QUATERNARY GEOLOGY OF THE ZAMA CITY AREA, NORTHWESTERN ALBERTA

by

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B.Sc., Simon Fraser University, 2003

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ABSTRACT

Geologic studies in the Moody Creek (84M/02) map area were undertaken to map surficial geology, establish glacial history, and classify materials geotechnically. Surficial geology mapping was completed in 2006. The stratigraphy is represented by 6 units: glaciolacustrine; till; englacial/subglacial gravels; retreat glaciolacustrine; readvance till; alluvium; and peat. The Laurentide Ice Sheet advanced over shale bedrock and glaciolacustrine sediments, resulting in clay-silt tills with high plasticities. During the last glacial maximum, ice flow was west-southwestward, and during deglaciation ice flow was westward. During deglaciation, regional drainage was blocked by the retreating ice margin, forming Glacial Lake Hay. Glaciolacustrine sediments occur below 410 m, and shorelines occur at 340 m. Iceberg scours are observed between 340 and 400 m. A late glacial readvance covered most of the area flooded by Glacial Lake Hay. Aggregate is in short supply, and the sole active pit in the study area exploits sub-till gravel.

Keywords: Laurentide glaciation; Quaternary; stratigraphy; NTS 84M; Fort Nelson Lowland; Alberta; glacial lakes.
EXECUTIVE SUMMARY

Geologic studies in the Moody Creek (84M/02) map area were undertaken to map surficial geology, establish glacial history, and classify materials geotechnically. Surficial geology mapping was completed in 2006, and is included in the back pocket of this thesis. The stratigraphy is represented by 6 units: 1) advance phase glaciolacustrine; 2) regional till; 3) englacial/subglacial gravels; 4) retreat glaciolacustrine; 5) readvance till; 6) alluvium; and 7) peat. The Laurentide Ice Sheet advanced over shale bedrock and glaciolacustrine sediments, resulting in clay-silt tills with high plasticities. During the last glacial maximum, ice flow was west-southwestward. During deglaciation, ice was constrained by topography, and flowed westward parallel to the Fort Nelson Lowland. During deglaciation, regional drainage was blocked by the retreating ice margin, forming Glacial Lake Hay. Glaciolacustrine sediments occur below 410 m, although the early phases of the lake likely reached 430 m. The initial phases of Glacial Lake Hay drained to the west, and the final phase drained to the east. During this final phase, shorelines developed at 340 m. Iceberg scours are observed between 340 and 400 m. A late glacial readvance covered most of the area flooded by Glacial Lake Hay, and is reconstructed based on a thin till layer overlying contorted glaciolacustrine sediments. Ice flow during the readvance is interpreted to have had a spreading, piedmont style, especially to the west of the study area. Aggregate is in short supply, and the sole active pit in the study area exploits sub-till gravel. This gravel has little to no surface expression, although the possible extents of the deposit have been mapped.
DEDICATION

To Niki, your support made this happen. Thank you for always believing in me.
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CHAPTER 1: INTRODUCTION

Quaternary studies in northwest Alberta and northeast British Columbia have only been completed at the reconnaissance and regional level. Yet, both of these regions are within the western limit of the Late Wisconsinan Laurentide Ice Sheet (LIS) and the discontinuous permafrost region of Canada, and support a well established oil and gas infrastructure including access roads, pipelines, well sites, gas plants, etc. The area has very subdued relief, making the differentiation of surficial materials a challenge. This study describes the distribution of glacial and non-glacial sediments in this region, which is necessary for infrastructure development, and contributes to reduce impacts on the environment. This is especially true of granular aggregate, as gravel is scarce, and geological studies can help identify new sources (Smith et al. 2005a). Furthermore, the ice-flow history of this region has only been studied at the reconnaissance level and is poorly constrained. Reconstructing ice movement in the region is important not only in refining the evolution of the northwest margin of the Laurentide Ice Sheet, but also to drift prospecting. Recent results jointly released by the Geological Survey of Canada (GSC) and the Alberta Geological Survey (AGS) indicate that the region might be the host of yet unrecognized zinc mineralization (Plouffe et al. 2006a). A drift prospecting methodology, based on the reconstruction of ice-flow direction will need to be used by the mineral exploration industry to trace the bedrock source of the zinc (present in the form of sphalerite) in till. Lastly, but
equally important, shallow gas is hosted in Quaternary sediments within buried channels in northwest Alberta (Pawlowicz et al. 2004). Additional information regarding the Quaternary succession of northwest Alberta helps to define the geological setting of shallow gas.

1.1 Objectives

This masters project was undertaken within the Moody Creek map area (NTS 84M/2) of northwest Alberta with the objectives of 1) mapping the surficial geology at 1:50,000 scale, 2) establishing the Quaternary stratigraphy of the area, 3) describing and interpreting glacial and non-glacial sediments, and 4) reconstructing the ice-flow, glacial, and post-glacial histories of the area (Figure 1-1). It is part of the larger Shallow Gas and Diamond Opportunities in Northwestern Alberta and Northeastern BC project (NRD 4450 Project). In order to aid in the economic development of the region, this collaborative four year project between the Geological Survey of Canada, the Alberta Geological Survey and the British Columbia Ministry of Energy, Mines and Petroleum Resources was initiated in 2003. The primary objectives of the NRD 4450 project are to locate aggregate resources, refine the stratigraphic and spatial setting of shallow gas (<100 metres) in buried channels, and establish the potential of the region to host Kimberlites. As a part of NRD 4450 Project, simultaneous mapping of surficial geology was performed in northeast British Columbia (94I and P) by J. Bednarski and R. Smith and in northwest Alberta (84L, M, N, and K) by R. Paulen, A. Plouffe, and R. Smith, and the author of this thesis.
This thesis is divided into five chapters. Chapter 1 is an introduction to the study site, previous work, and the methodology used in the field and the laboratory. Chapter 2 outlines the regional glacial history of the western Laurentide Ice Sheet. Chapter 3 presents the results of surficial mapping and geomorphology. Chapter 4 places the surficial materials into a stratigraphic context by dividing them into units, as well as describing their sedimentology. Chapter 5 presents the geotechnical characteristics of the surficial materials. Chapter 6 reconstructs the study area’s glacial history. Conclusions are listed in Chapter 7. Appendix A contains the stratigraphic logs, and Appendix B includes a table of sites presenting grain size and other observations. All ages are in radiocarbon years BP unless otherwise stated.

1.2 Study Area and Physiography

The study area is the Moody Creek (NTS 84M/2) 1:50,000 scale map sheet and the immediate vicinity, and encompasses the hamlet of Zama City. The Moody Creek map area lies about 200 km east of the Rocky Mountains in northwestern Alberta (Figure 1-1). Zama City services an oil and gas field currently experiencing rapid growth in the mature oil pools and newly emerging shallow gas fields.
The Moody Creek map area is an area of subdued topography and lies at the transition between the Fort Nelson Lowland to the south and the Alberta Plateau to the north (Figure 1-2) (Bostock 1967). Within the map area, the elevation of the Fort Nelson lowland varies between 345 to 450 m above sea level (asl), and the Alberta Plateau rises to 620 m in the northeast corner of the map area. The transition between the two is a gentle slope, otherwise, the area has no relief (Figure 1-3). Modern drainage is to the southeast into the Hay River, which flows northeastward, into Great Slave Lake (Figure 1-1).
Figure 1-2 The Moody Creek (84M/2) map area. Red line shows paved (solid) and gravel (dashed) roads.

(Data source: USGS 2006, Based on Smith et al. 2005a)
The Fort Nelson Lowland in this area forms a broad east-west trending valley sloping very slightly to the east. This is part of a much larger curving valley in the NWT where it trends NE-SW and then west (Figure 1.2). The Hay River originates at the southern margin of the lowland, south of the study area, flowing first to the west, crossing the British Columbia border, before changing direction back to the east in a broad arc. Hay and Zama lakes lie in the centre of the lowland and are both fed and drained by the Hay River. The lakes are presently very shallow, and fluctuate between isolated small lakes as shown in Figure 1-2, to a large coalescent lake filling much of the surrounding lowlands, depending on recent hydrologic conditions. Upland slopes are typically moderately well drained with prominent gullies. The top of upland areas are flat and poorly drained with
several small seasonal creeks with very low slopes draining to the south and southeast.

1.3 Bedrock Geology

The study area is underlain by thick, flat-lying, Mesozoic and Cenozoic sedimentary bedrock deposited in the Western Canada Foreland Basin adjacent to an active orogeny that formed the Rocky Mountains (Leckie and Smith 1992). The basin developed between the ancestral Rocky Mountains and the North American craton. Sediments accumulated within this basin decrease in thickness away from the Rocky Mountains, as thick as 6 kilometres in the foothills, and pinching out to the east. The major driving force behind subsidence and sedimentation was isostatic flexure of the lithosphere caused by adjacent crustal thickening due to plate accretion and compression (Leckie and Smith 1992).

Palaeozoic limestone and dolostone, and Mesozoic and Cenozoic sedimentary rocks accumulated over the Canadian Shield. Rocks of the Canadian Shield are typically very old red coloured (rich in K-feldspar), coarse crystalline, igneous and metamorphic rocks of felsic compositions. The Canadian Shield is exposed over much of Canada, and outcrops at the surface in northeastern Alberta and eastward. The Great Slave Lake Shear Zone is a major NE-SW structural break in the basement rocks which trends through the study area, and can be 10 to 20 km wide (Eaton and Hope 2003).

Bedrock mapping in the study area has delineated flat-lying Shaftesbury Formation of the Fort St. John Group, deposited during the Early Cretaceous
(Stott 1982) covering the entire 84M/2 quadrant (Green et al. 1970, Okulitch 2006). The Shaftesbury Formation was deposited as dark clay muds in deep marine conditions distal to prograding deltas along the mountain front (Leckie and Smith 1992). In the study area, bedrock outcrops as poorly lithified shale. It is best exposed along the southern slopes of Elsa Hill in the northern half of the Moody Creek map area, with excellent exposures along prominent gullies (Figure 1-2). The shale is usually dark grey and horizontally bedded, commonly marked by yellow native sulphur stains, with beds typically 0.7 cm to 1.5 cm thick. It is the source for the clay-rich glacial sediments found throughout the region.

1.4 Previous Work

In the immediate vicinity of the study area, previous work has focussed on bedrock geology mapping, aggregate surveys and geotechnical work associated with oil and gas development, and recent work associated with the NRD 4450 project. Aggregate surveys were conducted by Fox (1984, 1986), Fox et al. (1987a), Richardson (1985a, 1985b), and Edwards et al. (2004) identifying what is now the Zama Beach gravel pit (see unit 2b, section 4.3). Geotechnical work has been conducted in the area by Pilon et al. (1989) and Burgess and Smith (2003).

Other surficial geology maps within the Bistcho Lake 84 M map area include Andriashek (1985), Fox et al. (1987b), Edwards et al. (2004), Paulen et al. (2006a, 2006b), Plouffe et al. (2006b), and Smith et al. (2007). A preliminary interpretation of glacial history in the 84 M map area is provided by Paulen et al. (2005b). Relevant mapping adjacent to the study area includes exploratory soil
mapping by Lindsay et al. (1961), and mapping in the southern Mackenzie Valley by Rutter et al. (1980, 1993). Surficial geology mapping to the south of the study area in the 84 L map area was conducted by Plouffe (2004), Smith et al. (2005b), and Paulen et al. (2005c, d). Quaternary investigations in British Columbia to the west of the study area were conducted by Levson et al. (2004).

1.5 Methodology

1.5.1 Field Investigations

Transportation in the field was primarily by four wheel drive truck. The area has a large network of industrial secondary roads built from the local clayey till with little or no gravel surfacing. Consequently, roads quickly deteriorate during prolonged wet periods. Remote areas were visited by helicopter. Stratigraphy within the region was observed in borrow pits, pipeline trenches, gravel pits, hand-dug pits, and with an Oakfield soil probe. Existing borrow pits dug during road construction and oil and gas activity provided the vast majority of exposures (Figure 1-4). A few exposures were obtained in shallow trenches (1-2 m) dug for pipelines. The best exposures were in steep sided sump pits up to 4 metres deep that are dug to dispose of drilling fluids (Figure 1-5). Sections were carefully examined to determine whether the sediments were in-situ or if they had been disturbed. Sections that were unmistakably in-situ were described in detail. Borrow pits typically required extensive cleaning to expose undisturbed material as their walls are commonly reworked and flattened to improve stability.
Figure 1-4  Typical borrow pit exposure, site 521.

(Photo: B.C. Ward)

Figure 1-5  Typical sump pit exposure at site 621.

(Photo: C. Kowalchuk)
Sections were initially divided into lithostratigraphic units based on visible lithological characteristics such as colour, grain size, consistency or density, and structures. Each unit was then described in detail, noting thickness, lateral continuity, nature of lower contact, colour according to Munsell colour chart, texture, structures, clast size and shape, and, at selected sites, clast fabric.

Given the absence of bedrock glacial striations, till fabrics were measured at a number of sites to obtain an indication of ice-flow direction. The till fabrics measured the mean orientation of 25 prolate \((a:b:c = 1:1:2)\) clasts. Clasts were also examined for evidence of glacial modification such as striations, lee-ends, keels, and facets. When possible, the orientation of these features was also measured. The trend and plunge of clasts was plotted using StereoNett version 2.46, a freeware program created by Johannes Duyster of Ruhr University in Bochum, Germany. Contours were plotted at 4, 8, and 12 points within a circle that is 1\% of the total area, on a lower hemisphere of equal area.

Hicock et al. (1996) developed a till classification system based on modality and eigenvalue. Modality is the number of clusters of clast long axes in a fabric, being single, bimodal, spread, etc. In general, meltout and lodgement till have higher eigenvalues than deformation tills, and meltout till has shallow \(a\)-axis plunge angles than lodgement or deformation till. However, Kjær and Kruger (1998) demonstrate a high variability in fabrics over short lateral distances, and differences in fabrics depending on clast size bias, where fabric strength generally decreases for small clasts. They suggest using sedimentological evidence to support genetic interpretation. Caution in the interpretation of till
fabrics is stressed by several other authors (Bennett et al. 1999).

Sedimentological data useful in interpreting till fabrics include striations, facets, and lee ends observed on clasts of all sizes.

Time management in the field involved ensuring a balance between good spatial coverage for ground truthing for surficial mapping and detailed sedimentological and stratigraphic observations to make inferences of glacial history. As a result, in areas with good road access and few borrow pits, many small auger holes were dug and limited time was spent at each site. When pits were abundant, an effort was made to collect more detailed data, and several visits were made to some of the larger and more significant pits, especially where more than a single unit was exposed. The density of field observation sites within the map area was about 6.5 km$^2$ per observation (Figure 1-6).

1.5.2 Surficial Mapping

As part of this thesis, the surficial geology of the Moody Creek map area (NTS 84M/2) was mapped at a scale of 1:50,000. Mapping was accomplished through careful interpretation of aerial photographs, and corroborated by low elevation flights and ground truthing.

The surficial geology map was produced from 1:20,000 scale black and white aerial photos (Alberta Sustainable Resource Development, 1994) and from field investigations during the summers of 2004 and 2005. Line work was digitized by Géotech (Raymound Fournier) using a digital video plotter system. This method of digitizing was used as it allowed consistency with the other
surficial geology maps produced as part of the GSC-AGS collaborative project. Photogrammetric corrections were minor because of the subdued and flat topography.

Surficial materials within the map area were classified according to genesis and surface expression following a common legend developed by J. Bednarski, A. Plouffe, and R. Smith from the GSC. Using a common legend allowed the production of consistent surficial geology maps produced by different mappers. Surficial deposits present within this map area are, in decreasing age, of the following genetic types: bedrock, till, glaciolacustrine, glaciofluvial, colluvium, alluvium, organic, and anthropogenic. A simplified surficial geology map showing the location of field stations is shown in Figure 1-6.
1.5.3 Grain Size and Atterberg Limits

Samples of surficial materials were collected for both grain size analysis and measurements of the Atterberg or liquid and plastic limits according to the American Society for Testing and Materials (ASTM) D4318-05. In geological descriptions, the texture of materials is classified according to Wentworth (1922) (Table 1-1), and the ratio of sand, silt and clay is classified according to Shepard (1954). In engineering descriptions, grain size distribution and plastic limits are used to group materials according to the Unified Soil Classification System (USCS) (ASTM 2006) (Table 1-2, Table 1-3). Grain size measurements were
taken to calibrate descriptions of grain size made in the field. Atterberg limits were measured to obtain geotechnical information for the different surficial materials. Due to the clay-rich nature of most of the samples, it was necessary to use moist samples, as dried samples were very difficult to disaggregate satisfactorily. Samples processed for grain size were split in three: 1) ~100 g for moisture content; 2) ~200 g for >.075 mm; 3) ~10 g for <0.075 mm. For selected samples, ~200 g were also processed for Atterberg limits. Moisture content was determined by drying at 105°C for 24 hours. The dry weight of all other samples was approximated by weighing the moist samples and subtracting the corresponding moisture content. Grain size and Atterberg samples were disaggregated in a solution of 5% calgon (sodium hexametaphosphate) for 24 hours on a shaker table at 100 revolutions per minute prior to wet sieving.

Grain size samples were washed through a 0.075 mm sieve. For grain size determination, the <0.075 mm washings were collected, and stored with the water. The <0.075 mm washings were homogenized using a magnetic stirrer at the lowest setting. Several drops were sampled from halfway between the centre and edge of the vortex. A small amount of representative sample was then run through a Mastersizer 2000 particle size analyser. For the >0.075 mm fraction, the sediment left on the sieve was dried. The >0.075 mm dried sample was dry sieved using a stack with the following sieve sizes: 0.075 mm; 0.150 mm; 0.250 mm; 0.425 mm; 0.85 mm; 2.00 mm; and 4.75 mm.
Table 1-1  Grain size divisions following Wentworth 1922.

<table>
<thead>
<tr>
<th>Millimetres (mm)</th>
<th>Microns (µm)</th>
<th>Phi (φ)</th>
<th>Wentworth Class Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>4095 to 256</td>
<td></td>
<td>-12.0 to -8.0</td>
<td>Boulder</td>
</tr>
<tr>
<td>256 to 64</td>
<td></td>
<td>-8.0 to -6.0</td>
<td>Cobble</td>
</tr>
<tr>
<td>64 to 4</td>
<td></td>
<td>-6.0 to -2.0</td>
<td>Pebble</td>
</tr>
<tr>
<td>4 to 2</td>
<td></td>
<td>-2.0 to -1.0</td>
<td>Granule</td>
</tr>
<tr>
<td>2.00 to 1.00</td>
<td></td>
<td>-1.0 to 0.0</td>
<td>Very coarse sand</td>
</tr>
<tr>
<td>1.00 to 0.50</td>
<td></td>
<td>0.0 to 1.0</td>
<td>Coarse sand</td>
</tr>
<tr>
<td>0.50 to 0.25</td>
<td>500 to 250</td>
<td>1.0 to 2.0</td>
<td>Medium sand</td>
</tr>
<tr>
<td>0.25 to 0.125</td>
<td>250 to 125</td>
<td>2.0 to 3.0</td>
<td>Fine sand</td>
</tr>
<tr>
<td>0.125 to 0.0625</td>
<td>125 to 63</td>
<td>3.0 to 4.0</td>
<td>Very fine sand</td>
</tr>
<tr>
<td>0.0625 to 0.031</td>
<td>63 to 31</td>
<td>4.0 to 5.0</td>
<td>Coarse silt</td>
</tr>
<tr>
<td>0.031 to 0.0156</td>
<td>31 to 15.6</td>
<td>5.0 to 6.0</td>
<td>Medium silt</td>
</tr>
<tr>
<td>0.0156 to 0.0078</td>
<td>15.6 to 7.8</td>
<td>6.0 to 7.0</td>
<td>Fine silt</td>
</tr>
<tr>
<td>0.0078 to 0.0039</td>
<td>7.8 to 3.9</td>
<td>7.0 to 8.0</td>
<td>Very fine silt</td>
</tr>
<tr>
<td>0.0039 to 0.00006</td>
<td>3.9 to 0.06</td>
<td>8.0 to 14.0</td>
<td>Clay (Textural)</td>
</tr>
</tbody>
</table>

(Adapted from Wentworth 1922)
Table 1-2  The USCS soil classification system.

<table>
<thead>
<tr>
<th>USCS GROUP NAME</th>
<th>GROUP SYMBOL</th>
<th>GROUP NAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-graded GRAVEL</td>
<td>GW</td>
<td></td>
</tr>
<tr>
<td>Poorly-graded GRAVEL</td>
<td>GP</td>
<td></td>
</tr>
<tr>
<td>Silty GRAVEL</td>
<td>GM</td>
<td></td>
</tr>
<tr>
<td>Clayey GRAVEL</td>
<td>GC</td>
<td></td>
</tr>
<tr>
<td>Well-graded SAND</td>
<td>SW</td>
<td></td>
</tr>
<tr>
<td>Poorly-graded SAND</td>
<td>SP</td>
<td></td>
</tr>
<tr>
<td>Silty SAND</td>
<td>SM</td>
<td></td>
</tr>
<tr>
<td>Clayey SAND</td>
<td>SC</td>
<td></td>
</tr>
<tr>
<td>Low-plasticity CLAY</td>
<td>CL</td>
<td></td>
</tr>
<tr>
<td>High-plasticity CLAY</td>
<td>CH</td>
<td></td>
</tr>
<tr>
<td>Low-plasticity SILT</td>
<td>ML</td>
<td></td>
</tr>
<tr>
<td>High-plasticity SILT</td>
<td>MH</td>
<td></td>
</tr>
<tr>
<td>PEAT</td>
<td>PT</td>
<td></td>
</tr>
<tr>
<td>Low-plasticity Organic SILT</td>
<td>OL</td>
<td></td>
</tr>
<tr>
<td>High-plasticity Organic CLAY</td>
<td>OH</td>
<td></td>
</tr>
</tbody>
</table>

(ASTM 2006)

Table 1-3  Grain size divisions for engineering descriptions

<table>
<thead>
<tr>
<th>Sediment Name</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobble</td>
<td>greater than 75 mm</td>
</tr>
<tr>
<td>Gravel</td>
<td>4.75 to 75 mm</td>
</tr>
<tr>
<td>Sand</td>
<td>0.075 to 4.75 mm</td>
</tr>
<tr>
<td>Fines (silt and clay)</td>
<td>less than 0.075 mm</td>
</tr>
</tbody>
</table>

(ASTM 2006)
Atterberg limits were determined by measuring the liquid and plastic limits of remoulded moist samples wet sieved through a #40, 0.425 mm, sieve. The washings were allowed to air dry until the moisture content was appropriate for liquid and plastic limit tests. Liquid limits were measured using the multipoint percussion method (ASTM D4318-05). Three trials using increasing moisture content were put in a Casagrande cup, and the number of blows necessary to close a 12.7 mm groove was counted. The number of blows was then plotted against the measured moisture content, and the moisture content at 25 blows according to the trendline determined the liquid limit. Plastic limits were measured by hand rolling remoulded samples to a 3 mm thread. Moisture content was decreased by rolling on a frosted glass plate, and then measured by drying when a 3 mm thread began to crumble. Three trials were performed for each sample.

The shear strength of each unit was measured in the field using a pocket penetrometer and torvane. All measurements were taken on freshly exposed vertical faces, and do not account for anisotropy within the material. These tests provide approximate results and should be used as a guide only.

The pocket pen crudely measures unconfined compressive strength from 0 to 4.5 kg/cm². The pocket pen was used 5 times at each site and a representative value was recorded. Penetrometer values were divided by two to convert from confined compressive strength to shear strength, and converted to kPa. The highest shear strength that can be measured with the pocket pen is 220 kPa.
The Torvane was used 3 times and a representative value was recorded. The torque required to shear the sediment multiplied by the vane constant gives shear strength, which is read off the dial. The Torvane set includes three vanes with conversion dial. The regular vane (0 to 1 kg/cm$^2$) is used for most cohesive soils. The stress range permits it to be used for clays varying in consistency from very soft to stiff (0-100 kPa). The large vane (dial * 0.2 kg/cm$^2$) is for use with remoulded samples, and was not used in this study. The small vane (dial * 2.5 kg/cm$^2$) is for stiffer clays (100-250 kPa).

A summary value of shear strength for each unit was determined by discarding anomalously high values and averaging Torvane and pocket pen results together. Shear strengths determined using the two different methods were generally consistent for each unit.
CHAPTER 2: REGIONAL GLACIAL HISTORY

Limited Quaternary geology investigations have been completed in northwest Alberta. This chapter discusses the known glacial history in the region surrounding the study area. Previous and current research is focused on the number and provenance of glaciations and whether there was coalescence between the Cordilleran and Laurentide ice sheets. According to previous work, northwestern Alberta was glaciated by the western margin of the Laurentide Ice Sheet at least once. This has been done by establishing the provenance and chronology of Laurentide glacial deposits through clast lithology and radiocarbon analyses, respectively.

First, evidence of an extensive Late Wisconsinan Laurentide glaciation along the eastern slopes of the Canadian Cordillera is discussed. Western and southwestern Alberta, from Watino south, may only have been glaciated during the Late Wisconsinan. Second, evidence of Middle Wisconsinan ice free conditions exists in Alberta at sites in central Alberta, at least as far north as Birch Mountains. Third, sites in Yukon and Charlie Lake may show evidence of pre-Late Wisconsinan Laurentide glaciation. Finally, the known deglacial history of the study area is discussed, with special reference to glacial lakes.
2.1 Provenance and Chronology

The most recent glaciation, the Wisconsinan, has three sub-divisions, each correlated to a marine isotope stage (MIS) (Figure 2-1). The Early Wisconsinan was a period of ice building, and began during MIS 4, 115 – 75 ka BP, or possibly earlier near the end of MIS 5, the Sangamonian Interglacial. The Middle Wisconsinan was a period of more restricted ice cover during MIS 3, 75 - 28 ka (Shakelton 1987). The Late Wisconsinan, MIS 2, 28 - 10 ka, was the most recent continental glaciation. In northwestern Alberta and adjacent regions, the most recent glacial deposits are Late Wisconsinan in age and were deposited by Laurentide ice flowing roughly southwest from the Keewatin Ice Divide, northwest of Hudson Bay (Dyke et al. 2002). Radiocarbon dates discussed below are presented in Table 2-1.

Advance took place after 22,020 ± 450 BP (AECV 719C) to 24,400 ± 150 BP (BETA-183598) based on subtilt ages from High Level and Fontas River respectively (Burns 1996, Levson et al. 2004). Ice retreat began about 14,000 BP (Dyke et al. 2002). The oldest date for glacial retreat is 13,970 ± 170 BP (TO 2742) on wood just above the till-Glacial Lake Peace contact near Fort St. John (Catto et al. 1996). Other minimum deglacial dates range from 11,700 ± 260 (SFU 223) to 10,380 ± 100 (Beta 44201 - Woolf 1993). Optical ages on sand dunes near the study area range from 13,900 to 10,300 years ago, and dunes formed at nearby Mount Watt around 13,400 ± 1,200 years ago (SAW05-01 Wolfe et al. 2007). Sand dunes to the west of Glacial Lake Hay have been dated
by optically stimulated luminescence (OSL), yielding a date of 13,900 ± 1,200 calendar years (SUV050309 Wolfe et al. 2007).
Table 2-1 Radiocarbon ages from the area surrounding the study area (Based on Hartman 2005).

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Location</th>
<th>Coordinates</th>
<th>Dated material</th>
<th>Age (¹⁴C yrs BP)</th>
<th>Sedimentary Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSC 1019-2</td>
<td>Ft. Assiniboine</td>
<td></td>
<td>wood</td>
<td>&gt;52,200</td>
<td>sand between two tills</td>
<td>St-Onge 1972</td>
</tr>
<tr>
<td>GSC 1019</td>
<td>Ft. Assiniboine</td>
<td></td>
<td>wood</td>
<td>52,200 ± 1760</td>
<td>sand between two tills</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>GSC 4623HP</td>
<td>Simonette River</td>
<td>55°08' N, 118°12' W</td>
<td>wood</td>
<td>&gt;51,000</td>
<td>pre-glacial gravel below till</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>GSC 4263</td>
<td>Simonette River</td>
<td>55°08' N, 118°12' W</td>
<td>wood</td>
<td>&gt;51,000</td>
<td>Saskatchewan gravel</td>
<td>Bobrowsky and Rutter 1992</td>
</tr>
<tr>
<td>BGS 2585</td>
<td>Birch Mountains</td>
<td></td>
<td>organic detritus</td>
<td>&gt;50,000</td>
<td>Organic layer between two tills</td>
<td>Paulen et al. 2005a</td>
</tr>
<tr>
<td>BETA-195754 Prophet River</td>
<td></td>
<td></td>
<td>wood</td>
<td>&gt;44 730</td>
<td>Fine-grained sediment below till</td>
<td>Trommelen et al. 2005</td>
</tr>
<tr>
<td>BETA-195755 Prophet River</td>
<td></td>
<td>peat</td>
<td>&gt;45 100</td>
<td>Peat below till</td>
<td>Trommelen et al. 2005</td>
<td></td>
</tr>
<tr>
<td>GSC 1020</td>
<td>Watino</td>
<td>55°43’ N, 117°38’ W</td>
<td>wood</td>
<td>43,500 ± 620</td>
<td>fine-grained sediment below till</td>
<td>Catto et al. 1996</td>
</tr>
<tr>
<td>GSC 501</td>
<td>Goose River</td>
<td></td>
<td>wood</td>
<td>&gt;42,500</td>
<td>sand below till</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>Beta 183831 NTS 941</td>
<td></td>
<td>wood</td>
<td>&gt;40,590</td>
<td>Peat below till</td>
<td>Levson et al. 2004</td>
<td></td>
</tr>
<tr>
<td>AECV 414C</td>
<td>Watino</td>
<td>55°43’ N, 117°38’ W</td>
<td>wood</td>
<td>&gt;40,170</td>
<td>pre-glacial gravel below till</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>Sample no.</td>
<td>Location</td>
<td>Coordinates</td>
<td>Dated material</td>
<td>Age (^{14}C yrs BP)</td>
<td>Sedimentary Unit</td>
<td>Reference</td>
</tr>
<tr>
<td>------------</td>
<td>----------</td>
<td>------------------------------</td>
<td>----------------</td>
<td>---------------------</td>
<td>-----------------------------</td>
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</tr>
<tr>
<td>Beta 183832</td>
<td>NTS 941</td>
<td></td>
<td>wood</td>
<td>&gt;38,690</td>
<td>peat below till</td>
<td>Levson and Ferby 2004</td>
</tr>
<tr>
<td>GX 1207</td>
<td>Watino</td>
<td>55°43’ N, 117°38’ W</td>
<td>wood</td>
<td>&gt;38,000</td>
<td>fine-grained sediment below till</td>
<td>Catto et al. 1996</td>
</tr>
<tr>
<td>AECV 415C</td>
<td>Watino</td>
<td>55°43’ N, 117°38’ W</td>
<td>wood</td>
<td>36,220 ± 2520</td>
<td>pre-glacial sand below till</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>1 2615</td>
<td>Watino</td>
<td>55°43’ N, 117°38’ W</td>
<td>wood</td>
<td>35,500 +3300 / -2300</td>
<td>fine-grained sediment below till</td>
<td>Catto et al. 1996</td>
</tr>
<tr>
<td>1 2516</td>
<td>Watino</td>
<td>55°43’ N, 117°38’ W</td>
<td>wood</td>
<td>35,500 +2300 / -1800</td>
<td>fine-grained sediment below till</td>
<td>Catto et al. 1996</td>
</tr>
<tr>
<td>1 2626</td>
<td>Watino</td>
<td>55°43’ N, 117°38’ W</td>
<td>wood</td>
<td>34,900 +3000 / -2000</td>
<td>fine-grained sediment below till</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>TO-10545</td>
<td>Birch</td>
<td>55°43’ N, 117°38’ W</td>
<td>wood</td>
<td>32,690 ± 340</td>
<td>Organic layer between two tills</td>
<td>Paulen et al. 2005a</td>
</tr>
<tr>
<td>AECV 416C</td>
<td>Watino</td>
<td>55°43’ N, 117°38’ W</td>
<td>wood</td>
<td>31,530 ± 1440</td>
<td>pre-glacial sand below till</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>1 4878</td>
<td>Watino</td>
<td>55°43’ N, 117°38’ W</td>
<td>wood</td>
<td>27,400 ± 850</td>
<td>fine-grained sediment below till</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>GSC 2034</td>
<td>Taylor</td>
<td>56°09’ N, 120°43’ W</td>
<td>mammoth tooth</td>
<td>27,400 ± 580</td>
<td>interstadial paleovalley gravel</td>
<td>Mathews 1978</td>
</tr>
<tr>
<td>Beta 188305</td>
<td>Peace</td>
<td>56°08’ N, 120°42’ W</td>
<td>bison vertebrae</td>
<td>26,450 ± 310</td>
<td>fluvial gravel underlying glacial lacustrine seds</td>
<td>Hartman 2005</td>
</tr>
<tr>
<td>Sample</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta 183598</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Location</td>
<td>NTS 941</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Coordinates</td>
<td>wood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dated</td>
<td>Age ((^1\text{C yrs BP}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>material</td>
<td>24,400 ± 150</td>
<td></td>
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<td></td>
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<td>Sedimentary Unit</td>
<td>gravel underlying till</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Levson et al. 2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| AECV 719C  |
| Location | High Level |
| Coordinates | 58°10' N, 117°20' W |
| Dated | Age (\(^1\text{C yrs BP}\)) |
| material | mammoth tusk |
| 22,020 ± 450 |
| Sedimentary Unit | debris flow sediment on terrace |
| Reference | Burns 1996 |

<p>| n/a  |
| Location | Bear Flat |
| Coordinates | 56°17' N, 121°12' W |
| Dated | Age ((^1\text{C yrs BP})) |
| material | detrital charcoal |
| 20,000 (error N/A) |
| Sedimentary Unit | debris flow sediment on terrace |
| Reference | Geertsema and Jull 2002 |</p>
<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Location</th>
<th>Coordinates</th>
<th>Dated material</th>
<th>Age (¹⁴C yrs BP)</th>
<th>Sedimentary Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>TO 2742</td>
<td>Ft. St. John</td>
<td>56°10' N, 120°44' W</td>
<td>wood</td>
<td>13,970 ± 170</td>
<td>till-Glacial Lake Peace contact</td>
<td>Catto et al. 1996</td>
</tr>
<tr>
<td>SFU 223</td>
<td>Boone Lake</td>
<td>55°35' N, 119°26' W</td>
<td>wood</td>
<td>11,700 ± 260</td>
<td>postglacial sediment above till</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>GSC 2902</td>
<td>Watino</td>
<td>55°43' N, 117°38' W</td>
<td>bone</td>
<td>11,200 ± 100</td>
<td>postglacial terrace</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>GSC 859</td>
<td>Ft. Assiniboine</td>
<td></td>
<td>wood</td>
<td>10,900 ± 160</td>
<td>sandy silt covered by till or mudflow</td>
<td>St-Onge 1972</td>
</tr>
<tr>
<td>AECV-439C</td>
<td>Bushe River / High Level</td>
<td></td>
<td>bison</td>
<td>10,080 ± 150</td>
<td>upper Glacial Lake Peace sediment</td>
<td>Beaudoin 1988</td>
</tr>
<tr>
<td>SFU 454</td>
<td>Charlie Lake cave</td>
<td>56°17' N, 120°56' W</td>
<td>collagen from bone</td>
<td>10,770 ± 120</td>
<td>cultural layer</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>n/a</td>
<td>Bear Flat</td>
<td>56°17' N, 121°12' W</td>
<td>charcoal</td>
<td>10,500 (Error N/A)</td>
<td>debris flow sediment on postglacial terrace</td>
<td>Geertsema and Jull 2002</td>
</tr>
<tr>
<td>SFU 300</td>
<td>Charlie Lake cave</td>
<td>56°17' N, 120°56' W</td>
<td>collagen from bone</td>
<td>10,450 ± 150</td>
<td>cultural layer</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>GSC-3704</td>
<td>Snowshoe Lake</td>
<td>57°27' N, 120°40' W</td>
<td>gyttja-bulk</td>
<td>10,400 +/1 140</td>
<td>Gyttja</td>
<td>MacDonald 1987</td>
</tr>
<tr>
<td>SFU 378</td>
<td>Charlie Lake cave</td>
<td>56°17' N, 120°56' W</td>
<td>collagen from bone</td>
<td>10,380 ± 160</td>
<td>cultural layer</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>Sample no.</td>
<td>Location</td>
<td>Coordinates</td>
<td>Dated material</td>
<td>Age (¹⁴C yrs BP)</td>
<td>Sedimentary Unit</td>
<td>Reference</td>
</tr>
<tr>
<td>------------</td>
<td>----------------</td>
<td>------------------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>-----------------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Beta 44201</td>
<td>Tumbler Ridge</td>
<td>55°09' N, 121°00' W</td>
<td>collagen from bone</td>
<td>10,380 ± 100</td>
<td>deltaic sediment of Glacial Lake Peace</td>
<td>Woolf 1993</td>
</tr>
<tr>
<td>AECV 1206C</td>
<td>Taylor</td>
<td>56°09' N, 120°42' W</td>
<td>bone</td>
<td>10,240 ± 160</td>
<td>postglacial terrace</td>
<td>Bobrowsky and Rutter 1992</td>
</tr>
<tr>
<td>GSC 2895</td>
<td>Watino</td>
<td>55°43' N, 117°38' W</td>
<td>bone</td>
<td>10,200 ± 100</td>
<td>postglacial terrace</td>
<td>Catto et al. 1996</td>
</tr>
<tr>
<td>RIDDL 392</td>
<td>Charlie Lake cave</td>
<td>56°17' N, 120°56' W</td>
<td>bone</td>
<td>10,100 ± 210</td>
<td>cultural layer</td>
<td>Catto et al. 1996</td>
</tr>
<tr>
<td>AECV 272C</td>
<td>Watino</td>
<td>55°43' N, 117°38' W</td>
<td>elk rib</td>
<td>9920 ± 220</td>
<td></td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>GSC 2865</td>
<td>Peace River</td>
<td>55°09' N, 121°00' W</td>
<td>bone</td>
<td>9880 ± 130</td>
<td>postglacial terrace</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>GSC 1497</td>
<td>Rocky Mountain Trench</td>
<td>55°48' N, 123°38' W</td>
<td>sheep horn</td>
<td>9280 ± 200</td>
<td>ice-contact gravel</td>
<td>Rutter 1977</td>
</tr>
<tr>
<td>S 2614</td>
<td>Watino</td>
<td>55°43' N, 117°38' W</td>
<td>elk antler</td>
<td>9075 ± 305</td>
<td>postglacial terrace</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>UCI 13583</td>
<td>Zama City</td>
<td></td>
<td>twig</td>
<td>5057 ± 20</td>
<td>Fluvial fan</td>
<td>This thesis</td>
</tr>
<tr>
<td>GSC 2802</td>
<td>Grand Prairie</td>
<td></td>
<td>charcoal</td>
<td>4540 ± 230</td>
<td>paleosol</td>
<td>Liverman et al. 1989</td>
</tr>
<tr>
<td>GSC 4177</td>
<td>Grand Prairie</td>
<td></td>
<td>charcoal</td>
<td>2030 ± 90</td>
<td>silt overlying paleosol</td>
<td>Liverman et al. 1989</td>
</tr>
</tbody>
</table>
Laurentide glacial deposits are identified based on the presence of clasts derived from the Canadian Shield (e.g. Mathews 1978) which dominantly consist of feldspathic granitoid and gneissic lithologies. Exotic clasts from the Canadian Shield were transported westward up the regional slope towards the Cordillera, beyond the western edge of the Canadian Shield (Figure 2-2). Glacial transport is necessary to account for the presence of clasts from the Canadian Shield. Deposits that do not contain clasts from the Canadian Shield are inferred to have a westward (Cordilleran) provenance and to have been deposited prior to any Laurentide glaciation. Such deposits are defined as pre-Laurentide.
Figure 2-2  Ice cover and flow direction during the last glacial maximum. The Canadian Shield is shown in grey surrounding Hudson Bay.

(Ice flow based on Dyke et al. 2002)

2.2  Laurentide Stratigraphy

2.2.1  Edmonton Area

Catto (1984) records four stratigraphic units in an excavation in downtown Edmonton, starting from the base: (1) Cretaceous sandstone bedrock; (2) sand and gravel without Shield clasts; (3) Shield clast bearing diamicton; and (4) stratified silt and clay. The sand and gravel immediately above bedrock are interpreted as pre-Laurentide due to a lack of clasts from the Canadian Shield (Stalker 1968). The metamorphosed intrusive lithologies of the Shield are easily
differentiated from sedimentary and intrusive rocks originating from the Rocky Mountains. Sand and gravel of pre-Laurentide origin are collectively called the Saskatchewan sands and gravels (Stalker 1968). Catto (1984) interpreted the overlying diamicton with Shield clasts as Laurentide meltout till. The overlying stratified silt and clay was deposited in a proglacial lake during deglaciation. This stratigraphic sequence represents a single glacial cycle, with no evidence of a large unconformity between Laurentide till and pre-Laurentide deposits. No chronologic data were obtained, but Catto (1984) ascribes the till unit to the Late Wisconsinan since it is the uppermost unit in the sequence.

Andriashek and Fenton (1997) report evidence of more than one Laurentide glaciation at the Cooking Lake moraine near Edmonton. They describe 3 tills, with a radiocarbon age on organic remains of Middle Wisconsin age underlying the uppermost till sheet. Additional evidence of multiple Laurentide glaciations are multiple tills reported by Pawlowicz and Fenton (1998) in the Peerless map area (NTS 84B), Andriashek and Fenton (1989) in the Sand River area (NTS 73L), and Fenton et al. (2005) in the Buffalo Head hills.

Near Edmonton, Laurentide till overlies pre-Laurentide gravel that is cross-cut by ice wedge casts about 1 m deep (Young et al. 1994). This gravel is interpreted as pre-Laurentide due to a lack of Shield clasts. A periglacial environment existed during, or subsequent to, the deposition of the gravel due to the presence of ice wedge casts. The argument that Shield clasts may have weathered away is rejected due to the presence of unweathered Shield clasts in analogous pre-Illinoian gravels in Illinois (Young et al. 1994). Organic remains
within these pre-Laurentide gravel and sand yielded radiocarbon ages indicating that the overlying till is Late Wisconsinan in age and was deposited by a glacier which advanced over the area after 21,330 BP. The absence of pre-Late Wisconsinan till suggests that only a single glaciation took place. If the pre-Laurentide gravels predate the Middle Wisconsinan, then evidence of a pre-Late Wisconsinan glaciation could have been eroded. A less extensive pre-Late Wisconsinan glaciation could have left deposits in pre-existing valleys, which were then stripped off during the most recent glaciation.

Jennings (1984) described the hummocky terrain at Elk Island National Park east of Edmonton. Drilling revealed an organic bearing horizon between two tills, with radiocarbon dates on the organic remains of middle Wisconsin age. Jennings (1984) interpreted that the landforms were formed by uneven sedimentation associated with the melting of stagnant ice that was rich in debris. Deglacial radiocarbon dates indicate that stagnant ice remained in the area until 9,000 BP, well after the active ice front had retreated to the east around 11,000 BP.

2.2.2 Grande Prairie Area

Liverman et al. (1989) provide evidence that only a single Late Wisconsinan glaciation reached the Grande Prairie area based on the stratigraphic exposures near Watino. 5 to 10 m of quartzite dominated gravel overlies bedrock and is in turn overlain by 5 to 20 m of sand and silt. Radiocarbon ages of wood from the basal gravel and overlying sand and silt range between 27,400 ± 850 (14878) and >40,170 (AECV 414C) BP. A large
volume of wood fragments from the basal gravel was dated by Catto et al. (1996) to try to resolve an older, finite date. Wood fragments had an age of >51,000 BP (GSC 4623HP), and are interpreted to represent a mix of older and younger wood. A widespread till sheet overlies the section and contains abundant Shield clasts.

The basal gravel is interpreted by Liverman et al. (1989) as a moderate to low energy braided fluvial system. The contact between the basal gravel and overlying sand and silt is described as conformable. Fining upwards is ascribed to autocyclic changes such as channel abandonment in a fluvial system. Possible problems with this interpretation are the presence of heavy minerals derived from the Shield in the uppermost silt unit, and the 30+ m thickness of the sedimentary package, which is large for an autocyclic fluvial environment.

The basal gravel of the exposures described by Liverman et al. (1989) can confidently be interpreted as fluvial, and the lack of Shield clasts identifies it as pre-Laurentide. The overlying sand and silt may be glaciofluvial, and have been deposited as Laurentide ice advanced up-drainage, causing a rise in base level and eventual flooding. The uppermost unit of silt does contain sand sized grains of heavy minerals most likely derived from the Shield, supporting this interpretation. This does not affect the overall interpretation that only Late Wisconsinan ice reached this site.
2.2.3 Charlie Lake

Mathews (1978) reported a stratified succession of two tills separated by massive silt in the Dawson Creek area of British Columbia. Two tills are only observed at one site, whereas a single till sheet is observed in all other areas. A detailed sedimentological description of the site is not recorded, and without contradictory chronological data, a simpler interpretation is that both tills were deposited during the Late Wisconsinan.

Mathews (1978) and Hartman (2005) interpret at least three Laurentide glaciations based on the presence of rare red or pink igneous and metamorphic clasts from the Canadian Shield in paleovalley gravels older than the Late Wisconsinan Laurentide advance. The presence of pre-Late Wisconsinan Laurentide ice in this area is reconciled with the interpretations of Liverman et al. (1989) of a single advance at Watino by proposing that pre-Late Wisconsinan Laurentide ice reached the northern tributaries of the paleochannels at Charlie Lake, but not those at Watino (Hartman 2005), although this seems unlikely given the topography of the area. The above interpretation is not necessary if the rare red or pink igneous clasts originated within plutons of the Rocky Mountains (e.g. Ferri et al. 1999).

Bednarski and Smith (2007) used Cosmogenic $^{36}$Cl dating of mountain crests at around 2000 m asl, and obtained Late Wisconsinan ages of 14.8 ka to 13.2 ka in cal yr on surfaces striated by ice flowing eastward. They argue that only the Cordilleran Ice Sheet (CIS) was thick enough to flow over these crests, rather than local cirque glaciers. The Laurentide Ice Sheet did not advance into
the foothills until after the CIS had retreated, and advanced to at least 1600 m
asl, interacting with local Montane glaciers.

2.2.4 Swan Hills and Birch Mountains

Evidence for at least two Laurentide glaciations is present at sites in the
Swan Hills (St. Onge 1972, 1974) and the Birch Mountains (Paulen et al. 2005a).
Working in the Swan Hills, St-Onge (1972, 1974) found pre-Laurentide fluvial
gravel overlying Cretaceous bedrock. Overlying this were two layers of
Laurentide till separated by glaciofluvial sand and gravel. Wood found within the
glaciofluvial sediments had a non-finite age of >52,200 BP (GSC-1019-2). If the
wood is not significantly older than the glaciofluvial gravel, the lower till must be
Early Wisconsin in age or older. The upper till is most likely Late Wisconsinan.

Paulen et al. (2005a) present a site in the Birch Mountains with two till
units separated by an 80 cm thick organic layer. An AMS radiocarbon date of
32,690 BP ± 340 (TO-10545) on a pine wood fragment from the organic layer
provides evidence of non-glacial conditions at the site during the Middle
Wisconsinan. The two till units suggest that at least two glacial events took place
in north-central Alberta (Paulen et al. 2005a). The upper till unit was deposited
during the Late Wisconsinan, and the lower till unit was deposited prior to the
Middle Wisconsinan, unless the organic horizon is an intraclast within a Late
Wisconsinan till.
2.2.5 Fort Nelson Area

A pre-Late Wisconsinan site has been reported near Fort Nelson, along the Prophet River (Levson et al. 2004, Trommelen et al. 2005, Trommelen 2006). Peat and wood found within a massive to laminated clay unit yielded non-finite radiocarbon ages (>44,730 BP BETA-195754 and >45,100 BP BETA-195755) (Table 2-1). This unit overlies fluvial gravel containing no clasts from the Canadian Shield, and the fluvial gravel is interpreted as pre-Laurentide. The non-finite dates and lack of Shield clasts within the gravel suggest it records fluvial deposition prior to any Laurentide glaciations, and is older than Middle Wisconsinan in age.

Levson et al. (2004) report a radiocarbon date of 24,400 BP (BETA-183598) from advance phase glaciofluvial gravel deposited in front of the Laurentide Ice Sheet during the Late Wisconsinan. This gravel underlies Laurentide till, and contains abundant clasts from the Canadian Shield. Laurentide ice therefore advanced into the Fort Nelson area after 24,400 BP (Levson et al. 2004). Sand dunes to the west of Glacial Lake Hay have been dated by optically stimulated luminescence (OSL), yielding a date of 13,900 ± 1,200 calendar years BP (SUV050309 Wolfe et al. 2007). Work by Trommelen (2006) and Trommelen and Levson (2007) to the west of the study area identified levels of Glacial Lake Hay at 420 to 465 m asl.

2.2.6 Eastern Yukon and Adjacent Northwest Territories

In the northwestern sector of the Laurentide Ice Sheet along the Mackenzie Mountains, a thick section of Late Tertiary to Quaternary sediments
exposes multiple Cordilleran tills separated by paleosols (Duk-Rodkin et al. 1996). A single till sheet deposited by Laurentide ice caps these Cordilleran tills, and is the only unit containing Shield clasts. Cosmogenic dates on surface erratics confirm a Late Wisconsinan age for the Laurentide till. As the sections record a near complete record from Late Tertiary to Quaternary time and expose only a single Laurentide till, it is concluded that the Late Wisconsinan Laurentide ice sheet was the only continental ice to reach this far into the northern Cordillera (Duk-Rodkin and Hughes 1991, Duk-Rodkin et al. 1996). This hypothesis is supported by evidence that Late Wisconsinan Laurentide glaciation caused the redirection of the Mackenzie River to the north (Duk-Rodkin and Hughes 1992, Duk-Rodkin and Lemmen 2000).

In the northern Cordillera, Catto (1996) summarizes the stratigraphy of the Richardson Mountains. Three advances of Laurentide ice are identified, though their chronology is uncertain. The most recent advance during the Late Wisconsinan was likely the most extensive, agreeing with the interpretations of Duk-Rodkin et al. (1996). Earlier advances are identified through the presence of Shield clasts in gravels underlying glacial deposits of the Late Wisconsinan. Therefore, the Laurentide Ice Sheet advanced to the foothills of the Richardson Mountains sometime before the Late Wisconsinan, but was less extensive than the Late Wisconsinan advance.

The timing of the advance of Laurentide ice into eastern Yukon is problematic. In the Richardson Mountains in the north, the most extensive advance may have occurred during the Middle Wisconsinan ca. 30,000 BP (Duk-
Rodkin et al. 2004, Zazula et al. 2004). A Middle Wisconsinan maximum appears to conflict with the continental reconstruction of Dyke et al. (2002), in which the Middle Wisconsinan is an interstadial minimum. It is possible that ice advanced in this area out of phase with parts of the ice sheet farther to the south. It is also possible that this Middle Wisconsinan advance is actually an Early Wisconsinan maximum, and $^{36}$Cl ages on erratics are too young. An alternative explanation is that the maximum advance dates to the Late Wisconsinan, and dates are too old. It seems more likely for $^{36}$Cl dates to be too young because exhumation or weathering of large clasts removed the older surface. Laurentide ice likely reached as far as Banks Island (Vincent 1990) and the Horton upland during the Early Wisconsinan. Data from Banks Island and the Richardson Mountains (Duk-Rodkin et al. 2004, Zazula et al. 2004) may provide evidence of extensive Early Wisconsinan Laurentide ice in the western Arctic.

### 2.2.7 Summary of Laurentide Stratigraphy

Laurentide glaciation was most extensive during the most recent glaciation, the Late Wisconsinan, in the northern Cordillera (Duk-Rodkin et al. 1996, Duk-Rodkin et al. 2004), the Grande Prairie area (Liverman et al. 1989), the Fort Nelson area (Trommelen et al. 2005, Trommelen 2006), and southwestern Alberta (Young et al. 1999, Jackson et al. 1997, 1999, Barendregt and Duk-Rodkin 2004). This is shown by a lack of pre-Late Wisconsinan Laurentide glacial deposits. Evidence does exist, however, of pre-Late Wisconsinan Laurentide glaciation. This evidence consists of Shield clasts within gravels stratigraphically below Late Wisconsinan Laurentide till. Sites exposing
such materials exist in the Charlie Lake map area in northeastern British Columbia (Mathews 1978, Hartman 2005), and the foothills of the Richardson Mountains in the northern Cordillera (Catto 1996). Also, evidence of pre-Late Wisconsinan Laurentide glaciations exists in the form of till(s) present underneath the Late Wisconsinan succession (e.g. Birch Mountain (Paulen et al. 2005a); Cooking Lake moraine (Andriashek and Fenton 1997); and, in the Peerless map area (NTS 84B) (Pawlowicz and Fenton 1998)). Shield bearing gravels below till have also been found near the town of Peace River (Paulen pers. comm. 2008).

The extent of pre-Late Wisconsinan Laurentide ice was more restricted in the south than in the north. In the north, older glaciations may have reached near the Late Wisconsinan limit, but had a minor effect on the overall landscape in comparison to the last glaciation, which caused the diversion of the Mackenzie River from Hudson Bay to the Arctic Ocean (Duk-Rodkin and Hughes 1992). Coalescence during the Late Wisconsinan is uncertain in the Grande Prairie region (cf. Bobrowsky and Rutter 1992, Dyke et al. 2002), but the most recent Laurentide glaciation was still the most extensive (Liverman et al. 1989).

2.3 Maximal Configuration and $^{14}$C Chronology

Following the last interstadial, the Middle Wisconsinan, Laurentide ice advanced from the edge of the Canadian Shield beginning at approximately 27-30 ka BP in the northwest, and as late as 22-23 ka BP in the south (Dyke et al. 2002). In the Mackenzie Delta region over 1000 km north of the study area, the Laurentide Ice Sheet advanced to its maximum extent by 24 ka BP. In southern Alberta, 1000 km south of the study area, Laurentide ice took until 18-20 ka BP
to reach its most southwestern extent (Dyke et al. 2002). The study area may have remained ice free until after 22 ka BP based on a radiocarbon date of a Mammoth tusk from High Level (Burns 1996). Therefore, glacial maximum in the study area likely occurred around 18-20 ka BP. The ice sheet remained near its maximal configuration until 14 ka BP, although significant volume loss had occurred by this time (Dyke and Prest 1987; Dyke et al. 2002). Due to the low profile of the ice sheet during ice advance and retreat, ice flow during these times was largely controlled by topography, especially as the ice sheet thinned towards the end of Late Wisconsinan glaciation in the area (Mathews 1974; Dyke and Prest 1987). During glacial maximum, ice flow was not influenced by topography.

Topographic influence is especially prominent in the Buffalo Head Hills to the southeast (Mathews, 1978). This has implications for ice retreat, as a small change in the elevation of the equilibrium line would affect large areas, and margins would be more susceptible to calving into glacial lakes (Dyke and Prest 1987). The Laurentide Ice Sheet retreated rapidly between 14 and 8 ka BP (Dyke and Prest 1987; Dyke et al. 2002). Uplands near the study area may have been ice free by 13.5 ka BP (Bobrowsky and Rutter 1992, Dyke 2004). However, low lying areas were still occupied by ice or ice contact lakes until after 11.5 ka BP (Lemmen et al. 1994; Arnold, 2002). Sand dunes to the west of Glacial Lake Hay have been dated by optically stimulated luminescence (OSL), yielding a date of 13,900 ± 1,200 calendar years BP (SUV050309 Wolfe et al. 2007).
2.4 Pattern of Glacier Retreat

Mathews (1980) reconstructed the formation of large glacial lakes along the retreating margin of the Laurentide Ice Sheet. This work was the result of mapping in the Charlie Lake area (Mathews 1978) and reconnaissance scale interpretation of aerial photographs (Mathews 1980). He identified a number of stages of glacial lake formation, the most pertinent to this study being Indian Creek stage and Keg River stage. Indian Creek stage marked a switch in drainage of glacial Lake Peace from southeast to northwest (Mathews 1980). Subsequent retreat of Laurentide ice lead to the expansion of an ice dammed lake in the Hay River valley during the Keg River stage, draining westward into what is now the Fort Nelson River. Continued retreat led to the opening of the Meander River spillway, allowing drainage into early phases of Glacial Lake McConnell (Craig 1965, Smith 1994). A smaller lake persisted in the Hay valley into the Holocene, and incision of its outlet led to the formation of modern Zama and Hay lakes. The drainage pattern along the entire northwestern margin of the Laurentide Ice Sheet and its evolution as ice retreated was documented by Lemmen et al. (1994). This broad overview mentioned the scarcity of data for the area, and largely followed Mathews (1980) in reconstructing drainage and lake evolution in northwestern Alberta. Work by Trommelen (2006) and Trommelen and Levson (2007) to the west of the study area identified levels of Glacial Lake Hay at 420 to 465 m asl.
2.5 Implications for Moody Creek Map Area

The Moody Creek map area was glaciated at least once by Laurentide ice during the Late Wisconsinan. No exposures of pre-Late Wisconsinan sediments were found during the field investigation of this thesis project. Any pre-Late Wisconsinan glacial deposits, if present, might be preserved in deep paleovalleys. Pawlowicz et al. (2005a, b; 2007a, b) have mapped a system of buried valleys within the Bistcho Lake (NTS 84M) and Zama Lake (NTS 84L) map sheets. Paleovalleys have the potential to contain pre-Late Wisconsinan sediments. Deglacial lakes in this area are part of a larger regional system associated with blocked drainage from the Laurentide Ice Sheet (cf. Lemmen et al. 1994).
CHAPTER 3: SURFICIAL GEOLOGY

This chapter presents the results of fieldwork in the Moody Creek map area during the summers of 2004 and 2005. This fieldwork was conducted with the aim of reconstructing the glacial history of the area through: 1) the separation of surficial sediments into lithostratigraphic units, and 2) the mapping of surficial sediments at a scale of 1:50,000. This work resulted in the identification of six lithostratigraphic units and the creation of a 1:50,000 scale map of surficial geology (Kowalchuk et al. 2006, back pocket). A simplified version of the map is in Figure 1-6. Lithostratigraphic units are presented in Chapter 4: Stratigraphy and Sedimentology. The surficial geology and lithostratigraphic units are interpreted in a regional context along with a discussion of glacial history in Chapter 6: Discussion. Detailed sedimentology and lithostratigraphic logs of all exposures are contained in Appendix A.

3.1 Geomorphology

In general, the northern half of the study area is dominated by till, and the southern half is covered by 1 to 5 m of glaciolacustrine sediments. Organic deposits are also common in the southern half. For the purposes of discussion, the Moody Creek map area (NTS 84N/2) has been separated into five local geomorphic terrains: 1) bedrock slopes; 2) slope apron; 3) first bench; 4) intermediate slope; and 5) second bench (Figure 3-1). The bedrock slopes terrain lies between 480 and 630 m elevation, and is typically gently to moderately
sloping to the south, with shale bedrock near the surface, a thin cover of till, gullies up to 40 m deep, and flutings up to 5 m high. The slope apron lies along the base of the bedrock slopes from 410 to 480 m elevation, and is typically gently sloping, commonly marshy, has a thick cover of till, and has small moraines trending north-south and fluvial fans at the mouth of gullies. The first bench lies at elevations from 410 to 380 m, and is covered by a thin veneer of glaciolacustrine sediments. It is generally flat lying and covered with fens, bogs, and linear depressions interpreted as iceberg scours. Iceberg scours are present from 350 to 395 m elevation. The intermediate slope is covered with thin glaciolacustrine sediments over till. The intermediate slope lies between the first bench and second bench, and has gentle slopes to the south, with elevations between 380 and 350 m, and a thin cover of glaciolacustrine sediments overlying till. The intermediate slope has a smaller proportion of bogs and fens, compared with the first and second benches, as a result of better drainage due to the slight slope to the south. The second bench is a flat area largely covered by fens, and is from 350 to 340 m elevation.

Shorelines were identified during surficial mapping at 340 m asl, correlative with the Adair Creek spillway at 340 m asl, located 10 km to the southeast (Figure 3-2, Figure 3-3, Figure 3-4). The presence of glaciolacustrine sediments up to 410 m asl is at the same elevation as the ground above the divide between the Hay River and the Fontas River. As water spilled over the divide, it eroded the spillway channel down to 375 m asl (Figure 3-3). Both of these stages require the presence of ice to the east blocking drainage.
Figure 3-1  Geomorphic terrains of the Moody Creek map area (NTS 84M/2). The regional setting can be seen in Figure 1-1.

(Surficial Geology based on Kowalchuk et al. 2006. Elevation data source: USGS 2006.)
Figure 3-2  Airphoto showing shoreline at 340 m elevation.

Figure 3-3  Spillways draining Glacial Lake Hay.

(Data source: USGS 2006)
3.2 Surficial Mapping

The following list of material types is modified from the legend of the surficial map of the Moody Creek map area (84M/2) by Kowalchuk et al. 2006, and is ordered from oldest to youngest deposits (see map in back pocket). Map units are primarily defined according to genesis, and are further subdivided based on surface morphology (Table 3-1). For each material type, the description is presented as used on the surficial map. Surface expression and a description of each are provided in Table 3-1. Following this is a description of their typical characteristics and distribution within the study area.
Table 3-1  Surface expression symbols used with mapping symbols.

<table>
<thead>
<tr>
<th>Mapping Symbol</th>
<th>Material</th>
<th>Surface Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tb</td>
<td>Till</td>
<td>Blanket - &gt;1 m thick, continuous till cover forming undulating topography, bedrock controls topography but may be locally obscured</td>
</tr>
<tr>
<td>Th</td>
<td>Till</td>
<td>Hummocky - &gt;1 m thick, irregular hills and depressions</td>
</tr>
<tr>
<td>Tr</td>
<td>Till</td>
<td>Ridged - &gt;1 m thick, regular or organized hills and depressions, moraines or crevasse fillings forming a ridged topography</td>
</tr>
<tr>
<td>Tv</td>
<td>Till</td>
<td>Veneer - &lt;1 m thick, discontinuous till cover, underlying bedrock controls topography</td>
</tr>
<tr>
<td>Lb</td>
<td>Glaciolacustrine</td>
<td>Blanket - &gt;1 m thick, continuous cover</td>
</tr>
<tr>
<td>Lv</td>
<td>Glaciolacustrine</td>
<td>Veneer - &lt;1 m thick, discontinuous cover</td>
</tr>
<tr>
<td>Gih</td>
<td>Glaciofluvial</td>
<td>Ice-contact stratified drift with hummocky topography relating to melting of underlying ice.</td>
</tr>
<tr>
<td>Ap</td>
<td>Alluvium</td>
<td>Plain - flat lying alluvial deposits. Surface topography is not controlled by underlying units</td>
</tr>
<tr>
<td>Af</td>
<td>Alluvium</td>
<td>Fan - sloping area of alluvial sediments, typically at the toe of a slope</td>
</tr>
</tbody>
</table>

3.3  Pre-Quaternary

3.3.1  Bedrock

The regional bedrock is Cretaceous Fort St. John Group shales (including the Shaftesbury Formation) and Dunvegan Formation sandstone exposed in the highlands and along meltwater channels and canyon walls. Within the map area, bedrock lies close to the surface along the slopes of the Alberta Plateau. Bedrock is rarely exposed at the surface along the bedrock slope but is well exposed in gully walls which flank Elsa Hill (Figure 1-2). Sandstone overlies Shaftesbury Formation shale, but was not observed within the map area. Shale is horizontally bedded (Figure 3-5), with the result that much of the area has very subdued topography. For example, Elsa Hill in the northern part of the study area is flat.
topped, and the Fort Nelson Lowland in the southern part of the study area is extremely flat over many kilometres.

Figure 3-5  Shaftesbury shale bedrock underlying massive diamicton.

(Top: C. Kowalchuk)

3.4  Late Wisconsinan - Proglacial and Glacial Environments

3.4.1  Till

Till is broadly defined following Dreimanis (1982) as being sediment transported and deposited by or from ice with little or no sorting by water. Till includes subglacial, englacial, and supraglacial sediment. Depositional environments include the bed of an active or stagnant ice sheet, where lodgement of subglacial sediment and melt-out of englacial sediment occur, and
advancing, stable, or retreating margins of glaciers, where mass movements in supraglacial sediment predominate (Dreimanis 1989). For surficial mapping purposes, till was interpreted as either basal or supraglacial, since time didn’t allow detailed clast fabric and sedimentological analysis of each section.

Basal till has a sandy to clayey matrix with striated clasts of various lithologies, including Canadian Shield gneisses and granites, Paleozoic limestone and dolomite, Proterozoic sandstone erratics, and a local Cretaceous component. The local Cretaceous component is made up of poorly indurated shale, which is easily destroyed during grain size measurements, and is difficult to distinguish from the clay matrix of many diamictons. Indurated clast content (shield clasts and Paleozoic sedimentary rocks) is typically low (<10 %), however, the poorly indurated Cretaceous shale component can be as much as 50%. Till typically forms broad flat plains, especially on the slope apron above the limit of Glacial Lake Hay, and below the bedrock slopes bordering the Alberta Plateau. Where till has a flat surface morphology it is typically clay-rich, clast poor, at least 5 m thick. Till was also deposited in ridges and hummocky topography along the slope apron (Figure 3-1), and in these areas generally has a higher indurated clast content, up to 15% (Figure 3-6). Clasts in hummocky terrain are derived mainly from the Canadian Shield and platform sedimentary rocks along its margin, indicating long transport distances likely related to the meltout of long-travelled englacial debris. Along the bedrock slopes of the Alberta Plateau till occurs as a blanket or veneer draping the underlying bedrock. Till in these areas commonly contains a high proportion of shale fragments, however
indurated clasts of shield material are rare. It is interesting to note that the only indurated clasts present are typically boulders of carbonate or shield lithologies. Excavation of the till – bedrock contact at site 610 found small plucking features indicating ice flow to the west (Figure 3-7). Till also shows large scale flutings, as a result of ice flowing to the southwest and west (Figure 3-8 and Figure 3-9). These have been used to reconstruct ice flow, and are interpreted as ice flow indicators based on comparison to modern analogues (Evans et al. 1999). Regional scale subglacial floods have been suggested to form streamlined features, but due to their localization to the bedrock slopes, and a lack of acceptance in the literature (cf. Clarke et al. 2005), this interpretation was not considered. Regardless of the genetic origin of flutings, they are still indicative of ice flow, since subglacial meltwater flows subparallel to ice flow.
Figure 3-6  Higher clast content of till in area of hummocky topography.

Figure 3-7  Plucking feature at the till – bedrock contact resulting from flow to the west, which is down in the photo. The compass is facing true north, to the left.
Figure 3-8  Flutings in till.

(Photo: R.C. Paulen)

Figure 3-9  Till cored fluting on the bedrock slopes.

Photo: (C. Kowalchuk)
There are two types of hummocky topography present within the Moody Creek map area. The first type of hummocky topography contains massive till with larger (~15-30%) concentrations of exotic, indurated clasts (Figure 3-6). This type of hummocky topography is interpreted to be the result of the melting of stagnant ice (Eyles et al. 1999), or ice marginal deposition from active ice (Hambrey et al. 1997).

The second is believed to be the result of thrusting of bedrock by ice flowing to the southwest, commonly resulting in depressions up ice flow (e.g. Kupsch 1962). Deposits in this type of hummocky topography consist of thick successions of boulder diamicton, overlain by thin massive diamicton. Massive diamicton commonly overlying boulder diamicton is evidence of a transition from relatively short distance of transport (boulder diamicton), to longer transport (massive diamicton) (Figure 3-10). Massive diamicton is the result of prominent strain and grinding of clasts resulting in a higher percentage of sand. This is likely due to a change in bed conditions as there is little evidence of a change in ice flow.
3.4.2 Glaciolacustrine Deposits

Glaciolacustrine sediments are fine sand, silt, and clay, with minor diamicton, deposited in glacier-dammed lakes in valleys and along the margin of the Laurentide Ice Sheet. Glaciolacustrine sediments were deposited during the advance and retreat phases of the last glaciation. Advance-phase sediments were horizontally bedded, and appeared to be highly modified by glacial shearing. Retreat-phase glaciolacustrine deposits form areas of low relief, most commonly occurring in low lying areas (Figure 3-11). These deposits are mapped as veneers and blankets, but in some areas the blankets can be greater than 3 m thick, and mask the surface expression of the underlying units. Because they are poorly drained, glaciolacustrine sediments are usually overlain by organic
deposits, especially on the first and second benches (Figure 3-1). Till commonly underlies glaciolacustrine sediments, and the contact is generally gradational (Figure 3-12), although it is sharp in some areas. Below 410 m, small raised areas of a few hectares are till “windows” surrounded by flat glaciolacustrine sediments. Shorelines and iceberg scours are the most prominent geomorphic features seen in areas of glaciolacustrine sediments (Figure 3-13). Iceberg scours are found in many of the glacial lakes that surrounded much of the Laurentide Ice Sheet (Clayton et al. 1965, Dionne 1977, Dredge 1982, Eden and Eyles 2001). Also observed are draped flutings and streamlined landforms, formed parallel to ice flow.

Figure 3-11 Extremely flat topography characterizes the Ft. Nelson Lowlands where thin glaciolacustrine sediments overlie till.

(Photo: R.C. Paulen)
Figure 3-12 Stratified glaciolacustrine deposits overlying till.

(Photo: B.C. Ward)

Figure 3-13 Iceberg scours are highlighted by dashed lines.

3.4.3 Glaciofluvial Deposits

Glaciofluvial sediments are well to poorly stratified sand and gravel, with minor diamicton. They were deposited behind, at, or in front of the ice margin by glacial meltwater, and represent a potential aggregate source. Gravel was observed at the surface at only one site located at 59°12'N 118°39'W, with an area of 0.8 km$^2$ (Site 602). Gravel that is extensive enough to be exploited for aggregate is present beneath till, most likely deposited in subglacial conduits when the area was glaciated. Paleoflow measurements in the two gravel pits exploiting sub-till gravel (Sites 538 and 539) showed flow to the southwest, subparallel to the regional ice flow, and across the regional slope. This is consistent with an interpretation as subglacial conduit fill (Brennand 1994).
3.5 Post Last Glaciation – Nonglacial Environments

3.5.1 Organic Deposits

Organic deposits are peat and muck, usually 1 to 3 m thick, formed by the accumulation of plant material in various stages of decomposition. It generally occurs as flat, wet terrain (swamps and bogs) over poorly drained substrates, and is commonly underlain by permafrost and segregated ice. Zoltai (1993) uses basal peat ages to estimate that fen development in the study area began around 9,000 calendar years BP, and bog development began around 5,000 cal yrs BP. Bog development started with peat accumulation, and during dry periods, was
marked by disturbance by fire. Subsequent permafrost degradation caused subsidence and wet conditions (Figure 3-15). Halsey et al. (1998) also reconstruct the pattern of peatland development in western Canada. Peatland initiation is believed to have begun between 8,000 and 9,000 cal yrs. Saline (solonetzic) soils in areas of the Hay River Lowland may have delayed peat development (Halsey et al. 1998).

Figure 3-15  Area of bog organics burnt by a recent fire.

(Photo: R.C. Paulen)

Bog peat:

Units mapped as bog peat consist of sphagnum or forest peat formed in an ombrotrophic environment. They occur in areas of wet terrain, which may be treed or treeless. Trees in bogs are commonly stunted and small, and black spruce is the dominant species (Figure 3-16). Bogs are most extensive in
moderately drained areas in the flat transition between the slopes of the Alberta Plateau and the poorly drained fens typically found on the Fort Nelson Lowland. Bog peat forms plains with relief in the order of 1 m over 10 m caused by vegetation. The organic material making up bogs is typically fibric, with common charcoal horizons up to 1 cm thick (Figure 3-17). Seismic lines and drill pads cut in bog peat commonly result in melting of the underlying permafrost, causing subsidence of up to 1.5 m.

Figure 3-16 Recent pipeline trench through a flat area of bog organics.

(Photo: C. Kowalchuk)
Figure 3-17 Fibric bog peat excavated during pipeline construction in the southern part of the Moody Creek map area (NTS 84M.2)

(Foto: C. Kowalchuk)

*Fen peat:*

Fen peat is derived from sedges and partially decayed shrubs in a eutrophic environment. Areas mapped as fen peat form relatively open peatlands with a mineral-rich water table that persists seasonally near the surface. Fens are generally covered with low shrubs and rare sparse regions of black spruce and larch. Fens cover most of the ground surface in the poorly drained southeast corner of the Moody Creek map area, and typically overlie fine grained glaciolacustrine sediments deposited in Glacial Lake Hay. Fen peat forms plains with relief of 1 m vertically over 10 m horizontally caused by vegetation, commonly in the form of narrow ridges up to 1 m high forming polygon-like patterns (Figure 3-18).
Figure 3-18 Broad fens in the southeast corner of the map area are dominated by shrubs, grasses, and the characteristic larch.

(Photo: B.C. Ward)

Undifferentiated bog and fen deposits:

This map unit includes bog and fen deposits that are undifferentiated at the map scale. Areas mapped as undifferentiated organics may be a mix of areas of fen and of bog, or organic deposits that could not be differentiated at the scale of mapping.

3.5.2 Alluvial Deposits

Alluvial deposits are gravel, sand, minor silt, and organic detritus deposited by postglacial streams. They are commonly stratified, but may be massive, typically when fine-grained. Floodplain sediments are silty gravel and organic detritus >1 m thick. Typically these comprise active floodplains close to river level with meander channels and scroll marks. Fan deposits are typically sandier, and >1 m thick, and occur at the toe of the bedrock slope, in the slope apron area (Figure 3-1). On sloping areas in the north of the study area, alluvium
is confined to the base of gullies. In flat areas away from the bedrock slope, alluvium grades into fen sediments across broad wetlands (Figure 3-19). Very little sand and gravel is transported by modern streams because of the near horizontal topography and hence low stream energy. Fluvial sediments can contain as much as 50% silt and clay (Figure 3-20). Beavers probably have the largest effect on stream geomorphology, causing channel scouring during dam breaches, channel avulsion, and sediment storage (Butler and Malanson 2005). Broken twigs collected in alluvial deposits overlying a paleosol yielded an AMS age of 5075 ± 20 $^{14}$C yrs BP (UCI 13583), and provides the only chronological constrain on deglaciation in the map area, although it is a very loose constraint (Figure 3-20, Figure 3-21, and Figure 3-22).
Figure 3-19 Fluvial fan at the edge of a fen. The channel has moved steadily eastward leaving two abandoned channels. A twig was removed from a buried soil layer adjacent to one of the abandoned channels.

Figure 3-20 Buried soil horizon at site 523 where a twig was sampled for radiocarbon analysis. Buried soil marked as a white dashed line.

(Photo: C. Kowalchuk)

Figure 3-21 Photo of twig submitted for radiocarbon dating.

(Photo: C. Kowalchuk)
Figure 3-22 Stratigraphic column of the top 2.5 m of material shown in Figure 3-20. A radiocarbon age of 5075 ± 20 C14 yrs BP was obtained (UCI 13583) from a twig just above the Clayey peat horizon.

Silty clay with rare wood fragments

Matrix-supported granules and silty sand, with common wood fragments.

Very dark grey, massive silty clay

Clayey peat with grey silt-filled root traces

Matrix-supported, massive, clay-rich, clast-poor diamicton
3.5.3 Anthropogenic Deposits

Anthropogenic deposits consist of culturally-made or modified geological materials such that their original physical properties (e.g., structure, cohesion, compaction) have been drastically altered. These deposits are generally >1 m thick. Anthropogenic deposits form the foundations beneath large gas processing plants, oil batteries, and runways within the map area, as well as large stockpiles of sulphur. They are typically composed of compacted till and/or gravel. In many areas there has been alteration of surficial materials by road building, pipeline construction, borrow pit construction, and sump pit construction. However, these areas are too small to be shown at the scale of mapping. Gravel pits and mapping stations are shown in Kowalchuk et al. 2006 (back pocket).
CHAPTER 4: STRATIGRAPHY AND SEDIMENTOLOGY

Sediments described in a total of 126 exposures were grouped into 6 broad lithostratigraphic units (Figure 4-1 and Figure 4-2). These units are described and interpreted below. Each unit is time-transgressive, and may overlap other units in time of deposition through the region.
Figure 4-1 Lithostratigraphic units of the Moody Creek map area (NTS 84M/2).

- **Unit 6:** Alluvium
- **Unit 5:** Bog and fen organics
- **Unit 4:** Massive and deformed stratified diamicton
- **Unit 3:** Diamicton interstratified with sorted sediments, and massive sand silt and clay
- **Unit 2a:** Regional silty clay diamicton
- **Lithologically distinct diamicton**
- **Unit 2b:** Sand and gravel
- **Unit 2a:** Regional silty clay diamicton
- **Unit 1:** Clast free silt and clay
- **Shale Bedrock**
Figure 4-2  A) Unit 3 interstratified diamicton: diamicton and sand couplets are planar bedded; B) Unit 3 interstratified diamicton: complexly deformed diamicton and silty sand; C) Unit 3 sand silt and clay overlying unit 2a massive diamicton; D) Thin section across the contact between unit 2a and unit 3 shown in C; E) Unit 2a massive diamicton overlying unit 1 clast free silty clay; F) Thin section across the contact between unit 1 and unit 2a shown in E.

(Thin sections are courtesy of Mark Tarplee, University of London)
4.1 Unit 1: Clast Free Silty Clay

Unit 1 is fine grained, clast free silty clay underlying the regional till, and was only observed at two sites (515 and 530 in Appendix A and Figure 4-3). The best exposure is >1 m of stiff to very stiff dark grey silty clay with no lower contact exposed (Figure 4-4). The unit has horizontal fissility and vertical jointing, with prominent laminations that are sheared (Figure 4-5). Undulatory shears planes are striking at 230° and become more pervasive towards the upper contact with the till. The sheared nature of the unit is also prevalent in thin section (Figure 4-2 F). Microlamination in thin section is evidenced by variation in colour of the sediment. This banding has been severely disturbed, with evidence of both brittle and ductile deformation present. Normal faulting is evident at several locations, particularly near the upper contact.
Figure 4-3  Location of sites exposing unit 1. Roads are shown as solid black lines with no labels. Contours are in metres. The outline of NTS 84M/2 map area is shown as a dashed black line. The base is a hillshaded DEM derived from NASA SRTM data.

(Data source: USGS 2006)
Figure 4-4  Unit 1 underlying unit 2a at site 530. Note the absence of clasts within the lighter coloured unit 1 at the base, and the darker colour and presence of clasts in overlying unit 2a. The dashed line marks the contact. Scale card is 9 cm long.

(Photo: C. Kowalchuk)

Figure 4-5  Undulatory shears along bedding planes within unit 1 at site 530. Scale card is 9 cm long.

(Photo: B.C. Ward)
Unit 1 is interpreted as advance-phase glaciolacustrine sediments deposited in front of the Laurentide Ice Sheet. The undulatory shape of the shears suggests that overriding ice was flowing towards 230°, to the southwest. The grain size distribution of this unit closely matches that of the regional shale bedrock (see grain size data in Appendix B). The lack of organics and lithologic similarity to the overlying glacial deposits negates the interpretation that this clay could be non-glacial lacustrine sediments overridden by the Laurentide Ice Sheet.

4.2 Unit 2a: Silty Clay Diamicton

Unit 2a is silty clay diamicton. It is the most widespread unit in the study area, and corresponds to the Till mapping unit. Unit 2a includes three facies: boulder diamicton, massive diamicton, and crudely stratified diamicton.

4.2.1 Boulder Diamicton

Boulder diamicton lies at the surface along the bedrock slopes (Figure 3-1) along Elsa Hill. It is discontinuous, typically less than 1 m thick, underlying massive diamicton, and overlying shale bedrock. The matrix is 2% sand, 60% silt, and 38% clay (Figure 4-6), composed dominantly of shale fragments and clay, and is highly friable. At some sites, the boulder diamicton shows subhorizontal shear planes. Gneiss boulders derived from the Shield are common, with few other clasts. The surface expression is commonly hummocky or fluted. The lower contact with shale bedrock is typically gradational.
Boulder diamicton is interpreted as glaciotechnized shale bedrock (Hiemstra et al. 2007). Comminution was not pervasive, resulting in the preservation of intact shale fragments, suggesting short transport distance. The lower sand content when compared to the other facies of unit 2a is believed to reflect the dominance of shale fragments on the texture of the matrix. A glacial origin for boulder diamicton is suggested by the presence of boulders of red gneiss, as well as the presence of shear planes and prominent deformation within the unit. Hummocky topography associated with the unit likely reflects thrusting of the weak shale bedrock.
4.2.2 Massive Diamicton

Massive silty clay diamicton is by far the most prevalent material in the study area. It is exposed at the surface over most of the areas above 410 m elevation, and commonly outcrops in raised areas below these elevations. Along the bedrock controlled slopes of Elsa Hill (Figure 3-1), massive diamicton commonly overlies shale bedrock or boulder diamicton. In the bedrock slopes geomorphic terrain, massive diamicton is between 2 and 5 m thick over bedrock. Below 410 m asl, massive diamicton is commonly overlain by unit 3. The thickness of the massive diamicton increases towards the south, where it is at
least 8 m thick at the deepest exposure, and has been observed to be >15 m in adjacent areas (Smith et al. 2007). The surface expression of massive diamicton ranges from flat, to fluted, to hummocky.

The colour of unit 2a massive diamicton ranges from dark to very dark grey. The matrix texture is variable, ranging from clayey silt, through sand-silt-clay, to sandy silt (Figure 4-6). The proportion of silt to clay remains constant (2 parts silt to 1 part clay), with the amount of sand varying. Clast content varies from 1% to 20%, and averages 9%. Clasts range in size from pebbles to boulders up to 2 m in size with an average of about 3 cm. Clasts are typically subangular and commonly display striations, keels and facets. Lithologies are dominated by red gneiss and granite from the Canadian Shield along with limestone and quartzite from the margin of the shield, but also include dolomite, soft shale, ironstone, chert, and volcanic lithologies. Microscopic examination of samples of the massive diamicton reveal fairly well developed microfabric, subparallel lineation, attenuated sand layers and lenses, and circular alignment structures (M. Tarplee, pers. Comm. 2007) (Figure 4-2). These types of structures are generally associated with strain (deformation) due to subglacial shearing (e.g. Hart and Rose 2001). The unit is horizontally and vertically jointed, and contains rare lenses of sorted silt and sand. Sand lenses are typically squeezed and deformed laterally (Figure 4-7). Where shear planes are present they are commonly gently dipping to the east (Figure 4-8).
Figure 4-7  Lateral injection of sand from a tabular sand body into the surrounding clayey silt diamicton at site 530 in unit 2a. The sand body is to the right, and sand has been injected to the left and downwards. The card is 9 cm for scale.

(Photo: C. Kowalchuk)
Six fabrics were measured in massive diamicton, measuring the trend and plunge of clast a-axes as outlined in Section 1.5.1 Field Investigations (Figure 4-9). Sites where fabrics were measured are depicted in Figure 4-10, with details shown in Table 4-1. All but one of these fabrics, have moderate strengths with principal eigenvalues ranging from 0.55 to 0.76. They generally represent unimodal to slight girdle patterns except for Fabric 4 that has more of a girdle pattern with a weaker principal eigenvalue (cf. Hicock et al. 1996). Three of the fabrics indicate flow to the south west (2, 3, 6), one indicates flow to the south
(5), one indicates flow to the west (1), and one is not strong enough to determine ice flow (4), although it seems to reflect westward ice flow (Figure 4-9).
Table 4-1  Classification and interpreted ice flow of till fabrics.

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Unit #</th>
<th>N</th>
<th>E1</th>
<th>E3</th>
<th>Classification (Hicock et al. 1996)</th>
<th>Interpreted Ice Flow</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2a</td>
<td>25</td>
<td>0.688</td>
<td>0.040</td>
<td>Spread Unimodal</td>
<td>To West</td>
<td>Corroborates plucking features at bedrock contact</td>
</tr>
<tr>
<td>2</td>
<td>2a</td>
<td>25</td>
<td>0.755</td>
<td>0.039</td>
<td>Spread Bimodal</td>
<td>To Southwest</td>
<td>Clasts dip shallowly down to southwest.</td>
</tr>
<tr>
<td>3</td>
<td>2a</td>
<td>25</td>
<td>0.634</td>
<td>0.048</td>
<td>Girdle</td>
<td>To Southwest</td>
<td>Clasts dip down to northeast.</td>
</tr>
<tr>
<td>4</td>
<td>2a</td>
<td>25</td>
<td>0.548</td>
<td>0.115</td>
<td>Girdle</td>
<td>To West</td>
<td>Lee ends point west.</td>
</tr>
<tr>
<td>5</td>
<td>2a</td>
<td>25</td>
<td>0.771</td>
<td>0.070</td>
<td>Bimodal</td>
<td>To West</td>
<td>Transverse - possible compressive ice flow</td>
</tr>
<tr>
<td>6</td>
<td>2a</td>
<td>25</td>
<td>0.665</td>
<td>0.067</td>
<td>Spread Unimodal</td>
<td>To Southwest</td>
<td>Clasts dip down to northeast. Same site as Fabrics 7 and 9.</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>25</td>
<td>0.715</td>
<td>0.052</td>
<td>Spread Bimodal</td>
<td>To Southwest</td>
<td>Stratified - possibly waterlain. Same site as Fabrics 6 and 9.</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>25</td>
<td>0.665</td>
<td>0.048</td>
<td>Spread Bimodal</td>
<td>To Southwest</td>
<td>Massive diamicton.</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>25</td>
<td>0.674</td>
<td>0.122</td>
<td>Spread Bimodal</td>
<td>To Southwest</td>
<td>Transverse - possible compressive ice flow. Same site as Fabrics 6 and 7.</td>
</tr>
</tbody>
</table>
In general, fabrics have primary eigenvalues of between 0.55 and 0.75. The spread of many of the fabrics may be due to a combination of deformation and lodgement processes during deposition (cf. Dreimanis 1989, Hicock et al. 1996). Recent laboratory experiments indicate that pervasive deformation in till results in very strong fabrics (Hooyer and Iverson 2000). Thus the spread pattern of many of the fabrics could be a result of deposition through lodgement and
meltout, with non-pervasive deformation indicated by the preservation of structure in the diamicton, such as crude stratification, sand lenses, and raft of distinctive lithologies. The transverse orientation of Fabric 5, only 1 metre below the surface, could reflect compressive ice flow following glacial maximum and prior to deglaciation, assuming that till was deposited time-transgressively following glacial maximum.

Massive diamicton is interpreted to be basal till, likely a combination of lodgement and basal melt out. The diamicton is generally massive, overconsolidated, commonly has shears, and deformed sorted sand and silt layers and lenses; features that are all consistent with the above interpretation. Principal eigenvalues are generally consistent with ranges reported for basal till (Dreimanis 1989). All the microscopic structures described indicate significant levels of cumulative shear strain in response to applied shear stress, and are consistent with basal till.

4.2.3 Crudely Stratified Diamicton

Crudely stratified diamicton is between 2 and 5 m thick. Crudely stratified diamicton comprises interstratified grey and pink diamictons. Pink diamicton contains 20% clasts, and grey diamicton contains only 5% clasts. Clasts within pink diamicton include abundant poorly indurated pink dolostone and limestone, with lesser Canadian Shield gneiss. The matrix of the pink diamicton is sandy silt, contrasting with the clayey silt matrix of the grey diamicton (Figure 4-6). Pink and grey diamicton are separated by both subhorizontal shears and folds indicating deformation to the southwest (Figure 4-11). Strain within the crudely stratified
diamicton was accommodated along discrete shear planes. Grey diamicton is matrix supported with 3 to 5% clasts, subrounded and rounded clasts, ranging in size from pebbles to rare small cobbles. Clast lithologies are typically Canadian Shield gneiss and white limestone. Grey diamicton also contains small 5 to 10 cm sized blocks of grey deformed shale as well as rare larger rafts of shale up to 3 m long and 40 cm high (Figure 4-12). The lower contact of this unit varies from sharp to gradational, and is generally conformable.

Figure 4-11 Unit 2a at site 506. Pink diamicton and grey diamicton are separated by subhorizontal shears and vertical folds. Ruler is 1 cm wide.

(C. Kowalchuk)
Unit 2a crudely stratified diamicton is interpreted to be an englacially transported material deposited by passive meltout (till). Rafts of lithologically dissimilar materials and fragile shale bedrock have been deposited without comminution, indicating that the material was likely deposited through meltout by stagnant ice, and that there was not enough shearing during transport and deposition to homogenize the sediment. Clasts of Canadian Shield gneiss and limestone indicate that ice transported the material significant distances prior to stagnation.
Distinctive pink coloured diamicton was observed at several sites. The source of the pink coloured material is undetermined; however, it is unlikely to originate locally due to the dark grey nature of the surrounding Shaftesbury shale bedrock. Pink sediments were also reported east of High Level at the transition from Glacial Lake Peace glaciolacustrine sediments to the underlying Laurentide till (Plouffe et al. 2008a). The presence of pink material at sites separated by 170 km and lack of a local source area suggest that the pink sediments were transported over significant distances. In order to preserve the pink colour, transportation and deposition must have involved very little mixing, perhaps as rafts of sediment within the ice (Ruszczańska-Szenajch 1987).

4.3 Unit 2b: Sand and Gravel Within Diamicton

Unit 2b is sand and gravel underlying 2 to 3 m of the regional diamicton, and was observed at two gravel pits (Figure 4-13 and Figure 4-14). Sandy gravel makes up about 70% of the material; about 30% is pebbly sand beds that are more common near the base of the section (Figure 4-15). In the gravel, clasts range in size from granules to large cobbles and are dominantly subrounded. Lithologies include red gneiss and granitic rock derived from the Canadian Shield, and limestone, dolomite, white quartzite, and rounded shale. Many clasts show fracturing that is oriented normal to the ground. Clasts are typically weakly to moderately imbricated with a northeastward dip of a-b planes. The matrix, 20 to 30%, is composed of quartz rich medium to coarse sand, with very few fines (<5%). Stratification is dominantly subhorizontal with rare moderately dipping (~25°) beds of normally graded sand and granules. Sand beds are 30 to 50 cm
thick, are dominantly medium to coarse grained, and contain rare dispersed pebbles. Within sand beds there are prominent cut and fill structures, large scale trough cross-stratification and planar gently dipping bedding with rare climbing ripples with paleoflow to the south (Figure 4-16). Unit 2b is folded as much as 40 cm below the upper contact with unit 2a (Figure 4-17). At one site, dense dark grey diamicton (unit 2a) was observed underlying unit 2b suggesting that unit 2b is most likely a lens within unit 2a (R. Paulen 2005 pers. comm.)

The upper 1 m of gravel was deformed in some areas (Figure 4-17), and therefore to reconstruct paleoflow direction, clasts orientation measurements were made at least 2.5 m below the upper contact where no evidence of deformation was found. Paleoflow measurements within a zone of imbricated subhorizontal gravel indicated that plate shaped clasts have a-b planes dipping to the northeast, with a fair amount of spread, but good clustering. Dip is interpreted to be the result of glaciofluvial imbrication resulting from meltwater flow from the northeast to the southwest. The primary eigenvector is 055°, therefore meltwater flow is generally towards 235° (Figure 4-18).

At site 539 the direction of dip is somewhat variable, but appears to have distinct clusters in the northeast quadrant of the stereonet (Figure 4-19). Dip is interpreted to be the result of glaciofluvial imbrication resulting from meltwater flow from the northeast to the southwest. The primary eigenvector is 061°, therefore meltwater flow is likely towards 240°. This is very close to the interpreted paleoflow for site 538. The rose plot points up-dip, which is downflow.
Figure 4-13 Surficial geology map of Moody Creek (84M/2) showing possible extent of sub­till sand and gravel (unit 2b) as polygon Tv/G, representing a till veneer over gravel. Field sites 04PMA538, Zama Beach gravel pit, and 04PMA539, an active gravel pit, are also shown. Other units on the map are: Tb – Till blanket (>2m); Tv – Till veneer (<2m); Lv – Glaciolacustrine veneer (<2m); O1 – Bog organics; O2 – Fen organics; AN – anthropogenic deposits.

(Based on Kowalchuk et al. 2006).
Figure 4-14 Stratigraphic column of unit 2b gravel overlain by unit 2a diamicton. See sites 538 and 539 in Appendix A for more detail.

Unit 2b: Stratified sand and gravel

Unit 2a: Massive silty clay diamicton
Figure 4-15 Finer grained bed within unit 2b sand and gravel at site 539. Silt within finer beds is darker, and sand is lighter coloured. The fine bed overlies pebbly sand, and underlies moderately sorted pebble gravel. Scraper is 25 cm long for scale.

(Photo: C. Kowalchuk)

Figure 4-16 Climbing ripples in moderate to poorly sorted sand and granules of unit 2b at site 539. View is to the south and pick is 65 cm.

(Photo: C. Kowalchuk)
Figure 4-17 Contact between unit 2b sand and gravel and overlying unit 2a massive diamicton, shown by dashed line. Note the folds and deformation apparent along the contact and within the gravels immediately underlying the contact. The upper 1.5m of unit 2a has been removed and is not visible in the photo. Pick is 65 cm.

(Photo: C. Kowalchuk)
Figure 4-18 Rose plot of dip and dip direction of A-B planes of 100 plate shaped clasts at site 538 (Zama Beach). Density contours are at multiples of 1.5 points per 1% of total area. Plot is lower hemisphere, equal area.

Eigenvalues: 0.640 0.261 0.099
Eigenvector: 056/31
Unit 2b is interpreted to be glaciofluvial due to the coarse grain size of the unit in comparison to modern fluvial systems in the area, the abundance of red gneiss and granite clasts derived from the Canadian Shield, and its stratigraphic position. The presence of very hard shield clasts, cobble sized, with vertical fractures indicates that the deposit was overridden by ice with in-situ crushing. Deformation along the upper contact is interpreted to be the result of glacial
loading following deposition. It is unlikely that unit 2b was deposited subaerially as imbrication indicates flow to the southwest, across the local slope. Also, paleogeographic reconstruction implies the area would likely have been flooded by a glacial lake as the Laurentide Ice Sheet advanced into the area. Till overlying the gravel also suggests a subglacial origin. It is possible that sand and gravel were deposited as a subaqueous fan at the ice margin, but the lack of fine sand or silt in the matrix and lack of fine grained interbeds seems to rule out deposition in a proglacial lake. Therefore, unit 2b is most likely a subglacial channel deposit (cf. Brennand 1994).

4.4 Unit 3: Diamicton Interstratified With Sorted Sediments, and Massive Sand Silt and Clay

Unit 3 comprises a wide range of sediment types that are combined because of their stratigraphic position and inferred genesis. Unit 3 is commonly observed above unit 2a and below unit 4, if present. It is differentiated into two facies: 1) diamicton interstratified with sand, silt and clay, some of which is highly deformed (hereafter referred to as interstratified diamicton), and 2) massive to weakly stratified sand, silt and clay (hereafter referred to as sand silt and clay). Unit 3 corresponds to the glaciolacustrine mapping unit.

4.4.1 Interstratified Diamicton

Interstratified diamicton commonly comprises either couplets of thin diamicton and sorted sediments, or deformed beds of diamicton and sand, silt and clay (Figure 4-2 A and B). Thickness varies from less than 1 to 10 m, and is typically 1 to 2 m thick (Figure 4-20). It is generally laterally extensive over at
least 500 m. The lower contact of this unit with unit 2a, massive diamicton, is
diffuse, with sorted materials less common towards the base of the unit. Where
interstratified diamicton is overlain by unit 4 massive diamicton the upper contact
is also typically gradational and shear planes appear to displace sorted beds
within the upper 10 cm of unit 3, and dip gently to the east at about 5 to 10°.

Diamicton beds are 4-6 cm thick, with a clay silt matrix, and clasts up to
10% that are mainly small pebbles. Clasts are subangular spheres to plates, with
lithologies including pink gneiss and granite, weathered carbonate, ironstone,
shale, and unweathered striated limestone. A single fabric was measured in the
diamicton of unit 3 (Figure 4-9 #7 and Figure 4-20). It reveals a bimodal
clustering with a primary eigenvalue of 0.715, and a primary eigen vector to the
southwest. This fabric is believed to represent either subglacial or subaqueous
deposition by ice, or as a flow, moving to the southwest.

Sand layers are commonly <2 cm thick, medium grained, and contain
gypsum crystals. Stratification ranges from planar to tightly folded continuous
layers (Figure 4-21). Silt and clay layers are also laminated, and they are
commonly deformed, broken, and offset across diapirs. Where the unit is
deformed, dark clay forms undulating thin beds that dip to the east. Also
prominent are lenses of beige silty fine sand 5-15 cm thick, and 10-70 cm wide,
with crystals of gypsum about 3 mm in size on average, up to 2 cm. Zones of
stratification show evidence of shearing and deformation, and tend to be highly
attenuated. Gypsum crystals represent post depositional crystallization from
minerals present in the incorporated shale material. It forms granule sized
crystals in sand, in contrast to the large well formed crystals it forms in unit 2a massive diamicton. Where sand forms horizontal beds, the granular gypsum crystals have thickened the sand layers.

Figure 4-20 Lithostratigraphic column of site 626 showing unit 3 overlying unit 2a, and underlying unit 4. The fabric of unit 3 shows a moderately strong northeast, southwest orientation.
Figure 4-21 Unit 3 interstratified diamicton and sand at site 621. Trowel is 15 cm for scale, and notes the upper contact of unit 3 with overlying unit 4.

The stratification seen in unit 3 could be the result of: 1) rain-out from a floating ice margin (e.g. McCabe et al. 1987); 2) periodic subaqueous cohesive debris flows, from supraglacial debris (e.g. Krzyszkowski and Zielinski 2002); or 3) preserved englacial structure from till deposition by stagnant ice (Haldorsen and Shaw 1982). The first two interpretations are consistent with the presence of Glacial Lake Hay at the end of the last glaciation. The third interpretation does not imply the presence of a lake and thus does not confirm our paradigm and is rejected. Rain-out or debris flows imply an ice-proximal position for these
glaciolacustrine deposits. The unit shows evidence of dewatering and soft sediment deformation. Deformation associated with the overlying unit 4 represent glacier overriding with the vergence of structures indicating glacier flow to the west-southwest. Gypsum within the deposit originates from the composition of the incorporated Shaftesbury Shale bedrock. Oxidation products of minerals in the bedrock precipitate as gypsum crystals up to 2 cm across.

4.4.2 Sand, Silt and Clay

Sand, silt, and clay is massive, and ranges in thickness from <1 to 3 m (Figure 4-2 C). It overlies unit 2a with a generally sharp but conformable contact, and was observed to have a 2 cm basal zone with thin but distinct lenses of pink silty clay and lenses of grey sorted silt. Within finer grained material, obscure laminations become thinner upwards. Where unit 3 sand, silt, and clay is massive, it is generally clayey silt with minor fine sand, although one notable exception was observed at site 502 where poorly sorted sand immediately underlies unit 4 massive diamicton (Appendix A).

Unit 3 sand, silt, and clay is interpreted as glaciolacustrine sediments deposited in a more ice-distal environment than unit 3 interstratified diamicton. The lack of coarse grained material suggests deposition at the distal end of underflows from the glacier front (Ashley et al. 1985).

4.5 Unit 4: Massive Diamicton Veneer

Unit 4 is thin (<1 m), discontinuous, massive to stratified diamicton. It was observed at all sites at the surface, in gradational contact with unit 3. At these
sites, unit 3 showed prominent deformation which ranged from complete
destruction of sedimentary structures at the upper contact decreasing
downwards in intensity over 50 cm to undeformed horizontally stratified
sediments. The matrix of unit 4 is sandy, silty clay to sandy, clayey silt. Clast
content is generally 1-3%, rarely up to 5%. Clast shapes range from subangular
to rounded, with an average size of 3 cm. The unit is massive and relatively stiff.
Two fabrics obtained from this unit are moderately strong (eigenvalue of .665 and
.674, Figure 4-9). One fabric is oriented parallel, and the other perpendicular, to
the assumed flow direction (southwest).

This unit is interpreted as a basal till, deposited during a readvance into
the glacial lake represented by Unit 3 glaciolacustrine sediments, deforming and
incorporating previously deposited sediments into till. Ice deformed underlying
unit 3 sediments, and also formed glacially streamlined landforms identified in
regional mapping to the south (Paulen et al. 2005b). Glaciolacustrine deposits
were presumably deposited following this readvance, however, they were not
observed during mapping. The upper 50 cm of material is commonly altered by
soil development to such a degree that it is not differentiable. These retreat
phase glaciolacustrine sediments are most likely present at the surface in a thin
layer below about 400 m elevation.

4.6 Unit 5: Surface Organics

Low-lying parts of the map area in the south east are covered by 1-3 m of
mesic to fibric peat, overlying units 3, 4, and 5 (Figure 3-17). Peat is commonly
underlain by discontinuous permafrost. This unit is interpreted as Holocene
accumulation of organic matter in bogs and fens in low lying areas (peat) and along low relief modern streams (organic bearing silt and clay). Unit 5 is analogous to Section 3.5.1 Organic Deposits.

4.7 Unit 6: Alluvium

Unit 6 comprises gravel, sand, minor silt and organic detritus deposited by postglacial streams in three main environments: 1) small streams, 2) floodplains of rivers, and 3) fluvial fans. Associated with the modern streams and small river courses is weakly consolidated, poorly sorted organic bearing silt and clay. Texture is commonly stratified, but may be massive, typically when fine grained. Floodplain sediments on larger rivers are >1 m thick, and composed of gravel, sand, silt, and organic detritus. Typically these comprise active floodplains close to river level with meander channels and scroll marks. Fan deposits are typically poorly sorted gravel, sand and organic detritus >1 m thick.

Alluvial deposits overlying a paleosol were dated by radiocarbon dating of broken twigs in the alluvial material. An AMS age of 5075 ± 20 BP (UCI 13583) was obtained. See Section 3.5.2 Alluvial Deposits for more details.

4.8 Stratigraphy Summary

This study outlined 6 units of surficial sediments in the Moody Creek map area (NTS84M/2) (Figure 4-1). Shale bedrock underlies the region. Unit 1, clast free silty clay, was deposited due to the blocking of drainage as Laurentide ice advanced from the east, at the beginning of the Late Wisconsinan glaciation. No evidence of prior glaciations was observed. Unit 2a silty clay diamicton is the
regional Laurentide till deposited during the Late Wisconsinan, and covers most of the study area. Unit 2b sand and gravel is the result of subglacial glaciofluvial deposition. Unit 3 was deposited into Glacial Lake Hay during deglaciation, as ice blocked drainage during its retreat to the north and east. Unit 4 sediments were likely deposited as the result of a small readvance into Glacial Lake Hay. Unit 5 is bog and peat deposited since the retreat of Glacial Lake Hay. Unit 6 is fluvial material deposited under non-glacial conditions.
CHAPTER 5: APPLIED GEOLOGY

This chapter presents data related to mineral exploration, aggregate sources, and engineering properties of ground materials. The results are summarized below.

5.1 Drift Prospecting

One of the objectives the overall project this study was associated with (NRD Project 4450) was to collect bulk (25-35 kg) till samples to determine the potential of the region to host kimberlites and other ore deposits. The analysis of samples revealed that kimberlite indicator minerals (KIMs) are absent or rare, and consist of trace levels of pyrope and chromite (Plouffe et al. 2006a, Plouffe et al. 2008). However, Paulen et al. (2007) reported the presence of anomalous concentrations of sphalerite grains in these samples. Samples have up to 1000 sphalerite grains in the 0.25-0.5 mm size fraction in the south-central sector of the Bistcho Lake (NTS 84M) and north central sector of the Zama Lake (NTS 84L) map sheets. Based on ice flow information obtained through this study, the source area of the sphalerite should be to the north east or east.

Any future drift prospecting in the area will benefit from the glacial history reported here, specifically the ice flow history, in their sampling strategy and interpretation of results. Preferred sample medium for future drift prospecting would be basal till. Surficial geology mapping by Kowalchuk et al (2006) and
Paulen et al. (2005b) show where till is easily accessed at the surface. Based on the stratigraphic framework presented in this thesis, till composition is likely influenced by the presence of advance-phase glacial lake sediments which might dilute any high metal concentrations derived from the bedrock. In the low, flat areas in the southern half of the map area where organic and glaciolacustrine deposits are prominent, till sampling could probably only be achieved with heavy equipment (e.g. excavator) or from burrow pits. The presence of a till deposited during a glacial readvance will complicate the interpretation of results in the same area that is dominated by glaciolacustrine sediments. The source of the till will be, in part, reworked glaciolacustrine deposits and the dominant ice flow direction was westward.

5.2 Aggregate Resources

The Zama Beach gravel pit at sites 538 and 539 have supplied granular aggregate for the Zama City area (Figure 4-13). Of the two pits in the area one is currently active (site 539). According to Fox et al. (1987a), the now abandoned Zama Beach pit was 189 ha, 2.5 m deep, with a volume of 4,725,000 m$^3$. The gravel is present below 1 to 2 m of till. This gravel deposit is interpreted to have formed in a subglacial channel. Therefore, there may be additional gravel underlying till between the two gravel pits, and within the area mapped as till veneer surrounding them (Figure 4-13). It should be noted that water from an aquifer in gravel underlying till is currently being injected into deep oil wells to aid in recovery to the southwest of the gravel pits (Borneuf 1978, Borneuf and Pretula 1980). Consequently, further expansion of the gravel pits in the Zama
Beach area could cause contamination of the subtilt aquifer by polluted surface waters, and/or have an affect on the hydrology of the aquifer.

One new area of aggregate was found during fieldwork for this thesis. Site 602 (59°12'N 118°39'W) had 1 to 2 m of gravel, some sand, and some silt and clay. Resistant clasts have an average size of 6 cm, ranging up to 8 cm. It could not be determined if fines were present in the entire deposit. Surficial mapping determined the area of the deposit to be 0.7 km$^2$. If the thickness is 1.5 m, the potential aggregate volume at this site is 1,050,000 m$^3$.

### 5.3 Engineering Properties

The engineering properties of the sediments (Table 5-1, Table 5-2, Table 5-3, and Figure 5-1) are organized based on the stratigraphy that has been developed for the area, and are listed by unit numbers and facies. Units and facies are tied to lithostratigraphic units defined in Figure 4-1. The general distribution of till (unit 2a) and glaciolacustrine (unit 3) sediments is described in Section 4.1 – Geomorphology.

Grain size measurements were made on the matrix, and the amount of gravel was estimated in the field. Moisture content measurements are suspect and should be taken as a minimum, as some samples had partially dried due to holes in sample bags, and desiccation over about 4 to 6 months. The shear strength of dry sediments is consistently higher than for similar moist materials, and provides an indication of dry strength rather than a representation of in-situ shear strength, since all fine grained sediments are moist below about 1 m.
Descriptions below are made with reference to field observations of consistency (Table 5-1), and lab tests for plasticity (Figure 5-1, Table 5-2). The methodology is described in Section 1.5.3: Grain Size and Atterberg Limits. An engineering description for each unit according to ASTM 2006 (see Table 1-2) is provided below. Detailed descriptions can be found in Appendix A.

5.3.1 Unit 1 Silt and Clay

Silt (ML) and clay, 0% gravel, 0 to 2% very fine sand, low to medium plasticity, dry strength low to medium, dark grey, moist, firm to hard, laminated, advance phase glaciolacustrine.

5.3.2 Unit 2b Sand and Gravel

Gravel (GP) poorly graded, 20 to 50% fine to coarse sand, 2% fines, gap graded, subangular to rounded, flat and elongated to equant, max size trace boulders, coarse gravel and cobbles are fractured, but of very strong rock, non-cohesive, medium brownish grey, dry, stratified, no cementation, glaciofluvial.

5.3.3 Unit 2a Diamicton

Clay (CH-MH) and silt, 2 to 10% fine to coarse gravel, sandy to trace sand, angular to subrounded, elongated to equant, max size trace boulders, gravel and boulders are very strong rock, high to medium plasticity, high dry strength, dark grey, moist to wet, generally stiff below about 3 m, soft to firm above, homogenous to poorly stratified, no cementation, till, gypsum crystals.
5.3.4 Unit 3 Stratified Diamicton, and Sand, Silt, and Clay

Clay/silt (CH-MH), some to trace fine to medium sand, 0 to 10% fine to medium gravel, subangular to subround, up to cobbles, high plasticity, medium to high dry strength, dark grey, moist to wet, firm to stiff, stratified to homogenous, no cementation, retreat phase glaciolacustrine, gypsum crystals.

5.3.5 Unit 4 Massive to Stratified Diamicton

Clay/silt (CH-MH), trace fine to medium sand, 0 to 5% fine to medium gravel, subangular to subround, up to cobbles, high plasticity, medium to high dry strength, dark grey, moist, firm to stiff, stratified to homogenous, no cementation, till.

5.3.6 Unit 5 Surface Organics

Peat (PT), medium to dark brown, fibric to mesic, soft, wet, low dry strength.

5.3.7 Summary of Engineering Properties

Glacial sediments of the Moody Creek map area (84M/2) generally have high fines contents of greater than 60%. Moisture content in fine grained soils is around 20 to 25% in-situ, reflected by the highest measurements made in the lab on samples that remained sealed (Table 5-2). Plasticity is typically high, but plasticity index is variable, and plots against water content along the transition from silt to clay soil behaviour (Figure 5-1). Plastic limits are between 20 and 30%, and liquid limits are between 40 and 60%. These values are consistent with
previous work in the area (e.g. EBA 1984). Two exceptions are unit 1 and unit 2a pink diamicton, which have low plasticities and low activities, and behave as silts.

In-situ soils are at or above their plastic limit. Consistency is firm to stiff, and dry strength is high. Activities are between 0.8 and 1.4, with exceptions noted above, and clays are possibly composed of swelling phyllosilicates.

As described above, most ground materials in the study area are predominantly composed of clay at or near its plastic limit. Three metres or more of soft compressible soils may be found at the surface, especially in the southern half of the study area where glaciolacustrine sediments form a 1 to 3 m cover. Organic deposits such as peat are extremely compressible and should be avoided where ever possible. Disturbance of the surface organic layer can result in melting of underlying permafrost, resulting in settlements of up to 1.5 m. Burgess and Smith (2003) noted surface settlements of up to 0.7 m in organic soils and 0.4-0.7m in fine grained lacustrine soils, and 0.1-0.35 m in coarse grained till over 16 years on the Norman Wells to Zama pipeline right-of-way. Till becomes overconsolidated at depth, however, compressible sediments at the surface may require excavation and replacement with engineered fill for buildings sensitive to settling. Construction in the area is generally done on fill, due to the flat topography and high water table. Fills are taken from shallow borrow pits next to the road or well pad. Roads constructed of these clay-rich sediments cannot be driven when wet unless gravelled. As gravel is in short supply in the area, largely confined to the two pits at Zama Beach, roads deteriorate rapidly during when wet.
Table 5-1  Undrained shear strength of stratigraphic units. Shear strengths of dry sediments are not representative of in-situ strength.

<table>
<thead>
<tr>
<th>Site</th>
<th>Material Type</th>
<th>Unit Type</th>
<th>Shear Vane</th>
<th>Pen/2</th>
<th>Undrained Shear Strength</th>
<th>Moisture</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Number</td>
<td>kg/cm^3</td>
<td>kg/cm^3</td>
<td>kPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>504</td>
<td>Till</td>
<td>2a</td>
<td>0.63</td>
<td>0.67</td>
<td>65 firm</td>
<td>wet</td>
<td>till under lacustrine veneer</td>
</tr>
<tr>
<td>518</td>
<td>Till</td>
<td>2a</td>
<td>0.63</td>
<td>0.67</td>
<td>63 firm</td>
<td>wet</td>
<td></td>
</tr>
<tr>
<td>559</td>
<td>Till</td>
<td>2a</td>
<td>1.6</td>
<td>1.3</td>
<td>160 very stiff</td>
<td>moist</td>
<td>55 cm below surface in soil pit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>560</td>
<td>Till</td>
<td>2a</td>
<td>1.3</td>
<td>1.3</td>
<td>125 stiff</td>
<td>moist</td>
<td>under 20 cm of gravelly sediments</td>
</tr>
<tr>
<td>562</td>
<td>Till - cryoturbated</td>
<td>2a</td>
<td>1.3</td>
<td>1.3</td>
<td>125 stiff</td>
<td>moist</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sandy silt</td>
</tr>
<tr>
<td>562</td>
<td>Till - cryoturbated</td>
<td>2a</td>
<td>0.13</td>
<td>0.13</td>
<td>13 very soft</td>
<td>soft</td>
<td>clay</td>
</tr>
<tr>
<td>564</td>
<td>Till</td>
<td>2a</td>
<td>1.3</td>
<td>1.3</td>
<td>130 stiff</td>
<td>dry</td>
<td>at 10 cm depth</td>
</tr>
<tr>
<td>604</td>
<td>Till</td>
<td>2a</td>
<td>1.9</td>
<td>1.9</td>
<td>190 very stiff</td>
<td>moist</td>
<td></td>
</tr>
<tr>
<td>610</td>
<td>Till</td>
<td>2a</td>
<td>1.9</td>
<td>1.9</td>
<td>220 very stiff</td>
<td>moist-dry</td>
<td></td>
</tr>
<tr>
<td>502</td>
<td>Glaciolacustrine</td>
<td>3</td>
<td>2.5</td>
<td>2.3</td>
<td>240 very stiff</td>
<td>dry</td>
<td>pipeline trench</td>
</tr>
<tr>
<td>504</td>
<td>Glaciolacustrine</td>
<td>3</td>
<td>2.5</td>
<td>2.3</td>
<td>240 very stiff</td>
<td>dry</td>
<td>very dry and stiff</td>
</tr>
<tr>
<td>542</td>
<td>Glaciolacustrine</td>
<td>3</td>
<td>0.62</td>
<td>0.62</td>
<td>63 firm</td>
<td>moist</td>
<td>0.7m below surface</td>
</tr>
<tr>
<td>595</td>
<td>Glaciolacustrine</td>
<td>3</td>
<td>0.4</td>
<td>0.25</td>
<td>23 very stiff</td>
<td>very dry</td>
<td>30 cm below surface in soil pit</td>
</tr>
<tr>
<td>595</td>
<td>Glaciolacustrine</td>
<td>3</td>
<td>0.43</td>
<td>0.75</td>
<td>73 firm</td>
<td>moist</td>
<td></td>
</tr>
<tr>
<td>595</td>
<td>Glaciolacustrine</td>
<td>3</td>
<td>0.38</td>
<td>0.63</td>
<td>50 firm</td>
<td>moist-wet</td>
<td>sandy clay</td>
</tr>
<tr>
<td>595</td>
<td>Glaciolacustrine</td>
<td>3</td>
<td>0.88</td>
<td>0.88</td>
<td>88 stiff</td>
<td>moist-wet</td>
<td>clayey silt</td>
</tr>
<tr>
<td>595</td>
<td>Glaciolacustrine</td>
<td>3</td>
<td>1.0</td>
<td>1.0</td>
<td>71 firm</td>
<td>moist</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5-1 Atterberg limits of stratigraphic units

Atterberg Limits

<table>
<thead>
<tr>
<th>Plasticity</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Very High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

W_L - Water Content at Liquid Limit (%)

L_p - Plasticity Index (%)

Legend:
- Unit 1 Clast free silt and clay
- Unit 2a Massive diamicton
- Unit 2a Crudely Stratified Diamicton
- Unit 3 Stratified Diamicton
- Unit 3 Sand silt and clay
- Unit 4 Massive diamicton
- Unit 4 Crudely Stratified Diamicton
Table 5-2 Atterberg limits and associated properties of cohesive materials in the Moody Creek map area (NTS 84M/2)

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Unit No.</th>
<th>sub-unit</th>
<th>USCS</th>
<th>Moisture Content (%)</th>
<th>Liquid Limit</th>
<th>Plastic Limit</th>
<th>Plasticity Index</th>
<th>Liquidity Index</th>
<th>Consistency Index</th>
<th>Activity Scale</th>
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Table 5-3  Geotechnical properties of granular materials in the Moody Creek map area (NTS 84M/2).

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CHAPTER 6: DISCUSSION

6.1 Glacial History: Interpretation of Stratigraphy

The glacial history of the study area can be reconstructed based on the interpretation of the regional stratigraphy and the surficial geology. This study identified glacial sediments associated with a single Laurentide glaciation, with evidence for a minor readvance during deglaciation.

As initially proposed by Matthews (1980), advance of the Laurentide Ice Sheet up the regional slope into the area caused blockage of the regional drainage forming glacial lakes; this is recorded by unit 1. Advance took place after $22,020 \pm 450$ BP (AECV 719C) to $24,400 \pm 150$ BP (BETA-183598) based on bracketing ages from High Level and Fontas River respectively (Burns 1996, Levson et al. 2004). Faint laminations, fine grain size, lack of clasts, and stratigraphic position indicate that unit 1 was deposited in a low energy glaciolacustrine setting. If clast fabrics at the base of unit 2a, above the bedrock contact, record advance phase ice flow, initial advance of the LIS was directed by topography and flowed westward along the axis of the Hay River valley. During the glacial advance, glaciolacustrine sediments (unit 1) and shale bedrock were sheared and incorporated in the ice when the shear strength of the underlying material was less than the shear stress at the glacier bed. Evidence of this is intact blocks of sediment, truncated by discrete shear planes, seen within unit 2a diamicton (Figure 4-8).
It is most likely that the majority of glacial erosion occurred during ice advance, eroding pro and pre-glacial sediments and bedrock, and incorporating them into the till. The reworking of advance phase glaciolacustrine sediments, and the fine grained texture of the shale bedrock, resulted in a clay and silt rich, clast poor, till; distally derived shield and platform indurated clasts were diluted with this influx of local material. Thin sections do indicate numerous sand and granule sized clasts of local shale bedrock that commonly do not survive preparation for grain size analysis (Figure 4-2).

As ice thickened, its flow was decreasingly constrained by local topography, reflected in the ice-flow indicators (fabrics and streamlined bedforms) showing flow to the west-southwest (Figure 6-1). This is consistent with continental scale reconstructions showing ice emanating from an ice dome centred over the Keewatin sector of the Laurentide Ice Sheet (Dyke 2004). Also, Bednarski and Smith (2007) suggest deflection by Cordilleran ice during glacial maximum resulted in westerly, and even northwesterly, flow closer to the Rocky Mountains. At glacial maximum, glacial ice was at least 1300 m thick in the lowlands and 900 m thick in uplands (Bednarski and Smith 2007). Surface gradient on the Laurentide Ice Sheet is thought to be low based on run-up heights in the Mackenzie Mountains, north of the study area. Low gradient of the ice sheet is due to the fine grained bedrock, the presence of a deforming bed, and/or areas with elevated pore water pressures and low basal shear stress at the glacier bed (Mathews 1974, Beget 1987).
Boulder diamicton is interpreted to be shale bedrock which has been glacially transported and mixed with boulders. Transport distance must have been short, as the shale has been broken up into fine gravel and granule sized...
angular fragments, but not completely comminuted into clay. There is typically less than 3 m of till on the bedrock slopes, much less than the lowlands where thicknesses up to 20 m was observed. Pore water pressures at the glacier bed would have been lower at higher elevations than at lower elevations, especially as the ice sheet thinned. Low pore water pressures would have resulted in higher shear stress in higher elevation and better drained areas along the bedrock slopes. The slope may have also been sufficiently steep (5 to 10%) that water-saturated till deposited during deglaciation was remobilized as ice melted, and the clay-rich sediment was sufficiently water saturated and fluid to move downslope onto gentler ground below.

Sediments as thick as 200 m mask paleo valleys in the Fort Nelson Lowland (Pawlowicz et al. 2005a, b, 2007a, b). Evidence of more than one Laurentide glaciation may be preserved in these paleo valleys. Thicker accumulation of unit 1 advance phase glaciolacustrine sediments may be preserved in these paleo valleys. Any prominent valleys existing prior to Late Wisconsinan glaciation would have been filled with proglacial sediments as ice advanced into the area.

Deposition of thick accumulations of at least 20 m of unit 2a diamicton is interpreted to have taken place as a combination of deforming bed accretion (Larsen et al. 2003), lodgement, and meltout. Till is stiffer at depth, suggesting deposition through deformation and lodgement under active ice. The softer diamicton, up to 5 m thick, overlying the harder till was deposited as melt out from stagnant ice. While ice was active, a higher degree of strain occurred in
better drained areas, where the effective shear stress on the bed was highest. Evidence of this is in the more disorganized nature of fabrics from sites in the low areas, versus the stronger fabrics seen on the bedrock slopes (Figure 4-9). Hooyer and Iverson (2000) found in lab experiments that increasing strain results in strong clast fabrics, in line with the above interpretation.

During glaciation, sand and gravel were deposited underneath the glacier as indicated by unit 2b. These sediments were deposited by meltwater that was generally flowing parallel to ice-flow direction as determined from clasts fabrics in gravel and till. Evidence supporting a subglacial origin is the presence of diamicton (till) above and below the gravel, the fractured clasts, and the deformation and folding, induced by overriding ice, seen at the upper contact (Figure 4-17).

As the ice sheet thinned, topography exerted more of an influence on ice flow. Evidence of this are the small moraines at the base of the bedrock slopes along the slope apron that run northeast to southwest, and curved flutings along the margin of Elsa Hill (Figure 6-1). Ice retreat began about 14,000 BP (Dyke et al. 2002). The oldest date for glacial retreat is an optical age of 13.9 ka on sand dunes near Fontas River to the west (SUV050309 Wolfe et al. 2007).

Discontinuous patches of glaciolacustrine deposits along the margin of Elsa Hill reflect local deglacial ponding. Glaciolacustrine deposits become more common at lower elevations and once the ice margin retreated to the periphery of the study area, Glacial Lake Hay was established in the lowest portion of the basin. Lake levels are poorly constrained but relatively continuous deposits at
~410 m, provide a minimum water level. During the early phases of formation of Glacial Lake Hay, actual lake levels west of the study area were at least 30 m higher as meltwater spilled over the saddle to the west at 440 m asl, marking the formation of the Fontas River spillway (Figure 3-3). The base of the Fontas River spillway is presently at 360 m, and the lake would have lowered to this level as the channel eroded.

Figure 6-2 Reconstruction of ice positions during deglaciation, about 12 to 11 ka.

(Elevation Data Source: USGS 2006)
Iceberg scours are present along the intermediate slope from 350 to 380 m elevation. Their consistent pattern (Figure 4-10) may relate to flow in the lake towards the outlet as it was incised. The iceberg scours could also be the result of strong, uniform, katabatic winds (cf. Wolfe et al. 2007). Iceberg scour distribution suggests water depth at the level of the second bench was too great for icebergs to reach the bottom, and too shallow at the level of the first bench to allow icebergs to have floated (Figure 3-1). The presence of iceberg scour marks indicates that a calving ice margin was nearby. Calving ice margins are known to be fairly unstable and subject to rapid mass balance loss of ice, especially where the ice surface profile is low and advancing into glacial lakes (Beget 1987). The inferred deglacial readvance described below likely took place before the formation of these iceberg scours, and before the formation of the Adair Creek spillway.

The presence of deformed glaciolacustrine sediments associated with an overlying diamicton provide evidence of at least one readvance into Glacial Lake Hay (Figure 6-3). Unit 4 diamicton (Figure 4-9 fabric #9) is interpreted as the till deposited by this readvance, overlying deformed unit 3 glaciolacustrine sediments. A fabric in unit 4 implies ice flow to the west north west, possibly the result of divergent piedmont-type flow at the margin of the readvance. This stratigraphic and sedimentological evidence is supported by work to the south and east by Paulen et al. (2005b) who proposed a readvance based on a change in ice flow direction evidenced by surficial mapping. Iceberg scours discussed above (Figure 3-1, Figure 3-13, Figure 4-10) may also be associated with the
rapid breakup of the ice lobe which readvanced in Glacial Lake Hay. Whether the cause of this readvance is climatic or glaciologic remains enigmatic.

Figure 6-3 Possible extent of a minor readvance during deglaciation.

Glacial Lake Peace drained through the Meander River spillway (10 km north of High Level) which cuts through the area previously inundated by Glacial Lake Hay. Latter phases of Glacial Lake Peace in the High Level area flooded up to about 385 m asl (Figure 6-4). Glacial Lake Hay had likely drained before
Glacial Lake Peace drained via the Meander spillway (Paulen and Plouffe in press).

Within the map area, transition to non-glacial environments is only loosely constrained by a radiocarbon age of 5057 ± 20 BP (UCI 13583) on a twig in a buried soil horizon underlying fluvial sediments. Most deglacial dates range from 11,700 BP (SFU 223 Liverman et al. 1989) to 10,200 BP (GSC 2895 Catto et al. 1996), and Lemmen et al.’s (1994) deglacial reconstruction shows Glacial Lake Hay forming around 11.5 ka BP and draining by 10.5 ka BP.
Holocene processes in the area are dominantly low energy because of the flat topography. Most rivers have a very low gradient and they do not transport or erode significant volumes of sediment. Some low relief fans are building out from the edge of Elsa hill. Large wetlands in the southern sector of the study area contain thick peat sequences which have accumulated during the Holocene. A significant Holocene process is the invasion of permafrost into some of the sediments. This is most common in areas covered with a thick organic cover,
such as the southern portion of the study area. This can have significant affect on
development when the thick insulative organic cover is disturbed, with
settlements of up to 1.5 m.
CHAPTER 7: CONCLUSIONS

Geological studies in the Moody Creek (84M/02) map area were undertaken to 1) map the surficial geology at 1:50,000 scale, 2) establish the Quaternary stratigraphy, 3) interpret the sedimentology of glacial and non-glacial sediments, and 4) reconstruct the ice-flow, glacial, and post-glacial histories of the area. A surficial geology map was produced (Kowalchuk et al. 2006) that documents the distribution of bedrock, till, glaciolacustrine, glaciofluvial, colluvium, alluvium, organic, and anthropogenic deposits. The stratigraphy is represented by 6 units: 1) advance glaciolacustrine sediments; 2a) till; 2b) englacial/subglacial gravels; 3) retreat glaciolacustrine sediments; 4) readvance till; 5) postglacial alluvium; and 6) organic sediments. The area was completely covered by the Laurentide Ice Sheet. As ice advanced into the area, it blocked regional drainage forming a glacial lake. The Laurentide Ice Sheet advanced over weak shale bedrock and glaciolacustrine sediments, resulting in clay and silt rich tills. At maximum ice cover, ice flow was to the west-southwest, indicating topography had little to no influence, in contrast to ice flow during deglaciation. During ice cover, subglacial gravels were also deposited. As the area deglaciated, regional drainage was again blocked, forming Glacial Lake Hay, and smaller transient ice-contact glacial lakes. Glacial lake sediments occur up to 410 m asl, relating to the highest water plane, and well developed shorelines only occur at 340 m asl, relating to the lowest water plane. The highest level of Glacial
Lake Hay occurred when meltwater drained to the west via the Hay River spillway. The lowest level and shorelines were formed as meltwater drained to the west via the Adair Creek spillway. Icebergs calved into this lake as evidenced by the well developed iceberg scours. At least one readvance occurred during deglaciation resulting in deformed lake sediments and a discontinuous till, and is thought to have covered most of the study area flooded by Glacial Lake Hay. Glacial Lake Hay finally drained as ice continued to retreat to the east, and drainage via the modern Hay River was no longer blocked by ice.

Gravel aggregate is in short supply in the region, and the active pit at Zama Beach exploits sub-till gravel with an uncertain extent and reserves. Till and glaciolacustrine sediments have greater than 60% fines, have high plasticities, and have moisture contents close to the plastic limit, and roads require significant amounts of gravel for all-weather use.

Opportunities for future work in the area centre around deep paleovalleys (cf. Pawlowicz et al. 2005a, 2005b, 2007a, 2007b) which may contain a record of pre-Late Wisconsinan glacial events. Also, further analysis of pink till may reveal an as yet unknown source to the northeast. Refinement of ice flow during glacial maximum and deglaciation could help in drift prospecting for the source of sphalerite grains found in till (Paulen et al. 2007 and Plouffe et al. 2006a, 2008).
REFERENCE LIST


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Richardson, R.J.H. 1985a. Aggregate resources of the Zama Lake map area, NTS 84L; Alberta Resource Council, Map A84L, scale 1:250,000.
Richardson, R.J.H. 1985b: Aggregate resources of the Bistcho Lake map area, NTS 84M01-04; Alberta Resource Council, Map A84M01-04, scale 1:250,000.


APPENDICES: CD-ROM

The CD-ROM attached forms a part of this work. The appendices are in PDF and ZIP format, and were created with Adobe Acrobat and WinZip respectively. PDF files may be opened in any PDF program. ZIP files require WinZip to extract the compressed data.

Appendix A Stratigraphic Columns

File: PDF: Appendix A Stratigraphic Columns.pdf 1,500 kb

Appendix B Grain Size Data

File: PDF: Appendix B Grain Size Data.pdf 107 kb

Appendix C Moody Creek Surficial Geology Map


File: PDF: Map_397.pdf 25,775 kb

Appendix D Moody Creek Surficial Geology Data


File: ZIP: Map_397.zip 47,583 kb