIIC2	119-160+	0.08	2.50	0.00	0.08	0.68	0.01	0.03	3.38		

	Depth		<u>_</u>		Fe _o /	Fe _d /			
Horizon	(cm)	Alp	Alo	Fep	Feo	Fed	Sio	Fed	Fe _{Tot}
Bm	0-4	0.09	0.15	0.09	0.36	0.29	0.03	1.22	0.11
IIBm	4-10	0.26	0.48	0.13	0.60	1.11	0.14	0.54	0.30
IIIBm1	10-36	0.16	0.35	0.04	0.53	0.51	0.13	1.03	0.15
IIIBm2	36-60	0.11	0.24	0.04	0.53	0.42	0.11	1.26	0.13
IIIBC	60-90	0.08	0.19	0.03	0.47	0.51	0.10	0.92	0.16
IIIC1	90-119	0.04	0.11	0.03	0.46	0.52	0.07	0.88	0.14
IIIC2	119-160+	0.03	0.13	0.03	0.32	0.44	0.09	0.72	0.17

Subscripts: p = pyrophosphate; o = oxalate; d = dithionite-citrate-bicarbonate; Tot = total.

* Data are reported on an oven-dry basis.

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	Depth				pH	pН			
Horizon	<u>(cm)</u>	Sand	Silt	Clay	С	Ν	S	(H ₂ O)	(CaCl ₂)
Fm	4-0	-	-	-	38.08	1.21	0.11	4.13	3.34
Bm	0-10	39.7	57.7	2.6	1.28	0.06	-	4.62	3.68
IIBml	10-23	72.7	18.0	9.3	1.41	0.07	-	5.18	4.09
IIBm2	23-45	83.2	11.7	5.1	0.69	0.05	-	5.64	4.44
IIBm3	45-63	86.2	9.4	4.4	0.43	0.03	-	5.84	4.61
IIC	63-110+	83.0	13.9	3.1	0.22	0.02	-	6.07	4.88

Table A2-6: Selected physical and chemical properties, pedon Y08-16, penultimate moraine.

	Depth	cmol (+) / kg									
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	K ⁺	Mg ²⁺	Mn ²⁺	Na ⁺	CEC		
Fm	4-0	2.00	8.70	0.56	2.16	2.24	1.02	0.12	16.80		
Bm	0-10	1.11	0.25	0.10	0.05	0.04	0.00	0.06	1.61		
IIBm1	10-23	1.83	0.66	0.06	0.08	0.14	0.01	0.03	2.81		
IIBm2	23-45	0.75	0.58	0.01	0.05	0.12	0.01	0.02	1.55		
IIBm3	45-63	0.50	0.71	0.00	0.05	0.16	0.01	0.02	1.45		
IIC	63-110+	0.27	1.21	0.00	0.08	0.33	0.01	0.02	1.91		
	Depth				%			Fe _o /	Fe _d /		
Horizon	<u>(cm)</u>	Alp	Alo	Fep	Feo	Fed	Sio	Fed	Fe _{Tot}		
Bm	0-10	0.03	0.07	0.04	0.24	0.11	0.03	2.11	0.05		
IIBm1	10-23	0.39	0.64	0.25	0.62	1.09	0.15	0.57	0.29		
IIBm2	23-45	0.26	0.52	0.08	0.34	0.67	0.19	0.51	0.20		
IIBm3	45-63	0.20	0.40	0.05	0.37	0.65	0.15	0.57	0.20		
IIC	63-110+	0.14	0.27	0.05	0.36	0.54	0.12	0.66	0.16		

	Depth			pH	рН				
Horizon_	(cm)	Sand	Silt	Clay	С	Ν	S	(H ₂ O)	(CaCl ₂)
Fm	5-0	-	-	-	39.10	0.95	0.08	3.85	2.96
Bm	0-10	48.3	46.0	5.7	1.46	0.06	-	4.71	3.86
IIBm1	10-15	21.2	64.4	14.4	1.42	0.07	-	5.43	4.40
IIBm2	15-20	32.8	49.4	17.9	0.65	0.03	-	5.73	4.58
IIIBm1	20-40	65.1	25.7	9.2	0.25	0.02	-	5.91	4.69
IIIBm2	40-70+	67.2	23.1	9.8	0.21	0.02	-	6.04	4.76
	Depth				cmol	(+) / kg			
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	K ⁺	Mg ²⁺	Mn ²⁺	Na ⁺	CEC
Fm	5-0	3.84	4.43	0.64	1.76	1.78	0.21	0.12	12.77
Bm	0-10	1.70	0.12	0.09	0.04	0.04	0.00	0.04	2.03
IIBm1	10-15	1.42	3.72	0.00	0.11	1.13	0.29	0.08	6.74
IIBm2	15-20	0.50	4.96	0.01	0.07	1.58	0.06	0.11	7.30
IIIBm1	20-40	0.37	2.83	0.00	0.10	0.85	0.00	0.08	4.24
IIIBm2	40-70+	0.31	3.75	0.00	0.09	1.01	0.00	0.08	5.26
	Depth				⁰ /0			Fe _o /	Fe _d /
Horizon	(cm)	Alp	Alo	Fe _p	Feo	Fe _d	Sio	Fe _d	Fe _{Tot}
Bm	0-10	0.12	0.21	0.08	0.42	0.20	0.08	2.13	0.07
IIBml	10-15	0.12	0.30	0.17	0.85	1.37	0.11	0.62	0.39
IIBm2	15-20	0.10	0.31	0.10	0.64	1.19	0.12	0.54	0.31
IIIBm1	20-40	0.08	0.27	0.04	0.47	0.71	0.10	0.66	0.22
IIIBm2	40-70+	0.08	0.07	0.03	0.11	0.58	0.02	0.18	0.19

Table A2-7: Selected physical and chemical properties, pedon Y08-21, penultimate till over bedrock.

	Depth			0		рН	pН		
Horizon	(cm)	Sand	Silt	Clay	С	Ν	S	(H ₂ O)	(CaCl ₂)
Fm	5-0	-	-	-	40.98	1.35	0.12	5.08	4.28
Aej	0-2	41.2	55.5	3.4	1.08	0.05	-	4.77	3.80
Bm	2-9	51.4	42.1	6.5	1.18	0.05	-	5.18	4.20
IIBm	9-13	26.5	58.6	14.9	0.82	0.04	-	5.42	4.42
IIIBm1	13-36	70.1	19.5	10.3	0.36	0.02	-	5.59	4.51
IIIBm2	36-72	74.1	19.5	6.5	0.19	0.01	-	5.97	4.67
IIIBC	72-102+	74.3	19.8	5.9	0.17	0.01	-	5.92	4.61
Weathered	d Clast	47.0	24.9	28.1	0.25	0.02	-		

Table A2-8: Selected physical and chemical properties, pedon Y08-22, penultimate till over bedrock.

	Depth								
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	\mathbf{K}^{+}	Mg ²⁺	Mn ²⁺	Na ⁺	CEC
Fm	5-0	0.19	19.76	0.02	2.28	3.24	6.44	0.10	32.03
Aej	0-2	0.64	0.38	0.05	0.08	0.08	0.01	0.04	1.29
Bm	2-9	1.14	0.36	0.05	0.05	0.05	0.02	0.04	1.71
IIBm	9-13	1.12	2.95	0.01	0.21	1.19	0.05	0.05	5.57
IIIBm1	13-36	0.93	3.39	0.01	0.15	1.39	0.01	0.07	5.94
IIIBm2	36-72	0.43	2.80	0.00	0.14	0.92	0.01	0.08	4.37
IIIBC	72-102+	0.41	8.40	0.00	0.20	2.34	0.02	0.10	11.47
Weathere	d Clast	3.43	16.49	0.00	0.26	5.45	0.09	0.18	25.90

	Depth				Fe _o /	Fe _d /			
Horizon	(cm)	Alp	Alo	Fep	Feo	Fed	Sio	Fed	Fe _{Tot}
Aej	0-2	0.02	0.05	0.03	0.26	0.09	0.02	3.03	0.03
Bm	2-9	0.19	0.27	0.10	0.35	0.18	0.07	1.93	0.06
IIBm	9-13	0.15	0.32	0.14	0.77	1.44	0.10	0.53	0.37
IIIBm1	13-36	0.13	0.34	0.06	0.65	0.56	0.11	1.15	0.16
IIIBm2	36-72	0.08	0.24	0.03	0.63	0.44	0.10	1.43	0.13
IIIBC	72-102+	0.24	0.26	0.16	0.72	0.55	0.18	1.32	0.13
Weathere	d Clast	0.34	0.40	0.16	0.25	0.79	0.13	0.32	0.21

	Depth				%			pH	pН
<u>Horizon</u>	(cm)	Sand	Silt	Clay	С	N	S	(H ₂ O)	(CaCl ₂)
F	10-7	-	-	_	39.36	1.371	0.139	4.36	3.61
Fmi	7-0	-	-	-	19.30	0.69	0.09	4.59	3.84
Bmjy	0-18	31.1	65.4	3.6	1.01	0.05	-	5.57	4.45
IIAe	18-20	23.1	66.7	10.2	1.50	0.05	-	5.67	4.43
IIIBm1	20-36	67.1	24.3	8.7	0.54	0.03	-	5.99	4.78
IIIBm2	36-67	69.4	24.4	6.2	0.23	0.02	-	6.40	4.60
IIIBC	67-100	79.0	18.0	3.0	0.10	0.01	-	6.55	5.25
IIIC	100-110+	74.5	21.9	3.6	0.14	0.01	-	6.65	5.39

Table A2-9: Selected physical and chemical properties, pedon Y08-23, penultimate moraine.

	Depth _		cmol (+) / kg									
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	\mathbf{K}^{+}	Mg ²⁺	Mn ²⁺	Na ⁺	CEC			
F	10-7	1.10	17.77	0.15	1.88	4.93	1.65	0.25	27.73			
Fmi	7-0	2.96	9.34	0.28	0.96	2.30	0.17	0.16	16.17			
Bmjy	0-18	0.72	0.53	0.04	0.03	0.11	< 0.001	0.06	1.50			
IIAe	18-20	2.00	2.70	0.03	0.11	0.85	0.01	0.10	5.80			
IIIBm1	20-36	0.46	1.05	0.00	0.12	0.41	0.01	0.08	2.12			
IIIBm2	36-67	0.39	1.45	0.00	0.09	0.50	0.00	0.09	2.52			
IIIBC	67-100	0.08	4.18	0.00	0.11	1.04	0.01	0.08	5.51			
IIIC	100-110+	0.03	5.01	0.00	0.14	1.20	0.01	0.06	6.44			

	Depth				Fe _o /	Fe _d /			
Horizon	(cm)	Alp	Alo	Fep	Feo	Fed	Sio	Fed	Fe _{Tot}
Bmjy	0-18	0.11	0.17	0.05	0.25	0.11	0.06	2.34	0.05
IIAe	18-20	0.12	0.22	0.08	0.33	0.60	0.07	0.55	0.25
IIIBm1	20-36	0.19	0.59	0.08	0.49	0.78	0.23	0.63	0.23
IIIBm2	36-67	0.12	0.32	0.05	0.37	0.58	0.14	0.63	0.15
IIIBC	67-100	0.03	0.14	0.03	0.37	0.53	0.11	0.70	0.16
IIIC	100-110+	0.03	0.17	0.03	0.41	0.57	0.15	0.72	0.16

* Data are reported on an oven-dry basis.

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	Depth%								pН
Horizon	(cm)	Sand	Silt	Clay	С	N	S	(H ₂ O)	(CaCl ₂)
Fmi	4-0				22.09	0.59	0.06	3.24	3.25
Bmy	0-8	29.5	67.0	3.5	0.63	0.03		5.43	4.42
IIBm	8-14	47.5	41.2	11.3	0.79	0.03		5.72	4.70
IIIBm	14-30	66.8	27.0	6.2	0.25	0.02		6.07	4.97
IIIC	30-110+	74.7	21.6	3.8	0.15	0.01		6.92	5.99

Table A2-10: Selected physical and chemical properties, pedon Y08-36, penultimate till.

	Depth	cmol (+) / kg									
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	K ⁺	Mg ²⁺	Mn ²⁺	Na^+	CEC		
Fmi	4-0	4.02	3.84	0.96	0.87	1.00	0.46	0.12	11.27		
Bmy	0-8	0.50	0.26	0.04	0.03	0.05	0.01	0.06	0.94		
IIBm	8-14	0.51	2.57	0.01	0.07	0.75	0.01	0.06	3.99		
IIIBm	14-30	0.17	2.20	0.00	0.10	0.75	0.00	0.05	3.27		
IIIC	30-110+	0.02	3.25	0.00	0.11	1.24	0.00	0.05	4.67		
	Depth				%			Fe _o /	Fe _d /		
Horizon	(cm)	Al_p	Al _o	Fep	Feo	Fe _d	Sio	Fed	Fe _{Tot}		
Bmy	0-8	0.09	0.16	0.07	0.28	0.14	0.08	2.01	0.06		
IIBm	8-14	0.18	0.47	0.14	0.74	1.11	0.18	0.67	0.30		
IIIBm	14-30	0.08	0.25	0.04	0.36	0.52	0.12	0.69	0.18		
IIIC	30-110+	0.03	0.21	0.04	0.47	0.56	0.19	0.84	0.20		

Subscripts: p = pyrophosphate; o = oxalate; d = dithionite-citrate-bicarbonate; Tot = total. * Data are reported on an oven-dry basis.

	Depth			%)			рН	pН
Horizon	(cm)	Sand	Silt	Clay	C	Ν	S	(H ₂ O)	(CaCl ₂)
Ah	0-7	-	-	-	15.62	0.53	0.06	4.51	3.45
Bmjy	7-17	68.0	28.9	3.1	1.62	0.07	-	5.02	4.02
IIBm	17-22	28.6	56.9	14.5	2.05	0.11	-	5.58	4.60
IIIBmy1	22-47	72.5	17.0	10.5	0.42	0.03	-	5.58	4.41
IIIBmy2	47-62	68.2	20.0	11.8	0.18	0.01	-	5.68	4.43
IIIBmy3	62-97	74.4	15.7	9.9	0.19	0.01	-	5.67	4.43
IVBmy	97-117+	64.2	23.2	12.6	0.14	0.01	-	6.03	4.79

Table A2-11: Selected physical and chemical properties, pedon Y08-10, pre-Reid weathered granitic bedrock.

	Depth	cmol (+) / kg							
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	\mathbf{K}^{+}	Mg ²⁺	Mn ²⁺	Na ⁺	CEC
Ah	0-7	4.05	1.23	0.63	0.81	0.92	0.13	0.08	7.86
Bmjy	7-17	1.23	0.08	0.05	0.06	0.04	0.02	0.03	1.50
IIBm	17-22	0.68	1.46	< 0.001	0.05	0.43	0.12	0.07	2.80
IIIBmy1	22-47	1.18	2.09	< 0.001	0.06	0.51	0.02	0.04	3.89
IIIBmy2	47-62	1.07	8.15	< 0.001	0.19	2.21	0.05	0.05	11.74
IIIBmy3	62-97	0.79	6.30	< 0.001	0.22	1.64	0.04	0.04	9.03
IVBmy	97-117+	0.13	12.33	< 0.001	0.36	2.43	0.03	0.04	15.32

	Depth				Fe _o /	Fe _d /			
Horizon	(cm)	Alp	Alo	Fep	Feo	Fed	Si _o	Fed	Fe _{Tot}
Ah	0-7	-	-	-	-	-	-	-	-
Bmjy	7-17	0.15	0.21	0.10	0.32	0.18	0.07	1.77	0.05
IIBm	17-22	0.31	0.65	0.19	0.98	1.95	0.17	0.50	0.51
IIIBmy1	22-47	0.24	0.43	0.08	0.20	1.97	0.13	0.10	0.56
IIIBmy2	47-62	0.08	0.17	0.03	0.11	1.15	0.07	0.09	0.48
IIIBmy3	62-97	0.08	0.16	0.05	0.16	1.53	0.07	0.10	0.47
IVBmy	97-117+	0.09	0.16	0.04	0.09	1.16	0.09	0.08	0.43

	Depth				%			_ pH	pН
Horizon	(cm)	Sand	Silt	Clay	С	Ν	S	(H ₂ O)	(CaCl ₂)
Fm	6-0	-	-	-	30.56	1.04	0.09	4.64	3.77
Aey	0-3	58.3	39.3	2.4	1.32	0.06	-	4.58	3.64
Bmy	3-8	55.5	38.4	6.1	1.29	0.06	-	4.99	4.14
IIBmy1	8-13	21.4	63.1	15.6	1.40	0.07	-	5.47	4.37
IIBmy2	13-20	39.1	45.1	15.8	0.83	0.05	-	5.74	4.81
IIIBmy1	20-66	80.1	12.4	7.5	0.24	0.02	-	5.90	4.74
IIIBmy2	20-90	87.6	7.5	4.9	0.15	0.01	-	5.90	4.73
Silt Cap	90	66.6	29.5	3.9	0.14	0.01	-	-	-
IVBmy1	23-110+	71.5	19.4	9.1	0.15	0.01	-	5.90	4.65
IVBmy2	83-110+	75.3	17.4	7.3	0.12	0.01	-	6.13	5.08

Table A2-12: Selected physical and chemical properties, pedon Y08-13, pre-Reid weathered granitic bedrock.

	Depth		cmol (+) / kg									
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	<u>K</u> ⁺	Mg ²⁺	<u>Mn</u> ²⁺	Na ⁺	CEC			
Fm	6-0	0.92	11.54	0.19	1.71	3.70	1.41	0.10	19.57			
Aey	0-3	0.85	0.35	0.07	0.06	0.08	0.00	0.04	1.45			
Bmy	3-8	1.29	0.28	0.09	0.04	0.03	< 0.001	0.04	1.77			
IIBmy1	8-13	1.32	1.52	0.03	0.11	0.22	0.06	0.04	3.30			
IIBmy2	13-20	0.39	1.58	0.01	0.06	0.20	0.00	0.03	2.26			
IIIBmy1	20-66	0.43	1.45	< 0.001	0.06	0.25	0.01	0.03	2.24			
IIIBmy2	20-90	0.28	1.17	< 0.001	0.07	0.33	0.01	0.03	1.88			
Silt Cap	90	0.20	3.91	< 0.001	0.15	1.34	0.01	0.04	5.66			
IVBmy1	23-110+	0.27	6.13	< 0.001	0.23	2.01	0.03	0.05	8.72			
IVBmy2	83-110+	0.07	6.16	0.00	0.27	2.00	0.03	0.05	8.59			

	Depth				%			Fe _o /	Fe _d /
Horizon	(cm)	Alp	Al _o	Fep	Feo	Fed	Sio	Fed	Fe _{Tot}
Aey	0-3	0.03	0.07	0.03	0.30	0.12	0.02	2.50	0.04
Bmy	3-8	0.16	0.20	0.07	0.28	0.13	0.05	2.12	0.05
IIBmy1	8-13	0.24	0.42	0.17	0.74	1.89	0.11	0.39	0.45
IIBmy2	13-20	0.54	0.91	0.25	0.50	1.32	0.32	0.38	0.36
IIIBmy1	20-66	0.38	0.31	0.23	0.18	1.17	0.11	0.15	0.40
IIIBmy2	20-90	0.08	0.18	0.03	0.15	0.78	0.08	0.20	0.36
Silt Cap	90	0.04	0.18	0.03	0.22	1.82	0.10	0.12	0.45
IVBmy1	23-110+	0.06	0.14	0.03	0.20	2.12	0.06	0.09	0.64
IVBmv2	83-110+	1.71	0.10	0.47	0.09	0.90	0.04	0.10	0.62

	Depth%							pН	pН
Horizon	(cm)	Sand	Silt	Clay	С	Ν	S	(H ₂ O)	(CaCl ₂)
Fm	2-0	-	~	-	19.55	0.79	0.09	5.13	4.30
Bmy	0-5	43.3	52.9	3.8	1.80	0.09	-	5.30	4.38
IIBmy1	5-23	70.8	22.4	6.8	0.97	0.06	-	5.49	4.47
IIBmy2	23-85+	80.1	15.6	4.4	0.28	0.02	-	5.88	4.71
IIIBCy	39-85+	51.3	44.0	4.7	0.34	0.02	-	5.66	4.51

Table A2-13: Selected physical and chemical properties, pedon Y08-24, pre-Reid weathered granitic bedrock.

	Depth		cmol (+) / kg									
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	\mathbf{K}^{+}	Mg ²⁺	Mn ²⁺	Na ⁺	CEC			
Fm	2-0	0.25	16.89	0.06	1.43	3.64	2.20	0.06	24.53			
Bmy	0-5	0.66	1.05	0.03	0.13	0.23	0.06	0.03	2.19			
IIBmy1	5-23	0.84	0.84	0.03	0.04	0.11	0.00	0.01	1.87			
IIBmy2	23-85+	0.40	0.68	0.01	0.03	0.20	0.00	0.01	1.33			
IIIBCy	39-85+	0.54	1.78	0.00	0.04	0.56	0.01	0.02	2.96			

Depth%								Fe _o /	Fe _d /
Horizon	(cm)	Alp	Alo	Fep	Feo	Fe _d	Sio	Fed	Fe _{Tot}
Bmy	0-5	0.05	0.12	0.05	0.33	0.16	0.05	1.99	0.06
IIBmy1	5-23	0.24	0.50	0.13	0.41	0.71	0.17	0.58	0.31
IIBmy2	23-85+	0.42	0.29	0.17	0.18	0.36	0.11	0.49	0.23
IIIBCy	39-85+	0.11	0.25	0.06	0.21	0.31	0.10	0.67	0.14

Subscripts: p = pyrophosphate; o = oxalate; d = dithionite-citrate-bicarbonate; Tot = total. * Data are reported on an oven-dry basis.

	Depth			0	/0			рН	pН
Horizon	<u>(cm)</u>	Sand	Silt	Clay	С	N	S	(H ₂ O)	(CaCl ₂)
Fmi	1-0	-	-	-	17.42	0.66	0.06	4.36	3.36
Bm1	0-4	77.2	18.4	4.4	4.36	0.18	-	4.53	3.68
Bm2	4-7	72.5	23.7	3.8	2.08	0.08	-	4.97	4.03
IIAey	7-9	36.0	55.5	8.6	1.32	0.05	-	5.12	4.13
IIIBmy1	9-20	46.3	42.4	11.3	1.46	0.07	-	5.45	4.53
IIIBmy3	20-33	71.2	21.1	7.7	0.29	0.02	-	5.58	4.32
IIIBmy2	33-40	48.1	43.5	8.4	0.52	0.03	-	5.76	4.63
IIIBmy4	40-110+	81.3	12.7	6.0	0.20	0.01	-	5.71	4.39
IIIC	110+	75.2	19.0	5.8	0.20	0.01	-	5.87	4.63

Table A2-14: Selected physical and chemical properties, pedon Y08-28, pre-Reid weathered granitic bedrock.

	Depth				cmol	(+) / kg			
Horizon	(cm)	Al ³⁺	Ca ²⁺	Fe ³⁺	\mathbf{K}^{+}	Mg ²⁺	Mn ²⁺	Na⁺	CEC
Fmi	1-0	5.69	2.09	0.73	0.51	0.41	0.04	0.07	9.54
Bm1	0-4	2.76	0.62	0.22	0.11	0.09	0.01	0.05	3.86
Bm2	4-7	1.10	0.23	0.12	0.08	0.03	0.00	0.04	1.60
IIAey	7-9	2.15	0.77	0.05	0.03	0.04	0.01	0.05	3.10
IIIBmy1	9-20	0.54	0.50	0.03	0.03	0.03	0.01	0.03	1.17
IIIBmy3	20-33	2.14	6.83	0.00	0.07	2.27	0.04	0.06	11.40
IIIBmy2	33-40	0.78	3.35	0.00	0.03	0.94	0.01	0.03	5.15
IIIBmy4	40-110+	0.80	7.72	0.00	0.11	2.48	0.02	0.06	11.19
IIIC	110+	0.30	10.05	0.00	0.14	2.83	0.03	0.06	13.41

	Depth	<u> </u>	·	0	6			Fe _o /	Fe _d /
Horizon	(cm)	Alp	Alo	Fep	Feo	Fed	Sio	Fed	Fe _{Tot}
Bml	0-4	0.12	0.22	0.11	0.47	0.29	0.07	1.62	-
Bm2	4-7	0.10	0.16	0.07	0.40	0.16	0.05	2.54	0.04
IIAey	7-9	0.19	0.26	0.11	0.48	0.61	0.07	0.79	0.26
IIIBmy1	9-20	0.31	0.98	0.12	1.12	1.41	0.34	0.79	0.34
IIIBmy3	20-33	0.80	0.42	0.36	0.53	0.83	0.11	0.64	0.24
IIIBmy2	33-40	0.25	0.83	0.06	0.63	0.88	0.33	0.72	0.23
IIIBmy4	40-110+	0.87	0.24	0.37	0.30	0.58	0.10	0.52	0.19
IIIC	110+	0.08	0.20	0.04	0.26	0.85	0.11	0.31	0.20

* Data are reported on an oven-dry basis.

Appendix 3: Total elemental analysis of <2mm fractions.

	Ag	Ba	Ce	Co	Cr	Cs	Cu	Dy	Er	Eu	Ga	Gd	Hf	Ho	La	Lu	Мо	Nb	Nd
										ppm									
Bm	<1	726	30.7	10.7	20	0.94	15	1.73	0.93	0.85	20.2	2.43	3.4	0.32	16.2	0.13	<2	5.2	2 13.8
IIBm	<1	1175	25.1	12.3	110	1.5	22	1.8	1.07	0.71	17.4	2.23	3.4	0.36	12.1	0.16	<2	7.8	11
IIIBm	<1	1415	36.6	10.2	90	1.04	18	1.78	0.99	0.74	17.1	2.17	3.4	0.34	13.6	0.15	<2	4.9	11.7
IIIBC	<1	1300	30	11.5	110	0.98	19	2.48	1.42	0.96	16.6	3.06	3.7	0.49	17.5	0.2	<2	5.1	16.3
IIIC	<1	1310	30	10.5	100	1.12	25	2.73	1.62	1.02	16.5	3.2	3.3	0.55	16.7	0.23	<2	5.4	16.3
	Ni	Pb	Pr	Rb	Sm	Sn	Sr	Ta	ТЬ	Th	TI	Tm	U	v	W	Y	Yb	Zn	Zr
										ppm									
Bm	11	9	3.43	39	2.55	1	788	0.4	0.36	3.66	<0.5	0.1	1.55	93	1	9	0.86	65	122
IIBm	33	14	2.63	43.1	2.04	1	570	0.5	0.31	3.25	<0.5	0.04	1.03	123	1	9.9	1.15	61	128
IIIBm	24	11	2.96	40.3	2.28	1	767	0.3	0.34	3.24	<0.5	0.11	0.94	97	<1	9	0.99	45	129
IIIBC	27	10	3.94	39.8	3.12	1	73 9	0.3	0.47	2.94	< 0.5	0.16	1.01	101	<1	12.5	1.31	54	141
IIIC	26	13	3.9	41.7	3.2	1	733	0.4	0.5	3.03	<0.5	0.21	1.03	100	1	15.3	1.51	54	123
	SiO ₂	Al ₂	O ₃ F	e_2O_3	CaO	MgO	Na	2 0	K ₂ O	Cr ₂ O ₃	TiO	2 M	nO :	P_2O_5	SrO	Ba	ЪL	OI	Total
									%										
Bm	60.4	15.4	40 4	.11	4.23	1.84	3.1	79 .	2.07	< 0.01	0.57	7 0.	06	0.0 8	0.09	0.0	7 6	.64	99.4
IIBm	62.1	16.4	45 5	5.29	2.97	1.85	3.2	25	1.63	0.02	0.56	6 0.	06	0.09	0.07	0.0	8 6	.19	100.5
IIIBm	66.2	15.	85 4	.12	3.59	1.4 8	4.(07	1.7 8	0.01	0.36	5 0.	06	0.14	0.09	0.1	5 2	.59	100.5
IIIBC	64.2	15.5	55 4	.37	4.09	1.92	3.9	95	1.77	0.01	0.39) 0.	08	0.15	0.09	0.1	4 2	.5 8	99.3
IIIC	64.4	15.5	50 4	.36	3.96	1.66	3.9	99	1.84	0.01	0.40) 0.	08	0.16	0.09	0.1	4 2	.70	99.3

 Table A3-1: Geochemical data for site Y08-18, McConnell moraine.

Note: No data for horizon Ah.

* LOI = loss on ignition.

Table A3-	2: Ge(ochem	ical dɛ	ata for	site Y	08-19,	McCo	nnell	morair	le.									
	Ag	Ba	Ce	ů	Cr	Cs	Си	Dy	Er	Eu	Ga	Gd	Ηf	Ηo	La	Lu	Mo	qN	ΡN
										ppm									
Bm	$\overline{\nabla}$	736	32.3	10.1	20	0.97	15	1.74	0.99	0.85	19.8	2.41	3.4	0.33	17.2	0.13	\Diamond	5.3	14.3
lIBm	$\overline{\lor}$	1255	22.6	10.1	80	1.16	18	1.5	0.87	0.7	16.8	1.77	3.1	0.31	10.6	0.15	\Diamond	9	9.7
IIBC	$\overline{\lor}$	1365	32.6	9.6	90	1.15	24	2.86	1.6	1.08	17.7	3.5	3.5	0.55	19.4	0.22	\Diamond	5.9	18.8
IIC	$\overline{\lor}$	1400	31.6	9.4	80	1.05	24	2.54	1.51	0.96	17	3.1	3.6	0.51	17.4	0.23	\heartsuit	5.6	16.2
	ï	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Тb	Th	IT	Tm	Ŋ	>	Ŵ	Y	Уb	Zn	Zr
										ppm									
Bm	10	8	3.54	39.8	2.67	-	765	0.4	0.34	3.78	<0.5	0.12	1.66	87	1	8.9	0.83	61	124
llBm	22	13	2.29	39.9	1.96	1	650	0.4	0.29	2.96	<0.5	0.04	0.77	96	1	8.1	0.85	53	118
IIBC	23	12	4.47	37.7	3.57		750	0.4	0.53	3.18	<0.5	0.2	0.97	93	—	14	1.53	48	131
IIC	23	14	3.81	37.5	3.19	1	764	0.3	0.46	3.06	<0.5	0.19	0.89	89	1	14.5	1.49	50	140
	SiO ₂	Al ₂ (03 F	e_2O_3	CaO	MgO	Na_2	0 X	50	Cr ₂ O ₃	Ti0 ₂	Mn	0	2 0 5	SrO	BaO	FC	T	otal
								_	%										
Bm	61.6	15.3	35 3	.88	4.15	1.72	3.7	4 2	.13	<0.01	0.54	0.0	9 0	.06	0.09	0.07	4.8	6 0	8.2
IIBm	63.5	15.6	50 4	.32	2.95	1.34	3.4	5 1	.57	0.01	0.42	0.0	5 0	.07	0.08	0.09	4.5	6 L	8.0
IIBC	65.4	15.8	85 4	1.24	3.65	1.38	3.9	7 1	.67	0.01	0.41	0.0	7 0	.13	0.09	0.14	2.9	6 0	6.6
IIC	65.7	15.5	90 3	.95	3.86	1.46	4.0	7 1	.74	0.01	0.40	0.0	7 0	.13	0.09	0.15	2.4	8 1	0.00
* LOI = los	ss on ig	mition.																	

Table A3	-3: Ge	ochem	uical dí	ata for	site Y	08-31,	McCt	nnell	moraiı	Je.									
	Ag	Ba	Ce	C	Cr	ů	Си	Dy	Er	Eu	Ga	Gd	Ηf	Ηo	La	Lu	Mo	qN	ΡN
										ppm									
Bm	$\overline{\vee}$	826	37.7	8.9	20	1.06	18	1.63	0.92	0.77	19.9	2.29	3.5	0.31	18.6	0.13	7	5.9	14.9
llBm1	$\overline{\lor}$	1065	24.8	17.8	140	1.99	41	1.85	1.12	0.7	15.6	2.1	3.2	0.37	11.8	0.2	\Diamond	5.6	11.6
IIBm2	$\overline{\lor}$	1290	32.4	14.6	110	1.37	50	2.97	1.77	1.01	16.8	3.29	3.1	0.6	17.2	0.26	\Diamond	9	17.2
IIBC	$\overline{\lor}$	1340	32.3	11.7	80	1.5	35	2.52	1.41	0.89	15.5	3.01	3.6	0.5	16.2	0.24	\Diamond	5.9	15.3
IICk	$\overline{\nabla}$	1420	26.2	9.5	60	1.14	24	2.08	1.21	0.75	14.4	2.43	3.1	0.42	13.1	0.19	\heartsuit	4.6	12.9
	Ni	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Tb	Тћ	II	Tm	Ŋ	>	M	Y	Yb	Zn	Zr
										ppm									
Bm	8	13	3.91	46.7	2.54	1	653	0.4	0.31	4.98	<0.5	0.11	2.05	72	2	8.4	0.84	60	131
llBm1	39	10	2.99	42.6	2.47	-	510	0.4	0.34	2.86	<0.5	0.19	1.06	135	1	9.4	1.14	51	112
IIBm2	33	17	4.07	47.6	3.47	1	623	0.4	0.52	3.68	<0.5	0.26	1.21	117	7	16.5	1.6	53	117
IIBC	25	13	4.03	47.5	2.94	1	603	0.4	0.43	3.83	<0.5	0.21	1.19	66	1	12.9	1.45	47	137
IICk	17	15	3.29	46.2	2.68	-	620	0.4	0.37	2.88	<0.5	0.17		82	-	10.1	1.11	38	109
			E C	¢	C C				C	c t	Ē	ļ	6	¢	Č	¢		E	
	010	2 AI2'	ž Š	e2 0 3	CaO	ngm	Na Na		~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	CP203			2	205	5 C	DaU	FO	-	JIAI
Bm	63.6	14.	50 3	.47	3.32	1.37	3.7	6 2	.39	<0.01	0.47	0.0	5	.08	0.08	0.09	4.4	6 6	1.7
IIBm1	61.4	14.	45 6	6.20	3.81	2.87	3.0	1 1	.61	0.02	0.51	0.0	8	.11	0.07	0.10	6.2′	7 10	0.5
IIBm2	65.4	14.	40 4	16.1	3.65	1.89	3.3	6 1	.94	0.01	0.44	0.0	80	0.13	0.08	0.15	3.1(6 0	9.5
IIBC	66.1	14.	25 4	1.43	3.63	1.70	3.5	0 1	98.	0.01	0.43	0.0	8).16	0.08	0.13	3.8	4 1(0.3
IIC	68.1	13.	75 3	.80	3.96	1.45	3.5	4 2	.04	0.01	0.34	0.0	5	.14	0.08	0.14	3.3	0 1(0.7
* IOI = loo	ss on is	gnition.																	

Table A3	-4: Ge	ochemi	ical dâ	ata for	site Y	08-33,	McC	onnell	morai	ne.									
	Ag	Ba	Ce	ပိ	C	C	Cu	Dy	Er	Eu	Ga	Gd	Ηf	Ηo	La	Lu	Mo	qN	PN
										bpm									
Ahey	$\overline{\vee}$	752	29.2	11.2	40	0.99	13	1.79	0.96	0.85	20.1	2.27	3.3	0.35	14.2	0.14	\heartsuit	5.4	13.2
Bmjy	$\overline{\vee}$	793	33.3	5.9	10	1.03	15	1.26	0.72	0.61	17.1	1.83	3.4	0.24	17.4	0.11	0	5.4	12.8
IIAhb	ı	ı	ı	·	ı	ı	١	١	ı	ı	t	۱	١	ı	ı	•	•	•	ı
IIBm1	$\overline{\vee}$	1440	20.4	10.5	90	1.03	15	1.5	0.92	0.58	16.9	1.66	2.8	0.3	9.7	0.15	\heartsuit	6.2	9.3
IIBm2	$\overline{\lor}$	1455	21.5	10.6	60	0.93	18	1.47	0.89	0.55	17.1	1.69	2.8	0.3	10.4	0.14	\Diamond	5.5	9.4
IIC	$\overline{\vee}$	1490	34.1	9.3	110	0.9	15	1.88	1.09	0.73	16.4	2.19	3.2	0.37	16.8	0.17	\heartsuit	5.9	13.3
	Ni	Pb	\mathbf{Pr}	Rb	Sm	Sn	Sr.	Та	Tb	Тћ	II	Tm	n	>	M	Y	Yb	Zn	Zr
										bpm									
Ahey	12	11	3.29	39.4	2.51	-	760	0.4	0.32	3.55	<0.5	0.12	1.55	101	2	6	0.89	59	120
Bmjy	9	15	3.43	45.8	2.09	Ţ	530	0.4	0.25	4.97	<0.5	0.08	2.01	46	7	6.8	0.68	51	130
lIAhb	ı	ı	ı	ı	ı	ı	ı	•	·	ı	١	I	ı	ı	,	ı	ı	ı	1
IIBm1	18	18	2.31	47.3	1.86	1	647	0.3	0.27	2.36	<0.5	0.2	0.98	101	4	8.2	0.89	46	104
IIBm2	20	15	2.31	46.9	1.94	-	676	0.3	0.27	2.47	<0.5	0.07	0.9	89	S	8.1	0.9	50	105
IIC	18	16	3.41	49.4	2.4	-	691	0.4	0.32	3.71	<0.5	0.3	1.02	92	2	10.1	1.01	41	121
	SiO ₂	Al ₂ C	J 3 Fc	e2 0 3	CaO	MgO	Na	20 1	K20	Cr ₂ 03	TiO	2 Mr	Õ	205	SrO	BaO	rc	L IO	otal
	1			•)		I	%	1				1					
Ahey	60.8	14.7	70 4	.08	4.16	1.75	3.6	64	1.91	<0.01	0.57	0.0	<u>)5</u>	0.07	0.09	0.09	5.8	5	7.7
Bmjy	66.3	13.8	35 3	.08	2.75	0.99	Э.,	73	2.63	<0.01	0.40	0.0	05	0.07	0.07	0.10	4.9	9	0.6
lIAhb	ı			1	·	•	•			ı	ı	•	_	·	ı	ı	·		·
IIBm1	65.8	14.6	55 4	.49	2.94	1.30	3.1	57	2.01	0.01	0.37	0.()3	0.07	0.08	0.16	3.2	5 6;	8.8
IIBm2	67.3	14.7	70 3	68.	2.95	1.18	3.	74	2.03	0.01	0.31	0.()3	0.04	0.08	0.16	2.6	5 09	0.6
IIC	68.6	14.5	50 3	.87	3.39	1.24	3.	75 .	2.12	0.01	0.36	0.(96	0.13	0.08	0.17	1.5	8 1	00.5

* LOI = loss on ignition.

Table A3	-5: Ge	sochem	vical dɛ	ata for	site Y	08-15,	penul	timate	morai	ine.									
	Ag	Ba	Ce	ပီ	Cr	Cs	Си	Dy	Er	Eu	Ga	Gd	Ηf	Ho	La	Lu	Mo	qN	PN
										bpm									
Bm	$\overline{\vee}$	171	31.4	9.2	20	1.43	18	1.76	0.98	0.81	20	2.36	3.7	0.33	16.7	0.14	\heartsuit	6.2	13.6
lIBm	$\overline{\vee}$	1170	40.4	10.3	60	2.09	21	2.43	1.43	0.86	19.3	ŝ	4.2	0.48	20.3	0.22	\Diamond	8.9	16.9
IIIBm1	$\overline{\vee}$	1330	32.9	10.2	60	0.98	15	2	1.15	0.8	17.9	2.55	3.3	0.41	15.3	0.17	\Diamond	6.4	14.3
IIIBm2	$\overline{\vee}$	1345	50.2	10.1	60	0.95	17	2.31	1.32	0.97	18.8	3.14	3.3	0.44	27.5	0.19	\Diamond	6.9	18.4
IIIBC	$\overline{\vee}$	1325	37.2	10.5	60	1.19	22	2.2	1.24	0.88	18.6	2.71	4.2	0.43	17.7	0.19	\Diamond	6.4	14.8
IIIC1	$\overrightarrow{\vee}$	1365	42.5	11.3	80	1.37	26	2.46	1.38	0.94	18.8	3.14	4.3	0.47	18.6	0.2	\heartsuit	7.2	16.5
IIIC2	$\overline{\nabla}$	1395	37.7	8.9	50	1.22	21	1.89	1.08	0.81	17.9	2.41	2.5	0.37	18.2	0.15	\heartsuit	5.4	13.9
	Ni	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Tb	Тh	Π	Tm	Ŋ	Λ	M	Υ	Yb	Zn	Zr
										bpm									
Bm	11	10	3.45	43.5	2.54	1	702	0.4	0.35	3.81	<0.5	0.11	1.69	91	-	9.1	0.95	65	135
IIBm	23	15	4.2	51.1	3.11		589	0.6	0.47	4.55	<0.5	0.11	1.31	121	—	13.4	1.4	72	161
IIIBm1	17	13	3.42	42.7	2.76	Ξ	171	0.5	0.38	3.15	<0.5	0.15	0.89	103	-	10.7	1.07	48	127
IIIBm2	16	11	4.9	40.1	3.13	-	801	0.5	0.44	5.63	<0.5	0.16	0.99	103	$\overline{\vee}$	11.8	1.24	56	122
IIIBC	20	12	3.7	45	2.81	-	796	0.4	0.41	3.74	<0.5	0.15	1.06	105	-	11.4	1.22	55	160
IIIC1	22	12	4.07	47.7	3.25	1	770	0.5	0.45	3.71	<0.5	0.16	1.13	118	З	12.6	1.3	58	160
IIIC2	17	12	3.52	45.9	2.49		803	0.4	0.35	3.56	<0.5	0.13	0.9	85	$\overline{\lor}$	9.9	1	46	16

	SiO ₂	Al_2O_3	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Cr_2O_3	TiO ₂	MnO	P_2O_5	SrO	BaO	LOI	Total
							%	_							
Bm	60.4	14.65	3.95	3.65	1.52	3.57	2.09	<0.01	0.55	0.06	0.11	0.08	0.07	8.43	99 .1
IIBm	62.8	15.55	5.21	2.94	1.54	3.18	1.82	0.01	0.56	0.06	0.07	0.07	0.08	6.19	100.0
IIIBm1	64.4	15.95	4.86	3.62	1.26	3.79	1.84	0.01	0.34	0.05	0.10	0.09	0.14	2.56	99.0
IIIBm2	63.8	16.60	4.68	4.20	1.64	3.97	1.77	0.01	0.40	0.07	0.12	0.10	0.14	2.50	100.0
IIIBC	65.4	16.35	4.66	4.00	1.60	3.92	1.86	0.01	0.39	0.07	0.14	0.09	0.14	2.10	100.5
IIIC1	63.8	16.30	5.19	3.93	1.62	3.86	1.94	0.01	0.42	0.07	0.17	0.09	0.14	2.20	99.7
IIIC2	66.6	16.25	3.73	3.81	1.32	3.93	1.98	0.01	0.32	0.06	0.11	0.09	0.15	1.89	100.5

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Table A3-5 (continued): Geochemical data for site Y08-15, penultimate moraine.

* LOI = loss on ignition.

Table A3	-6: Ge	ochem	uical da	ata for	site Y	08-16	, penu	ltimate	e mora	ine.									
	Ag	Ba	Ce	C	Cr	Cs	Cu	Dy	Er	Eu	Ga	Gd	Ηf	Ηo	La	Lu	Mo	qN	PN
										ppm									
Bm	$\overline{\nabla}$	LLL	33.1	8.2	10	1.14	15	1.56	0.87	0.75	19.6	2.2	3.6	0.29	17.7	0.13	2	5.6	13.8
IIBm1	$\overline{\lor}$	1065	23.7	10.3	70	1.56	30	1.76	1.01	0.68	17.8	2.15	2.9	0.35	12.3	0.15	\Diamond	6.4	11.2
IIBm2	$\overline{\lor}$	1180	35.1	11.5	70	1.25	25	2.11	1.26	0.84	18.1	2.72	3.9	0.41	18.6	0.19	\Diamond	6.3	15.1
IIBm3	$\overline{\vee}$	1230	34.8	10.8	80	1.22	24	2.19	1.28	0.86	17.6	2.8	4.6	0.43	17.9	0.19	\Diamond	6.4	15.3
IIC	$\overline{\vee}$	1190	33.6	9.7	0 <i>L</i>	1.16	23	2.27	1.34	0.87	16.8	2.94	4.9	0.46	16.3	0.21	\heartsuit	6.4	15.2
	ïŻ	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Tb	Тh	IT	Tm	n	>	M	Y	Xp	Zn	Zr
										mqq									
Bm	8	∞	3.46	45	2.48	-	706	0.4	0.32	4.25	<0.5	0.1	1.86	74	1	8.3 0	.79	61	35
IIBm1	19	12	2.67	38.5	2.16	1	639	0.4	0.32	2.66	<0.5	0.02	0.73	113	-	9.2	Ī	67	10
IIBm2	21	11	3.76	41.6	2.83	1	730	0.4	0.4	3.73	<0.5	0.16	1.01	106	1	1.3	.21	59	44
llBm3	21	12	3.76	42.3	2.83		719	0.4	0.41	3.57	<0.5	0.19	1.1	105	1	12	.24	53	74
IIC	18	Ξ	3.66	41	2.92		712	0.5	0.43	3.04	<0.5	0.17	1.07	109	-	2.2	.24	50	86
	SiO ₂	Al ₂ (0 F	e203	CaO	Mg(Ž	120	K20	Cr ₂ O ₃	ΠÖ	2 W	Ou	P_2O_5	SrO	BaC	E	[IO	Cotal
									%										
Bm	63.8	14.9	90 3	3.46	3.57	1.46	ы.	84	2.38	<0.01	0.5	0	90	0.05	0.08	0.08	\$	95	99.1
IIBm1	61.1	15.	25 5	5.34	3.17	1.54		26	1.54	0.01	0.4	0	90	0.14	0.08	0.06	5.5	84	97.8
llBm2	63.2	16.	15 4	1.89	3.68	1.50	Э.	82	1.72	0.01	0.4	0	08	0.18	0.09	0.12	9.4	04	6.66
IIBm3	65.2	15.	80 4	1.65	3.56	1.36	3.	80	1.81	0.01	0.31	.0	07	0.17	0.09	0.13	3.	20	00.0
IIC	64.6	15.	30 4	1.90	3.67	1.38	Э.	77	1.76	0.01	0.3	0	07	0.18	0.08	0.13	2.	29	98.5
* TOI = lo	ss on ig	znition.																	

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Table A3	-7: Ge	ochem	nical d	ata for	site Y	08-21,	penu	ltimat	e till o	ver bed	lrock.								
	Ag	Ba	Ce	C	Cr	Cs	Cu	Dy	Er	Eu	Ga	Gd	Ηf	Ho	La	Lu	Mo	qN	ΡN
										bpm									
Bm	$\overline{\nabla}$	745	32.5	10.6	20	1.03	16	1.76	0.96	0.85	21.2	2.49	3.4	0.33	17	0.14	7	5.4	14.6
IIBm1	$\overline{\vee}$	1035	42.7	15.7	70	1.76	40	3.13	1.95	-	19	3.49	5.9	0.65	21.2	0.32	3	13.2	20.4
IIBm2	$\overline{\vee}$	1135	36.5	12.5	70	1.82	20	2.51	1.61	0.8	21.4	2.91	5.7	0.53	19	0.26	6	11.1	16.1
IIIBm1	$\overline{\lor}$	1280	35.4	10.9	60	1.48	22	2.52	1.49	0.87	19.4	2.82	4.5	0.5	16	0.22	\Diamond	9.3	16.3
IIIBm2	$\overline{\nabla}$	1315	37.7	9.9	60	1.29	16	2.1	1.25	0.86	19.9	2.51	4.2	0.43	19	0.2	\heartsuit	7.8	15.1
	ïŻ	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Тb	Тh	II	Tm	Ŋ	Λ	M	Y	Yb	Zn	Zr
										ppm									
Bm	11	10	3.59	41.1	2.6	-	806	0.4	0.36	3.87	<0.5	0.1	1.71	92	1	9.1 ().85	65	129
IIBm1	21	16	4.87	51.7	3.87	7	391	-	0.55	4.39	<0.5	0.2	2.02	132	1	17.9	2.03	81	221
IIBm2	21	16	4.1	55.3	2.91	-	427	0.7	0.42	4.79	<0.5	0.16	7	137	5	14.3	1.55	78	223
IIIBm1	21	15	3.94	47.9	3.09	-	633	0.6	0.44	5.09	<0.5	0.2	1.53	104	7	13.2	1.39	59	170
IIIBm2	17	13	3.77	41.8	2.77	-	709	0.5	0.38	5.15	<0.5	0.17	1.36	100	2	11.5	1.18	58	58
	SiO ₂		0, F	e2O3	CaO	MgC) Na	20	K ₂ 0	Cr ₂ 03	TiO	D ²	Ou	P_2O_5	SrO	Ba(E C	IO	[otal
									%										
Bm	62.6	15.	80 2	4.21	4.23	1.77	3.	88	2.17	<0.01	0.5(5	.06	0.10	0.09	0.0	7 5.	01	00.5
IIBm1	66.2	13.	; 09	5.01	2.43	1.37	2.(67	1.44	0.01	0.8	0	.30	0.07	0.04	0.0	5.5.	95	0.00
IIBm2	64.5	14.	; 06	5.56	2.38	1.50	5	76	1.61	0.01	0.7	0	.10	0.03	0.05	0.13	2 5.	59	99.8
IIIBm1	64.3	16.	10 4	4.64	3.16	1.42	Э.	46	1.80	0.01	0.5	1	.06	0.05	0.08	0.13	5 3.	46	99.2
IIIBm2	63.6	16.	₹ 09	4.45	3.39	1.36		20	1.63	0.01	0.4	5	90.	0.04	0.09	0.13	5 3.	60	98.6
* TOI = Io	ss on is	gnition.																	

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	Ag	Ba	Ce	Co	Cr	Cs	Cu	Dy	Er	Eu	Ga	Gd	Hf	Но	La	Lu	Mo	Nb	Nd
										ppm									
Aej	<1	766	32.5	9.4	10	0.99	15	1.54	0.87	0.76	1 9.9	2.19	3.4	0.31	16.7	0.12	<2	5.5	13.4
Bm	<1	700	31.2	11.5	20	0.87	15	1.71	0.94	0.82	20.7	2.29	3.2	0.33	15.6	0.13	2	5.2	13.9
IIBm	<1	971	40.1	12.7	80	2.47	21	2.8	1.73	0.88	19.6	3.02	5.3	0.55	19.4	0.29	<2	12.1	1 8 .3
IIIBm1	<1	1205	39	9.9	30	2.31	14	2.3	1.38	0.88	21.4	2.84	4.4	0.47	17.5	0.21	<2	9.9	17.1
IIIBm2	<1	1265	44.7	9.4	30	1.83	9	2.6	1.53	0.98	21.2	3.23	4.8	0.52	20.8	0.23	<2	10.2	19.3
IIIBC	<1	1175	96.8	10.7	30	3.39	8	3.48	2.01	1.43	23.6	5.21	5.1	0.69	51.3	0.29	<2	12.1	37.2
Weathered. Clast	<1	837	76.7	10.9	10	29.7	14	1.55	0.86	0.57	26.6	2.19	3.5	0.28	34.1	0.13	<2	8.4	15.1
	Ni	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Tb	Th	Tl	Tm	U	v	W	Y	Yb	Zn	Zr
	Ni	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Tb	Th ppm	Tl	Tm	U	V	W	Y	Yb	Zn	Zr
 Aej	Ni 9	Pb	Pr 3.48	Rb 42.8	Sm 2.46	Sn 1	Sr 673	Ta 0.4	Tb	Th ppm 4.52	Tl <0.5	Tm 0.11	U 1.9	V 83	W	Y 8.1	Yb 0.77	Zn 61	Zr 131
Aej Bm	Ni 9 11	Pb 10 9	Pr 3.48 3.49	Rb 42.8 37.5	Sm 2.46 2.55	Sn 1 1	Sr 673 748	Ta 0.4 0.3	Tb 0.3 0.33	Th ppm 4.52 3.96	Tl <0.5 <0.5	Tm 0.11 0.11	U 1.9 1.68	V 83 94	W 2 2 2	Y 8.1 8.6	Yb 0.77 0.83	Zn 61 60	Zr 131 121
Aej Bm IIBm	Ni 9 11 21	Pb 10 9 16	Pr 3.48 3.49 4.5	Rb 42.8 37.5 66.5	Sm 2.46 2.55 3.54	Sn 1 1 2	Sr 673 748 392	Ta 0.4 0.3 0.7	Tb 0.3 0.33 0.47	Th ppm 4.52 3.96 4.74	Tl <0.5 <0.5 <0.5	Tm 0.11 0.11 0.21	U 1.9 1.68 2.06	V 83 94 138	W 2 2 6	Y 8.1 8.6 15.4	Yb 0.77 0.83 1.77	Zn 61 60 91	Zr 131 121 205
Aej Bm IIBm IIIBm1	Ni 9 11 21 12	Pb 10 9 16 14	Pr 3.48 3.49 4.5 4.22	Rb 42.8 37.5 66.5 54.7	Sm 2.46 2.55 3.54 3.22	Sn 1 1 2 1	Sr 673 748 392 695	Ta 0.4 0.3 0.7 0.6	Tb 0.3 0.33 0.47 0.42	Th ppm 4.52 3.96 4.74 5.51	Tl <0.5 <0.5 <0.5 <0.5	Tm 0.11 0.11 0.21 0.19	U 1.9 1.68 2.06 1.83	V 83 94 138 93	W 2 2 6 2	Y 8.1 8.6 15.4 12.3	Yb 0.77 0.83 1.77 1.3	Zn 61 60 91 72	Zr 131 121 205 164
Aej Bm IIBm IIIBm1 IIIBm2	Ni 9 11 21 12 10	Pb 10 9 16 14 13	Pr 3.48 3.49 4.5 4.22 4.72	Rb 42.8 37.5 66.5 54.7 49.5	Sm 2.46 2.55 3.54 3.22 3.61	Sn 1 1 2 1 1 1	Sr 673 748 392 695 757	Ta 0.4 0.3 0.7 0.6 0.6	Tb 0.3 0.33 0.47 0.42 0.5	Th ppm 4.52 3.96 4.74 5.51 5.05	Tl <0.5 <0.5 <0.5 <0.5 <0.5	Tm 0.11 0.21 0.19 0.22	U 1.9 1.68 2.06 1.83 1.61	V 83 94 138 93 97	W 2 2 6 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	Y 8.1 8.6 15.4 12.3 14.1	Yb 0.77 0.83 1.77 1.3 1.45	Zn 61 60 91 72 67	Zr 131 121 205 164 178
Aej Bm IIBm IIIBm1 IIIBm2 IIIBC	Ni 9 11 21 12 10 8	Pb 10 9 16 14 13 12	Pr 3.48 3.49 4.5 4.22 4.72 10.1	Rb 42.8 37.5 66.5 54.7 49.5 63.5	Sm 2.46 2.55 3.54 3.22 3.61 5.92	Sn 1 1 2 1 1 1 1	Sr 673 748 392 695 757 768	Ta 0.4 0.3 0.7 0.6 0.6 0.8	Tb 0.3 0.33 0.47 0.42 0.5 0.67	Th ppm 4.52 3.96 4.74 5.51 5.05 8.83	Tl <0.5 <0.5 <0.5 <0.5 <0.5 <0.5	Tm 0.11 0.21 0.22 0.22 0.26	U 1.9 1.68 2.06 1.83 1.61 2.37	V 83 94 138 93 97 106	W 2 2 6 2 2 2 2 2 2	Y 8.1 8.6 15.4 12.3 14.1 19	Yb 0.77 0.83 1.77 1.3 1.45 1.81	Zn 61 60 91 72 67 88	Zr 131 121 205 164 178 194

 Table A3-8: Geochemical data for site Y08-22, penultimate till over bedrock.

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Cr ₂ O ₃	TiO ₂	MnO	P_2O_5	SrO	BaO	LOI	Total
							%								
Aej	63.5	14.10	3.64	3.48	1.44	3.66	2.22	< 0.01	0.51	0.05	0.06	0.08	0.09	4.65	97.5
Bm	60.2	15.20	4.25	4.14	1.77	3.73	2.02	< 0.01	0.56	0.05	0.16	0.09	0.08	5.46	9 7.7
IIBm	66.1	14.05	5.53	2.42	1.45	2.80	1.56	0.01	0.82	0.05	0.01	0.05	0.11	4.80	99.8
IIIBm1	61.3	17.25	4.94	3.27	1.48	3.57	1.89	<0.01	0.52	0.06	0.11	0.09	0.14	4.27	98.9
IIIBm2	63.7	17.20	4.88	3.84	1.51	3.91	1.84	< 0.01	0.52	0.07	0.13	0.09	0.15	2.59	100.5
IIIBC	59.2	17.40	5.87	4.03	1.85	3.76	1.88	<0.01	0.62	0.11	0.21	0.09	0.14	3.47	98.6
Weathered.															
Clast	<u>59.0</u>	17.05	5.41	1.72	1.60	2.42	1.64	<0.01	0.42	0.05	0.07	0.05	0.09	8.51	98.0

 Table A3-8 (continued): Geochemical data for site Y08-22, penultimate till over bedrock.

* LOI = loss on ignition.

Table A3-	. 9: Ge	ochem	ical da	ta for	site Y(08-23,	penult	imate	moraiı	ne.									
	Ag	Ba	Ce	C	C	Cs	Cu	Dy	Er	Eu	Ga	Gd	Ηf	Ho	La	Lu	Mo	qN	PN
										bpm									
Bmjy	$\overline{\vee}$	860	39.4	7.4	10	1.19	20	1.51	0.87	0.73	19	2.27	3.8	0.29	20.3	0.12	2	5.9	16.1
IIAe	$\overline{\lor}$	923	41.9	5.8	110	1.96	30	2.97	1.96	0.86	19.4	3.14	9	0.64	21	0.3	2	12	18.4
IIIBm1	$\overline{\vee}$	1385	37.6	11.9	70	1.81	28	2.43	1.42	0.84	16.5	2.83	4.3	0.49	18	0.23	\Diamond	7.9	16.9
IIIBm2	$\overline{\lor}$	1170	37.2	13.5	80	1.52	33	2.47	1.4	0.91	16.1	2.86	4	0.48	18.5	0.22	\Diamond	6.6	16
IIIBC	$\overline{\lor}$	1200	39.2	12.3	100	1.04	28	2.37	1.39	0.84	17.1	2.75	3.3	0.48	19.1	0.21	\Diamond	6.5	16
IIIC	$\overline{\vee}$	1195	40.6	12.3	90	1.21	32	2.75	1.57	1.05	16.2	3.26	5.3	0.57	21	0.25	\heartsuit	6.7	19.7
	Ņ	Pb	Pr	Rb	Sm	Sn	Sr.	Ta	Tb	Тh	IT	Tm	Ŋ	>	A	Y	Yb	Zn	Zr
										ppm									
Bmjy	7	10	4.13	48.8	2.51	1	584	0.4	0.29	5.35	<0.5	0.11	2.19	60	2	8	0.78	57	143
IIAe	24	17	4.63	52	3.36	7	373	0.8	0.5	4.53	<0.5	0.26	2.43	136	9	17	2.04	56	231
IIIBm1	24	15	4.5	50	3.25	-	579	0.6	0.44	4.73	<0.5	0.23	1.44	100	7	12.6	1.44	56	153
IIIBm2	22	12	4.34	41.9	3.3	-	609	0.5	0.44	4.28	<0.5	0.2	1.25	121	1	12.2	1.39	51	141
IIIBC	21	13	4	46	2.93	1	657	0.4	0.41	3.77	<0.5	0.2	1.21	120	7	12.7	1.33	52	127
IIIC	21	12	5.19	44.9	3.88	-	659	0.5	0.52	4.1	<0.5	0.23	1.39	120	-	13.8	1.59	51	199
	C:S		ي م	Ċ		MaO	N	à C	Ģ		C,E	M	0			Dog	C	Ĕ	40]
		7.12.7	5	503		Ng m	7 10 1 7		2 %	6710				\$					
Bmjy	64.4	13.5	90 3.	.24	2.87	1.10	3.6	7 2	.54	<0.01	0.43	0.0	5 0	.13	0.07	0.10	5.09	6	7.6
IIAe	69.7	12.5	55 3.	.39	2.32	1.12	2.7	3 1	.63	0.01	0.94	0.0	2 0	.01	0.04	0.10	5.5(5 10	0.0
IIIBm1	64.0	15.2	20 4.	.82	3.10	1.62	3.3	1 1	.91	0.01	0.49	0.0	7 0	.10	0.07	0.14	5.66	5 10	0.5
IIIBm2	63.3	15.()5 5.	.55	4.24	2.13	3.4	1 1	.73	0.01	0.49	0.0	9 0	.13	0.08	0.11	4.25	5 10	0.6
IIIBC	65.0	14.8	80 4.	.68	4.06	1.71	3.6	0 1	.83	0.01	0.44	0.0	7 0	.17	0.08	0.14	1.99	6	8.6
IIIC	64.1	14.8	80 5.	60.	4.35	1.83	3.6	1	.82	0.01	0.47	0.0	0 6	18	0.08	0.12	3.28	96	9.8
* IOI = Ior	ss on ig	șnition.																	

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Table A3-	·10: G	eochen	nical d	lata fo:	r site J	(08-36	, penu	ltimat	e till.										
	Ag	Ba	Ce	ပိ	C	Cs	Cu	Dy	Er	Eu	Ga	Gd	Ηf	Ho	La	Lu	Mo	qN	ΡN
										mqq									
Bmy	$\overline{\nabla}$	876	39.9	8.2	10	1.11	17	1.61	0.89	0.78	19	2.38	3.8	0.3	20.2	0.13	2	5.8	16.2
IIBm	$\overline{\lor}$	1145	38.2	12.7	80	1.58	27	2.24	1.4	0.86	18	2.73	4.2	0.46	17.9	0.21	\Diamond	8.3	17.8
IIIBm	$\overline{\vee}$	1290	26	10.2	110	1.03	25	1.9	1.15	0.7	16.5	2.09	3.9	0.39	12.2	0.18	\heartsuit	6.2	11.7
IIIC	$\overline{\lor}$	1360	33.4	6	100	1.09	28	2.5	1.46	0.93	16.7	3.08	4.3	0.49	17.4	0.2	\heartsuit	5.9	16.3
	ïŻ	Pb	\mathbf{Pr}	Rb	Sm	Sn	Sr	Ta	Tb	Тh	I	Tm	n	>	Ň	Y	Yb	Zn	Zr
										bpm									
Bmy	7	13	4.26	49.8	2.7		621	0.4	0.3	5.41	<0.5	0.1	2.19	63	2	8.3	0.78	59	140
IIBm	22	16	4.4	45.4	3.34	1	524	0.5	0.41	5.66	<0.5	0.15	1.46	135	S	12.2	1.24	60	162
IIIBm	18	14	2.89	43.1	2.32	1	664	0.4	0.32	3.02	<0.5	0.16	1.1	106	7	10.4	1.09	43	152
IIIC	20	15	4.22	47.5	3.31	-	729	0.4	0.47	3.84	<0.5	0.21	1.17	98		12.7	1.42	39	151
			G G	ç	Q°,	M eO	No	N C	Ċ		C:L	M			C"S	DoD	F	F	atal 1
	2010			203	CaO		142		%				2	205	0	Cert		-	חומו
Bmy	65.8	14.3	0 3.	.46	3.04	1.15	3.7	7	.57	<0.01	0.44	0.0)5 (0.12	0.08	0.10	4.2	8	9.2
llBm	64.4	14.6	0 5.	.26	3.05	1.44	3.0	7 1	.61	0.01	0.56	0.0	3 (0.03	0.06	0.12	4.6	2	8.9
IIIBm	65.1	14.8	5 4.	.19	3.51	1.24	3.5	3 1	.84	0.01	0.39	0.0)5 (60'(0.08	0.15	2.6	1 9	7.6
IIIC	66.6	14.7	0.4	.07	3.90	1.37	3.7	6 1	.96	0.01	0.37	0.0) ().16	0.08	0.14	2.0	6	9.3
•		•																	

* LOI = loss on ignition.

	Ag	Ba	Ce	Co	Cr	Cs	Cu	Dy	Er	Eu	Ga	Gd	Hf	Ho	La	Lu	Мо	Nb	Nd
										ppm									
Bmjy	1	510	39.5	12.8	20	0.8	12	1.96	0.94	1.06	19.7	3.29	2.6	0.34	19.2	0.12	2	5.3	18.5
IIBm	<1	940	41	20.7	70	9.65	23	2.95	1.83	0.92	20.6	3.22	5.8	0.6	20.1	0.28	2	12.5	17.6
IIIBmy1	<1	1130	28	11	40	22.1	20	1.35	0.87	0.45	22.3	1.36	4.5	0.28	8.3	0.15	<2	10.5	6.9
IIIBmy2	<1	986	69.9	8.5	40	26	18	2.29	1.35	0.88	22.8	3.37	4	0.45	41	0.18	<2	9.3	21.8
IIIBmy3	<1	1210	69.2	9.3	40	34.1	13	2.14	1.17	0.81	23.1	2.91	4.6	0.43	35	0.19	<2	10.2	19.4
IVBmy	<1	1345	65.7	5.2	40	47.4	12	3.31	1.8	1.21	22.8	4.79	6.3	0.65	49.3	0.23	<2	8.8	31.9
	Ni	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Tb	Th	TI	Tm	U	V	W	Y	Yb	Zn	Zr
										ppm									
Bmjy	5	12	4.76	29.7	3.62	1	827	0.3	0.36	8.73	<0.5	<0.01	1.19	118	1	8.9	0.82	76	98
IIBm	18	18	4.37	78.1	3.41	2	437	0.9	0.5	5.05	< 0.5	0.15	2.15	144	1	16.2	1.79	92	208
IIIBmy1	16	17	1.81	95.9	1.42	2	722	0.6	0.23	6.17	<0.5	0.04	2.99	96	1	7.5	1.01	86	163
IIIBmy2	11	17	6.07	103	3.4	1	716	0.6	0.48	6.9	< 0.5	0.09	2.48	79	1	13.5	1.07	60	142
IIIBmy3	12	20	5.53	126	2.99	2	632	0.6	0.41	8.45	0.5	2.41	3.66	92	1	11.6	1.29	77	161
IVBmy	42	19	8.93	135	5.04	2	497	0.5	0.68	6.91	0.7	0.25	4.31	79	1	18.1	1.55	64	226
	SiO	Ala	0₂ F	e 2O 2	CaO	ΜσΟ	Na	-0	K ₂ O	Cr ₂ O ₂	TiO	Mn	0 P1	٥	SrO	BaO	LO	Т	otal
	2102	2	~J	203	••••			20	%	01203		,	2	.03	~~~	200	201		
Bmjy	58.3	15.	95 5	.19	5.10	2.31	3.1	76	1.66	< 0.01	0.66	0.0	6 0.	09	0.11	0.06	5.58	9	8.8
IIBm	61.3	14.	35 5	.42	2.02	1.26	2.7	78	1.82	0.01	0.83	0.4	0 0.	07	0.05	0.04	8.09	9	8.4
IIIBmy1	61.5	17.	65 5	.05	1.78	0.88	3.8	33	2.88	0.01	0.49	0.0	8 0.	15	0.09	0.08	4.59	9	9.1
IIIBmy2	63.2	18.	30 3	.40	1.86	0.52	3.5	56	2.81	<0.01	0.39	0.1	1 0.	16	0.08	0.05	4.60	9	9.0
IIIBmy3	62.8	17.	95 4	.68	1.62	0.84	3.5	58	3.35	<0.01	0.45	0.1	1 0.	26	0.07	0.08	3.87	9	9.7
IVBmy	62.3	19.	05 3	.87	1.04	0.63	2.5	53	3.86	0.01	0.38	0.0	70.	13	0.06	0.09	5.58	9	9.6

 Table A3-11: Geochemical data for site Y08-10, pre-Reid weathered granitic bedrock.

Note: No data for horizon Ah.

* LOI = loss on ignition.

	Ag	Ba	Ce	Co	Cr	Cs	Cu	Dy	Er	Eu	Ga	Gd	Hf	Ho	La	Lu	Mo	Nb	Nd
										ppm									
Aey	<1	722	31.5	11.1	20	1.62	236	1.81	0.99	0.86	20.6	2.56	3.4	0.34	16.8	0.14	<2	5.5	14.3
Bmy	<1	709	31.6	11.1	20	1.69	15	1.7 9	0.99	0.89	20.9	2.54	3.2	0.35	16.9	0.13	<2	5.3	14.5
IIBmy1	11	859	36.8	9.8	80	4.49	23	2.71	1.7	0.83	20.5	3.06	5.5	0.57	18.5	0.31	2	13.7	15.9
IIBmy2	<1	1120	41.9	14	70	6.29	27	2.39	1.6	0.79	19.2	2.79	4.5	0.5	19.1	0.24	<2	10.8	16
IIIBmy1	<1	1110	31.4	9.3	40	13.3	12	1.47	0.98	0.49	22	1.74	3.9	0.31	10.9	0.18	<2	11.3	8.6
IIIBmy2	<1	1370	36.2	5.8	30	7.53	10	1.5	0.91	0.56	20.7	1.97	3.9	0.3	17.5	0.14	<2	8	11.6
Silt Cap	<1	1145	73.2	11.5	50	22.4	19	3.58	2.22	1.16	22.9	4.69	8.3	0.73	41.1	0.36	<2	18	27.2
IVBmy1	<1	1085	63.5	10.2	50	19.4	19	2.96	1.64	0.98	24.3	3.93	4.2	0.58	32.2	0.28	3	11.4	23.5
IVBmy2	<1	1270	51.4	3.5	40	21.1	17	2.51	1.27	1.01	23.7	3.71	4.2	0.45	33	0.17	<2	9.8	25.3
	Ni	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Тb	Th	TI	Tm	U	v	W	Y	Yb	Zn	Zr
	Ni	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Tb	Th ppm	Tl	Tm	U	V	W	Y	Yb	Zn	Zr
Aey	Ni	Рb 10	Pr 3.52	Rb	Sm 2.73	Sn	Sr 824	Ta	Тb 0.36	Th ppm 3.76	TI <0.5	Tm 0.11	U 1.67	V 98	W	Y 9.2	Yb	Zn 67	Zr 124
Aey Bmy	Ni 11 10	Рb 10 9	Pr 3.52 3.51	Rb 40.2 39.4	Sm 2.73 2.77	Sn 1 1	Sr 824 838	Ta 0.4 0.4	Tb 0.36 0.36	Th ppm 3.76 3.63	TI <0.5 <0.5	Tm 0.11 0.12	U 1.67 1.62	V 98 99	W	Y 9.2 9.3	Yb 0.9 0.9	Zn 67 67	Zr 124 117
Aey Bmy IIBmy1	Ni 11 10 16	Pb 10 9 18	Pr 3.52 3.51 4.39	Rb 40.2 39.4 65.2	Sm 2.73 2.77 3.11	Sn 1 1 2	Sr 824 838 334	Ta 0.4 0.4 0.9	Tb 0.36 0.36 0.46	Th ppm 3.76 3.63 5.05	Tl <0.5 <0.5 <0.5	Tm 0.11 0.12 0.27	U 1.67 1.62 2.22	V 98 99 158	W 1 1 3	Y 9.2 9.3 15.2	Yb 0.9 0.9 1.85	Zn 67 67 81	Z r 124 117 211
Aey Bmy IIBmy1 IIBmy2	Ni 11 10 16 29	Рь 10 9 18 16	Pr 3.52 3.51 4.39 4.03	Rb 40.2 39.4 65.2 70.2	Sm 2.73 2.77 3.11 2.86	Sn 1 1 2 2	Sr 824 838 334 463	Ta 0.4 0.4 0.9 0.7	Tb 0.36 0.36 0.46 0.43	Th ppm 3.76 3.63 5.05 6.18	Tl <0.5 <0.5 <0.5 <0.5	Tm 0.11 0.12 0.27 0.11	U 1.67 1.62 2.22 1.81	V 98 99 158 114	W 1 1 3 1	Y 9.2 9.3 15.2 13.5	Yb 0.9 0.9 1.85 1.56	Zn 67 67 81 95	Z r 124 117 211 158
Aey Bmy IIBmy1 IIBmy2 IIIBmy1	Ni 11 10 16 29 13	РЬ 10 9 18 16 18	Pr 3.52 3.51 4.39 4.03 2.42	Rb 40.2 39.4 65.2 70.2 92.5	Sm 2.73 2.77 3.11 2.86 1.67	Sn 1 1 2 1 1	Sr 824 838 334 463 760	Ta 0.4 0.9 0.7 0.6	Tb 0.36 0.36 0.46 0.43 0.24	Th ppm 3.76 3.63 5.05 6.18 6.4	Tl <0.5 <0.5 <0.5 <0.5 0.6	Tm 0.11 0.12 0.27 0.11 0.16	U 1.67 1.62 2.22 1.81 1.71	V 98 99 158 114 83	W 1 1 3 1 1	Y 9.2 9.3 15.2 13.5 8 .3	Yb 0.9 0.9 1.85 1.56 1.03	Zn 67 67 81 95 82	Z r 124 117 211 158 148
Aey Bmy IIBmy1 IIBmy2 IIIBmy1 IIIBmy2	Ni 11 10 16 29 13 13	Рь 10 9 18 16 18 16	Pr 3.52 3.51 4.39 4.03 2.42 3.08	Rb 40.2 39.4 65.2 70.2 92.5 85.4	Sm 2.73 2.77 3.11 2.86 1.67 2	Sn 1 1 2 1 1 1 2 1 1	Sr 824 838 334 463 760 885	Ta 0.4 0.9 0.7 0.6 0.5	Tb 0.36 0.46 0.43 0.24 0.3	Th ppm 3.76 3.63 5.05 6.18 6.4 4.15	TI <0.5 <0.5 <0.5 <0.5 0.6 <0.5	Tm 0.11 0.12 0.27 0.11 0.16 0.07	U 1.67 1.62 2.22 1.81 1.71 1.06	V 98 99 158 114 83 66	W 1 1 3 1 1 </td <td>Y 9.2 9.3 15.2 13.5 8.3 8.3</td> <td>Yb 0.9 0.9 1.85 1.56 1.03 0.93</td> <td>Zn 67 67 81 95 82 74</td> <td>Zr 124 117 211 158 148 144</td>	Y 9.2 9.3 15.2 13.5 8 .3 8 .3	Yb 0.9 0.9 1.85 1.56 1.03 0.93	Zn 67 67 81 95 82 74	Z r 124 117 211 158 148 144
Aey Bmy IIBmy1 IIBmy2 IIIBmy1 IIIBmy2 Silt Cap	Ni 11 10 16 29 13 13 21	Pb 10 9 18 16 18 16 32	Pr 3.52 3.51 4.39 4.03 2.42 3.08 7.23	Rb 40.2 39.4 65.2 70.2 92.5 85.4 111	Sm 2.73 2.77 3.11 2.86 1.67 2 4.67	Sn 1 1 2 1 1 2 1 2	Sr 824 838 334 463 760 885 708	Ta 0.4 0.4 0.9 0.7 0.6 0.5 1	Tb 0.36 0.36 0.43 0.24 0.3 0.67	Th ppm 3.76 3.63 5.05 6.18 6.4 4.15 7.31	TI <0.5 <0.5 <0.5 <0.5 0.6 <0.5 0.6	Tm 0.11 0.12 0.27 0.11 0.16 0.07 0.23	U 1.67 1.62 2.22 1.81 1.71 1.06 3.48	V 98 99 158 114 83 66 117	W 1 3 1 1 <1 1	Y 9.2 9.3 15.2 13.5 8 .3 8 .3 20	Yb 0.9 0.9 1.85 1.56 1.03 0.93 2.4	Zn 67 67 81 95 82 74 136	Z r 124 117 211 158 148 144 314
Aey Bmy IIBmy1 IIBmy2 IIIBmy1 IIIBmy2 Silt Cap IVBmy1	Ni 11 10 16 29 13 13 21 9	Pb 10 9 18 16 18 16 32 23	Pr 3.52 3.51 4.39 4.03 2.42 3.08 7.23 6.77	Rb 40.2 39.4 65.2 70.2 92.5 85.4 111 125	Sm 2.73 2.77 3.11 2.86 1.67 2 4.67 4.37	Sn 1 1 2 1 1 2 2 2	Sr 824 838 334 463 760 885 708 580	Ta 0.4 0.9 0.7 0.6 0.5 1 0.6	Tb 0.36 0.36 0.46 0.43 0.24 0.3 0.67 0.57	Th ppm 3.76 3.63 5.05 6.18 6.4 4.15 7.31 7.11	TI <0.5 <0.5 <0.5 <0.5 0.6 <0.5 0.6 1.9	Tm 0.11 0.12 0.27 0.11 0.16 0.07 0.23 0.25	U 1.67 1.62 2.22 1.81 1.71 1.06 3.48 3.39	V 98 99 158 114 83 66 117 108	W 1 3 1 1 <1 1 2	Y 9.2 9.3 15.2 13.5 8.3 8.3 20 15	Yb 0.9 0.9 1.85 1.56 1.03 0.93 2.4 1.58	Zn 67 67 81 95 82 74 136 85	Z r 124 117 211 158 148 144 314 151

 Table A3-12: Geochemical data for site Y08-13, pre-Reid weathered granitic bedrock.

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Cr ₂ O ₃	TiO ₂	MnO	P_2O_5	SrO	BaO	LOI	Total
							%	_							
Aey	61.3	15.60	4.24	4.39	1.88	3.85	2.11	<0.01	0.59	0.06	0.06	0.10	0.07	4.97	99.2
Bmy	60.0	15.85	4.14	4.43	1. 8 7	3.79	2.04	< 0.01	0.57	0.06	0.08	0.10	0.06	5.22	98.2
IIBmy1	65.3	12.95	5.96	1.83	1.21	2.43	1.66	0.01	0.86	0.07	0.10	0.04	0.11	6.34	98.9
IIBmy2	62.1	16.10	5.19	1.82	1.44	2.83	2.15	0.01	0.61	0.06	0.10	0.05	0.07	6.73	99.3
IIIBmy1	66.6	16.90	4.17	2.04	0.85	4.17	2.61	0.01	0.42	0.08	0.10	0.09	0.14	2.84	101.0
IIIBmy2	67.1	16.60	3.14	2.19	0.82	4.47	2.88	<0.01	0.31	0.08	0.10	0.10	0.09	1.90	99.8
Silt Cap	62.5	16.40	5.80	2.28	1.34	4.09	2.66	0.01	0.77	0.14	0.36	0.08	0.07	3.17	99.7
IVBmy1	63.1	17.75	4.72	1.32	0.62	3.25	3.36	0.01	0.48	0.11	0.19	0.07	0.14	5.59	100.7
IVBmy2	64.8	18.60	2.09	0.82	0.55	3.32	4.08	<0.01	0.41	0.07	0.10	0.07	0.08	3.60	98.6

Table A3-12 (continued): Geochemical data for site Y08-13, pre-Reid weathered granitic bedrock.

* LOI = loss on ignition.

	Ag	Ba	Ce	Co	Cr	Cs	Cu	Dy	Er	Eu	Ga	Gd	Hf	Ho	La	Lu	Ma	Nb	Nd
										ppm									
Bmy	<1	786	37.6	10.5	20	1.07	16	1.71	0.93	0.87	20	2.45	3.5	0.32	19	0.13	<2	5.6	16.2
IIBmy1	<1	1475	24.1	7.1	40	1.39	13	1.5	0.92	0.49	16.6	1.63	3.3	0.29	11.6	0.14	<2	6	9.3
IIBmy2	<1	1520	23.9	4.8	80	1.15	7	1.16	0.71	0.46	15.8	1.35	2.5	0.24	9.5	0.12	<2	4.6	8
IIIBCy	<1	1245	43.1	7	80	1.79	9	2.16	1.31	0.72	18.4	2.47	5	0.46	17.5	0.22	<2	9.3	14.4
	Ni	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Tb	Th	Tl	Tm	U	v	W	Y	Yb	Zn	Zr
										ppm									
Bmy	10	10	4.11	43.7	2.86	1	700	0.4	0.33	5.51	<0.5	0.21	1.88	86	2	8.6	0.8	61	129
IIBmy1	17	20	2.32	59.4	1.63	1	563	0.4	0.24	2.97	<0.5	0.12	1.04	66	11	7.8	0.88	43	123
IIBmy2	10	26	2.09	60.9	1.44	1	573	0.3	0.2	3.38	<0.5	0.08	0.93	37	2	6.1	0.69	31	89
IIIBCy	14	23	3.76	61.5	2.78	1	541	0.6	0.38	5.09	<0.5	0.19	2.04	65	2	12	1.4	50	175
	SiO ₂	e Al ₂	O ₃ F	e ₂ O ₃	CaO	Mg(D Na	a ₂ O	K2O %	Cr ₂ O	3 TiC	D_2 M	[nO	P ₂ O ₅	SrO	Ba	0	LOI	Total
Bmy	62.8	14.	.55 3	3.84	3.66	1.53	3 3	.77	2.22	<0.01	0.5	3 0	.05	0.07	0.09	0.0)9	6.27	99.5
IIBmy1	67.8	14.	40 3	3.30	1.98	0.73	3 3	.68	2.31	<0.01	0.3	2 0	.01	0.02	0.07	0.1	17	4.20	99.0
IIBmy2	70.5	14.	20 2	2.23	1.86	0.48	3 3	.94	2.54	0.01	0.2	1 0	.04	0.03	0.07	0.1	17	1.79	98 .1
IIIBCy	67.5	14.	80 3	3.20	2.10	0.84	4	.03	2.22	0.01	0.4	3 0	.07	0.05	0.07	0.	14	2.68	98 .1

* LOI = loss on ignition.

Table A3-	14: G	ieochei	mical (data fc	or site	Y08-2{	s, pre-	Reid v	veathe	red gra	anitic l	bedroc	ĸ.						
	Ag	Ba	Ce	Co	C	Cs	Cu	Dy	Er	Eu	Ga	Gd	Ηf	Ηo	La	Lu	Mo	qN	PN
										mdd									
Bml	ı	ı	ı	I	·	ı	ı	1	ı	ı	I	ı	ı	I	ł	ı	ı	ı	I
Bm2	$\overline{\lor}$	607	32.8	14	30	0.81	17	1.99	1.12	0.98	20.5	2.5	3.2	0.38	15.7	0.14	7	5.3	15.3
llAey	$\overline{\lor}$	1095	40.1	4.5	90	1.75	11	3.19	2.02	0.94	21	3.39	6.6	0.68	18.9	0.33	\Diamond	14.3	19.2
IIIBmy1	$\overline{\vee}$	1135	44.4	10.2	60	1.94	16	2.85	1.79	0.91	19.6	3.33	4.7	0.61	19.3	0.27	\Diamond	11.7	19.2
IIIBmy3	$\overline{\vee}$	1600	52.6	10.6	20	1.14	٢	1.41	0.98	0.48	22.3	1.54	5.1	0.29	11	0.19	\Diamond	16.5	×
IIIBmy2	$\overline{\lor}$	1165	65.6	12.9	80	1.88	15	3.4	2.11	1.02	20.7	3.46	9	0.68	21.6	0.35	\Diamond	17	19.7
IIIBmy4	$\overline{\vee}$	1540	65.3	7.3	40	1.23	9	1.92	1.21	0.61	20.6	2.24	4.2	0.39	17.9	0.2	\Diamond	12.8	12.2
IIIC	$\overline{\vee}$	1500	140	11.6	30	1.41	8	4.69	2.77	1.37	24.2	5.53	6.7	0.92	44.3	0.42	\Diamond	23.4	32.8
	Ŋ	Pb	Pr	Rb	Sm	Sn	Sr	Ta	Tb	Тћ	II	Tm	Ŋ	>	M	Y	Yb	Zn	Zr
										bpm									
Bml							,	ŀ	1							1		1	.
Bm2	18	29	3.79	32.8	2.99	-	833	0.3	0.4	4.09	<0.5	0.09	1.46	122	ŝ	9.8	.96	76 1	22
IIAey	11	22	4.77	58.9	3.9	7	448	-	0.53	4.5	<0.5	0.24	2.46	122	5 1	8.3	66.1	52	253
IIIBmy1	19	30	4.86	58.7	3.37	7	513	0.7	0.48	5.29	<0.5	0.17	1.87	124	5 1	6.4	.65	85	176
IIIBmy3	10	37	2.11	75.3	1.62	7	650	-	0.23	69.9	<0.5	0.15	1.52	90	ŝ	7.4	.14	88	94
IIIBmy2	22	56	5.17	62.2	4.04	7	473		0.58	7.27	<0.5	0.3	2.38	120	6 1	8.6	2.16	96	24
IIIBmy4	8	38	3.24	79.7	2.26	7	624	0.7	0.34	7.56	<0.5	0.15	1.69	84	7	10	.28	85	59
IIIC	Ξ	43	8.83	82.3	5.85	З	612	1.3	0.82	12	<0.5	0.37	2.89	134	13 2	4.3 2	2.72	126	238

NU NINE T		'non min			nala IVI				רמוזורו רו	ı ğıanın		Ņ.			
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Ca0	MgO	Na ₂ O	K20 %	Cr_2O_3	TiO ₂	MnO	P_2O_5	SrO	Ba()	ΙΟΊ	Total
Bm1		.			.		2,		1			ı	.		.
Bm2	58.9	15.25	5.25	4.70	2.15	3.70	1.68	<0.01	0.69	0.03	0.02	0.10	0.06	6.13	98.7
IIAey	69.3	13.25	3.34	2.15	0.79	2.98	1.85	0.01	0.91	0.02	0.03	0.06	0.12	4.77	9.66
IIIBmy1	62.6	15.40	5.89	2.46	1.44	3.13	1.82	0.01	0.64	0.04	0.11	0.07	0.13	6.85	100.6
IIIBmy3	62.1	17.00	4.91	1.55	1.22	3.60	2.54	<0.01	0.49	0.10	0.20	0.08	0.19	5.39	99.4
IIIBmy2	61.4	15.95	5.50	2.12	1.76	3.04	1.92	0.01	0.69	0.08	0.16	0.06	0.13	5.99	98.8
IIIBmy4	64.2	15.95	4.33	1.32	1.24	4.08	2.50	<0.01	0.42	0.09	0.16	0.08	0.18	3.49	98.0
IIIC	60.3	15.80	6.18	2.22	1.70	3.48	2.59	<0.01	0.66	0.18	0.53	0.08	0.17	4.28	98.2

* LOI = loss on ignition.

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Appendix 4: XRD diffraction patterns for clay (<2µm) fraction.

Figure A4-1: XRD diffraction pattern for select horizons in pedon Y08-31 (McConnell); clay (<2µm) fraction.





1.02 0.714

1,40

1.62

5

10

Vermiculite > Smectite > Chlorite > Chl.

Integrades ~ Mica >> Quartz ~ Feldspar

0.499

Y08-31-05

۸^{0.334}

IBC

CaGly

CaEG

Ca 54% RH

K 550⁰

к 300⁰

K 54% RH 💧

K 0% RH

20

ο2θ

30

McConnell Till

Vermiculite > Smectite > Chlorite ~ Chl. Integrades ~ Mica >> Feldspar > Quartz





Figure A4-2: XRD diffraction pattern for select horizons in pedon Y08-18 (McConnell); clay (<2µm) fraction.


Figure A4-3: XRD diffraction pattern for select horizons in pedon Y08-15 (penultimate); clay (<2µm) fraction.



Figure A4-4: XRD diffraction pattern for select horizons in pedon Y08-21 (penultimate); clay (<2µm) fraction.



°20

Figure A4-5: XRD diffraction pattern for select horizons in pedon Y08-23 (penultimate); clay (<2µm) fraction.



Figure A4-6: XRD diffraction pattern for select horizons in pedon Y08-36 (penultimate); clay (<2µm) fraction.



Figure A4-7: XRD diffraction pattern for select horizons in pedon Y08-10 (pre-Reid); clay (<2µm) fraction.



Figure A4-8: XRD diffraction pattern for select horizons in pedon Y08-13 (pre-Reid); clay (<2µm) fraction.

Appendix 5: Select thin section images

Figure A5-1 (next page): Select thin section images for sample Y08-18-B, till from McConnell moraine (IIIBm). The till horizon is made up primarily of loosely packed, coarse material (a and b) with some thin grain argillans (c and d), and brown macro-coatings (e) of weakly inversely graded clay, silt and sand size grains with oxides (non-birefringent) (f). The c/f ratio varies from coarse monic to chito-gerufuric. Voids are primarily simple packing voids and b-fabric is crystallitic and granostriated in places. Some bridges between grains are evident but are uncommon (g and h). Grain argillans are very thin or absent through many parts of the thin section. Oxides are present in aggregates and some infillings of cracks and organic tissue is observed.



Figure A5-2 (next page): Select thin section images for sample Y08-18-C, till from McConnell moraine (IIIBC). The till horizon is made up primarily of loosely packed, coarse material (a). The c/f ratio varies from coarse monic to chito-gerufuric with simple packing voids dominant. Cappings are present (c and d) where enaulic c/f ratio is typically observed. Few grain argillans are indicated by birefringence (f) and those that are present are very thin. Cappings of inversely graded clay/silt and sand are observed but not as large or common as higher in the profile (g and h).



Figure A5-3 (next page): Select thin section images for sample Y08-31-A, till from McConnell moraine (IIBm1). This till horizon horizon is influenced by eolian inputs (no distinct loess horizon was discernible in the field but translocation of silt into the upper till was noted). The c/f ratio varies from single spaced porphyric (c) to coarse enaulic and voids are dominated by vughs and channels in most of the section (e) with complex packing voids dominant in other portions of the section. It has a granular microstructure with some very weak lamellar development (e). The b-fabric is crystallitic and granostriated with thin grain argillans (d). They are not ubiquitous throughout the section but are found around the full circumference of many clasts. Fine material, oxides and possibly organic matter accumulates in cracks (f). Some bridges are present but not common.



Figure A5- 4 (next page): Select thin section images for sample Y08-15-A, penultimate till (IIIBm1). The till B horizon is dominated by loosely packed clasts and coarse fragments with very little fine matrix (*a* and *b*). The c/f ratio varies from dominantly coarse monic (*b*) to chitonic (*c*) in places. The soil has a single grain microstructure and voids are simple packing voids. B-fabric is dominantly crystallitic but grain argillans are noted. Argillans are discontinuous (*d*, *e* and *f*); they rarely travel around the complete exterior of a coarse grain but are present in multiple orientations. Coatings consist of fine matrix (oriented clay, unoriented clay and/or fine silt) and oxides with no coarser material (*d*). Thick cappings of poorly sorted material are not noted. Both fresh and decaying organic matter is noted. Till is made up of complex mineralogy but is dominated by feldspars and quartz (*f*) with significant biotite and other accessory minerals like pyroxene (*g*).



Figure A5- 5: Select thin section images for sample Y08-16-A, penultimate till enriched in loess (IIBm1). The till horizon consists of clasts and coarse grains with infrequent grain argillans, as well as aggregates of coarse and fine particles (*a* and *b*). The c/f ratio is dominantly double spaced coarse enaulic. Granular microstructure occurs in areas of high density of aggregates but not throughout. Coatings on coarse grains include oxides and possibly organic material (*c* and *d*). Lack of birefringence indicates lack of argillans (*d*). Cappings of clay/silt/sand size grains occur on larger particles in several orientations and are poorly sorted. They may be up to approximately 300 μ m but are often less thick Complex packing voids and vughs are present. B-fabric is speckled with granostriations (clay argillans) (*f*). Clay argillans do not appear on all coarse grains nor are they as thick as in pre-Reid sites. While most clay appears to be along the edges or larger grains, some short order repetition is evident in parts of the groundmass.



Figure A5- 6 (next page): Select thin section images for sample Y08-16-B, penultimate till (IIBm3). The till horizon is made up primarily of coarse fragments with some aggregates (*a*). The c/f ratio varies from coarse monic and chito-gefuric to coarse enaulic. Fine components mixed with oxides in both free aggregates (*c* to *f*) and cappings (*g* and *h*). The coatings in this sample are less frequent than those in the overlying sample, but reach a thickness of up to 450 μ m. The coatings are poorly sorted (*g*). Only some grains have a thin grain argillan separating the clast and cap (*h*). Grain argillans do not appear on all coarse grains nor are they as thick as in pre-Reid sites. Oxides occupy cracks of larger clasts.



Figure A5-7 (next page): Select thin section images for sample Y08-21-A, penultimate till enriched in eolian material (IIIBm1). The c/f ratio ranges from chito-gefuric to single spaced coarse enaulic (a). There are free aggregates but the section is dominated by coarse fragments and their coatings (b). The microstructure varies widely from pellicular (c) (some sub parallel orientation is seen at 50X magnification) to bridged grain to intergrain microaggregate structure. Coatings are common and vary from poorly sorted to weakly inversely graded (e to h). They occur in all orientations but tend to be thicker on the upper side of the clast. Grain argillans are present but discontinuous and very thin. B-fabric is speckeld to crystallitic with granostriations from oriented clay.



Figure A5- 8: Select thin section images for sample Y08-21-B, penultimate till (IIIBm2). Sample has a c/f ratio from chito-gefuric (*a*) to single spaced porphyric in thick coatings and aggregates (*c*). Some inverse grading is noted in cappings although not ubiquitous. Cappings may be very thick (>2mm) or very thin (<45 μ m). The B-fabric is both crystallitic and granostriated (*d*). Oxides and, in some cases, clay occupies cracks in coarse fragments (*e* and *f*).



Figure A5-9: Select thin section images for sample Y08-23-A, penultimate till enriched in eolian material (IIIBm1). Coarse fragments are common and both free aggregates and thick cappings occur (a). The c/f ratio ranges from double spaced coarse enaulic to open porphyric (c). There is a highly separated granular microstructure with both compound packing voids and vughs present (b). The b-fabric is largely crystallitic (b and d). There are fewer grain argillans; embedded grain argillans are not noted; argillans are noted in some cracks with oxides (e). Alteration of micaceaus minerals is common (e).



Figure A5- 10: Select thin section images for sample Y08-36-B, penultimate till (IIIC). This section is made up of both larger clasts with thick coatings (a) and unsorted aggregates (b). Thick bridges occur in places between large grains. The c/f ratio is dominantly coarse enaulic but ranges to closed porphyric in some large aggregates and cappings (d). Very few thin grain argillans and embedded grain argillans are noted. Cappings are thick and range from unsorted to slightly inversely graded. The largest caps are located primarily on the top side of grains but thinner cappings occur on other orientations as well. The microstructure varies from weakly separated crumb to pellicular.



Figure A5- 11 (next page): Select thin section images for sample Y08-10-A, tephra at a pre-Reid site (Bmjy). The tephra horizon (Y08-10-A Bmjy) is coarse monic with some oxides visible between individual grains (a). There are no aggregates, coatings, cutans or bridges of fine textured material. It has a single grain microstructure with simple packing voids. The bfabric is crystallitic (b) due to individual primary minerals. Primary minerals consist mainly of volcanic glass (VG in c), amphibole (hornblende) (H in c), pyroxenes (Py in c) and plagioclase feldspars (Pg in e). Twinning of feldspars (f) is apparent under cross-polarized light (XPL). Weathering of volcanic glass is evident through the presence of oxide staining (indicated by arrow in g) but no other minerals appear to be weathered. Fresh organic tissue with no apparent decomposition is visible (not shown).



Figure A5- 12: Select thin section images for sample Y08-10-A, loess at a pre-Reid site (IIBm). Loess is dominated by the silt size fraction with crude subhorizontal orientation of aggregates (*a*), possibly due to ice lensing. The peds are organized in a moderately separated granular to weakly separated platy microstructure. The c/f ratio is double spaced coarse enaulic. Voids are primarily compound packing voids (*a*) with vughs (*c*) in more densely packed portions of the groundmass. Dark, partially decomposed organic matter is common (OM in *a*) and includes fungal sclerotium (*e*, *f*).



Figure A5-13 (next page): Select thin section images for sample Y08-10-B, colluvium at pre-Reid site (IIIBmy1). Sample is made up primarily of loosely packed, coarse material (a and d) brown macro-coatings of weakly inversely graded clay, silt and sand size grains with oxides (non-birefringent) (b and c) and thin clay argillans (e). Coatings in thin section view are over 1mm in places but commonly up to 0.5mm with much thinner argillans. Argillans occur on all faces of coarse grains (not just upper surface of coarse grains). Although thick cappings are most common on the upper surface of coarse grains, they may occur in other orientations, likely due to reorientation of grains through cryoturbation. Bridges between coarse grains are present but uncommon (outlined in red box in d). These bridges would be destroyed through cryoturbation thus likely relatively young features due to significant evidence or cryoturbation in this site. Simple packing voids dominate as few aggregates are present. The soil is chito-gefuric with pellicular grain microstructure. Groundmass has two main types of b-fabric: mosaic speckled due to small birefringence of small grains, and granostriated due to oriented clay along surfaces of coarse material and within cracks. No void argillans or nodules were observed. Some weathering of quartz is evident, with surfaces appearing slightly pitted (b). Oxides and oriented clays fill cracks (e). Intense weathering of feldspar (f) and micaceous minerals (h) is evident. Other important minerals include biotite (Bi in g) and chlorite (Cl in g).



Figure A5- 14 (next page): Select thin section images for sample Y08-10-C, residuum at pre-Reid site (IVBmy). Sample is made up primarily of loosely packed material (*a* and *b*, *e* and *f*). Grain argillans are present but the thick coatings seen in colluvial horizons higher in the pedon are not as common. The c/f ratio ranges from dominantly chito-gefuric to single spaced eunalic in aggregates. Granular to pellicular microstructure dominates with simple to complex packing voids. B-fabric dominated by crystalline material (secondary weathering products of feldspars) with oriented clays granostriated. No void argillans or nodules were observed. No organic matter is observed but dark staining, likely from oxides (*c*) is common.



Figure A5- 15 (next page): Select thin section images for sample Y08-10-D, cryoturbated colluvial horizons (upward involution of IIIBmy3 into IIIBmy2). IIIBmy2 is made up primarily of loosely packed material (*a*). The c/f ratio ranges from double-spaced fine enaulic to chito-gefuric (*a* and *b*). Voids range from complex packing voids to vughs in aggregates. Grain argillans are present, but not common (lack of birefringence observed in *d*). Brown coatings likely consist dominantly of oxides and possibly organic material. In these thin sections, IIIBmy3 shows a finer matrix than IIIBmy2 (*e* and *f*). The c/f ratio varies from closed porphyric (*g*) to open fine enaulic with vughy to moderately separated subangular blocky microstructure (*e* and *f*). Voids range from vughs to complex packing voids. Oriented clay is not common (*h*) and is only sometimes visible around large coarse fragments and in cracks. Thick coatings occur on top side of large clasts, thinner coatings occur on all other sides (*e*). Aggregates occur independently from coatings.



Figure A5-16 (next page): Select thin section images for sample Y08-13-A, loess at a pre-Reid site (IIBmy1). Microstructure varies from weakly separated platy (*a*) to highly separated crumb microstructure (*c*). Organic tissue present (OM in *a*), however lack of birefringence indicates cellulose has decomposed (*b*). Organic residue varies from brown/red to black. The c/f ratio is open porphyric to double spaced coarse enaulic. Complex packing voids dominate but vughs and planes are evident within peds. Oriented clay coatings are not apparent, except in very thin coatings on a few coarse grains. The b-fabric is mosaic speckled, due to primary minerals (*d*). Cappings are present on coarse grains (*e* and *g*). Cracks are filled with oxides and some oriented clay (*g* and *h*).



Figure A5-17 (next page): Select thin section images for sample Y08-13-B, colluvial horizon at a pre-Reid site (IIIBmy1). Sample is made up of loosely packed, coarse material (a) with brown macro-coatings of weakly inversely graded clay, silt and sand size grains with oxides (non-birefringent) (c and d) and argillans argillans (g). The c/f ratio ranges from chito-gefuric to double spaced coarse enaulic in main portions of the section to single-spaced porphyric in aggregates and coatings (c). Microstructure ranges from granular in regions of thin section dominated by aggregates to pellicular grain in others. Aggregates are poorly sorted. B-fabric is crystallitic from primary minerals in groundmass (f) and granostriated (clay coatings) (g). Cappings appear on all orientations of clay, likely due to cryoturbation and mixing of grains. Cracks in grains are in-filled with oriented clay particles and oxides.



Figure A5- 18 (next page): Select thin section images for sample Y08-13-C, a capping of fine material on a decomposing granite fragment at a pre-Reid site. The thick capping (~2.5 cm) consists primarily of fine material that has been translocated from higher in the profile and accumulated on the granitic clast (a and b). The c/f ratio varies from single spaced porhyric (c) throughout the majority of the section to fine enaulic at the extremities. Individual aggregates have formed within the capping causing the microstructure to vary from platy (d) to granular and in some areas a massive microstructure persists. Voids change from primarily planes close to the face of the granitic clast to vughs in the centre of the capping (a and b). Moving farther to the top of the capping, voids become dominated by vughs and compound packing voids. Rough inverse grading occurs through the capping, with finer material dominating near the base and coarse fragments dominating near the top of the capping. Thin clay coatings (birefringent) occur on individual coarse grains within the capping but are thin and not ubiquitous (f). B-fabric is stipple speckled. A high proportion of cracks in primary minerals such as quartz and feldspar are infilled with clay coatings and oxides.


Figure A5- 19: Select thin section images for sample Y08-24-A, translocated fine material within skeletal bedrock (IIBC) at a pre-Reid site. Sample consists of fine, relatively unweathered material filling large cracks at depth (a and b). Pores consist of both vughs and vesicles (b and c). In thin section this horizon ranges from closed and single spaced porphyric to coarse enaulic. The b-fabric is crystallitic with some embedded grain argillans. There is oriented clay in cracks of coarse grains (d).



Figure A5- 20: Select thin section images for sample Y08-28-B, colluvial horizon from pre-Reid site (IIIBmy3). Sample is made up primarily of loosely packed, coarse material (*a*) with thin clay argillans (*b*), and brown macro-coatings of weakly inversely graded clay, silt and sand size grains with oxides (non-birefringent) (*a* and *b*). Coating thicknesses are up to approximately 0.45mm, with grain argillans up to approximately 15 μ m thick. Argillans and cappings occur on all faces of coarse grains (*c*). Voids range from primarily simple packing voids throughout most of the groundmass to vughs within cappings and infrequent aggregates. The c/f ratio is chito-gefuric throughout most of the groundmass but is single to double-spaced enaulic within aggregates and coatings. B-fabric is both crystallitic and granostriated. Primary minerals show evidence of weathering: quartz grains are pitted with oxides and oriented clays filling cracks on surfaces; feldspar grains are coated in alteration products (*d*).

