Characterization of glacial tills from an excavation near Fort McMurray, Alberta

Andrew Ian Bayliss
Klohn Crippen Berger, Calgary, Alberta, Canada

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
An excavation conducted beneath the north starter dyke of the Sand Cell 2 Tailings Dam has permitted the geological mapping and geotechnical characterization of complex sub-glacial assemblage composed of glacial tills and rafted bedrock that overlie an infilled, tunnel valley, known as the Kearl Channel. The mapping data was supplemented with borehole and laboratory testing data from drilling programs and geographical information system data from the Alberta Geological Survey. This study concluded that the moraine was composed of a sub-glacial traction till, analogous to the Firebag Till, and rafted bedrock derived from the Clearwater Formation. The moraine was overlain and interbedded by deformed sands and gravels indicative of a sub-glacial braided canal system. Updated interpretations of the glacigenic units are proposed based on recent developments in glaciological studies.

RÉSUMÉ
Une excavation réalisée sous la digue de démarrage Nord du barrage de résidus Sand Cell 2 a permis la cartographie géologique et la caractérisation géotechnique du complexe d'assemblage sous-glaciaire composé de tills glaciaires et de fragments de socle rocheux reposant sur une vallée tunnel remblayée, connue sous le nom de Kearl Channel. Les données de cartographie ont été complémentées d'un forage et de données de laboratoire issus de campagnes de forages, ainsi que des données du système d'information géographique de l'Alberta Geological Survey. Cette étude permet de conclure que la moraine est composée d'un till de traction sous-glaciaire analogue au till de Firebag et de fragments de socle rocheux issus de la Formation de Clearwater. La moraine a été recouverte et interstratifiée par du sable et du gravier déformés, indicatifs d'un système de canaux sous-glaciaires anastomosés. Des interprétations actualisées des unités glaciaires sont proposées et basées sur les récents développements d'études glaciologiques.

1 INTRODUCTION

Jackpine Mine is an oil sands mining facility located on the Athabasca Plain, approximately 70 km north of Fort McMurray and 14 km east of Fort McKay (Figure 1). It is operated by Shell Canada Energy (SCE). Sand Cell 2 (SC2) is a 56 m high tailings dam being constructed in a staged manner to store tailings and water from the mining operation. It is located in the southeast corner of the Lease 13 and has an approximate footprint of 8 km^2.

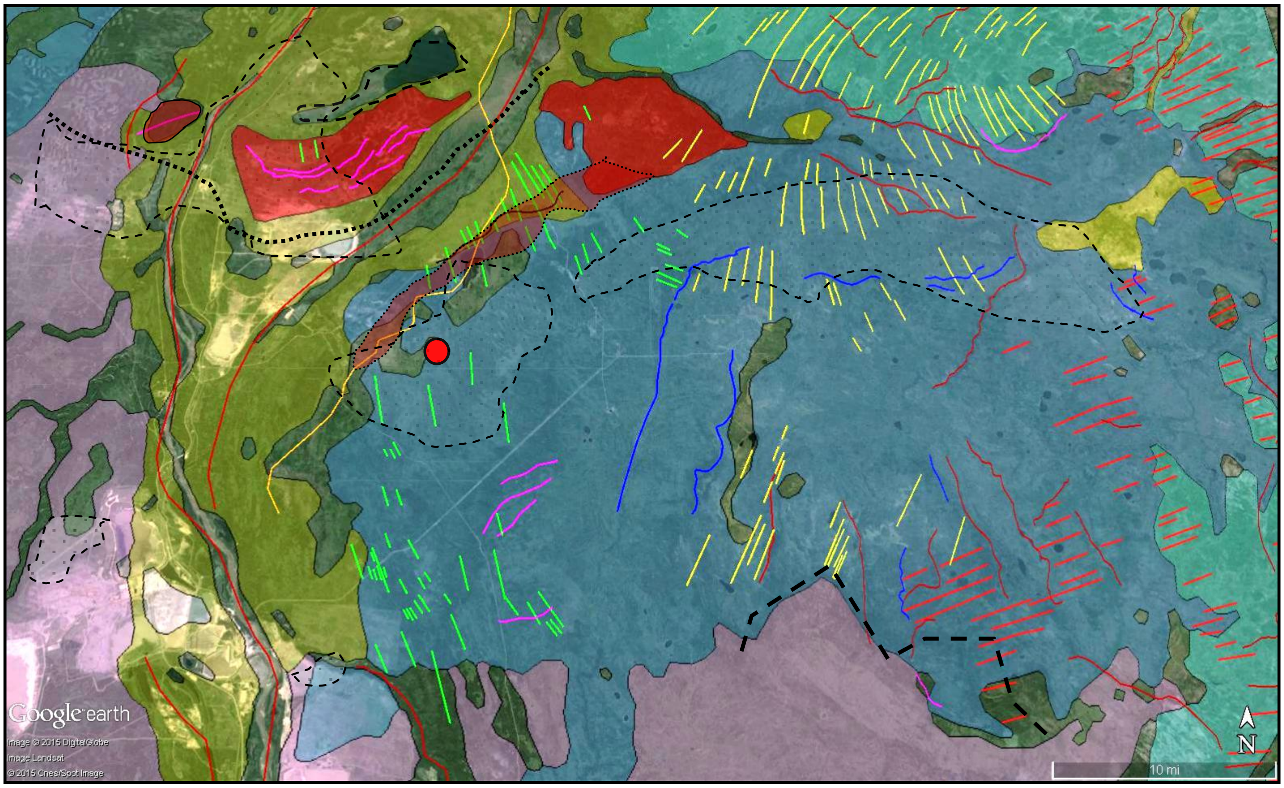
Figure 1. JPM ETF Location (from SCE, 2007)

Drilling programs undertaken for the design of SC2 have indicated that the tailings dam is underlain by a complex moraine assemblage of glacial tills, rafted bedrock and sand lenses; an infilled, tunnel valley, known as the Kearl Channel and the partially eroded and glaciotectonized Cretaceous Clearwater (Kc) and McMurray Formations (Km).

The glacigenic units that form part of a glacial moraine can affect overlying tailings dams through a range of mechanisms. The composition, stress history, thickness and distribution of a glacial till influences its ability to provide passive resistance at the toe; the presence and interconnectivity of sand lenses within a glacial till affect seepage paths and foundation pore pressure response under loading and the composition and moisture content of a glacial till affect its potential for use as a construction fill in dam construction.

In 2013, a 420 m long, 10 m deep (average) and 30 m wide (at the base) shear key was constructed under the north starter dyke prior to operation of SC2. The excavation presented a unique opportunity to map the lithology and internal structure within the moraine assemblage and to characterize its relationship with the underlying Kearl Channel and overlying glacial-fluvial and glacial-lacustrine units. This was supplemented by borehole and geotechnical laboratory data from the surrounding area.

This paper summarizes the findings this study. Annotated figures of the southern excavation face are provided. Updated interpretations of the glacial tills and overlying glacial-fluvial sands are proposed based on recent developments in glaciological studies. The aim of this paper is to supplement to the existing body of published information on glacial tills within the Fort McMurray region.



KEY:

UNDIVIDED MORAINE. Diamicton (till) deposited directly by glacial ice. Mixture of clay, silt, sand and minor pebbles, cobbles and boulders. Locally, this unit may contain blocks of bedrock, pre-existing stratified sediment and till, and/or lenses of glaciolacustrine and/or glaciofluvial sediment *(Commonly known as the firebag Till)*

THRUST MORAINE. Till formed from the glaciotectonic displacement blocks or rafts in a more or less intact state. Characterized by high to moderate relief glaciotectonic moraines; includes hill-hole pairs, rubble moraine and thrust block moraine. Sediment may include syngenetic till, as well as masses of pre-existing sediments and/or bedrock. *(Fort Hills Moraine)*

FLUTED MORAINE. Glacially-streamlined sediments, mainly till. Terrain varies from alternating furrows and ridges to nearly equidimensional smoothed hills; all landforms parallel the local ice flow direction; includes flutes, drumlins and drumlinoids. Sediment is mainly till may locally include stratified glaciolacustrine and/or glaciofluvial sediments.

GLACIAL-LACUSTRINE. Primarily fine-grained, distal sediments deposited in or along the margins of glacial lakes. Comprises a) Off-shore sediment; rhythmically laminated to massive fine sand, silt and clay, locally debris released from floating ice. b) Littoral and nearshore sediments; massive to stratified, well-sorted silty sand, pebbly sand and minor gravel.

GLACIAL-FLUVIAL. Sediments deposited by glacial meltwater streams in subaerial, subaqueous and subglacial environments. Sediment ranges from massive to stratified, poor- to well-sorted, coarse- to fine- grained. In places, this unit includes till. May show evidence of ice melting (slumped structures).

Ice thrust ridge
Overridden Moraine
Moraine Ridge
Streamlined Bedform (N-S)
Streamlined Bedform (NE-SW)
Streamlined Bedform (W-E)
Meltwater Channel
Kearl Channel Thalweg
Jackpine Mine SC2 Location
Glacially-displaced bedrock or 'complex stratigraphy' (Andriashek and Atkinson, 2007)
Glacial tear faulting and quarrying (Andriashek and Atkinson, 2007)
Southern limits of the Fort Hills Till mapped by Kathol and McPherson (1977)

Note:
Surficial geology extents are generalized and compiled from existing AGS Maps 601 and 604. Localized ground conditions will vary.
Base map from Google earth.
Surficial geological units: Digital GIS datasets 2013-02 (2013) based on Fenton et al (2013)
Glacial landforms: Digital GIS datasets 2014-22 based on Atkinson et al (2014), Fisher et al (2009), Andriashek & Atkinson (2007)

Figure 2. Regional Surficial geology map showing the site location, extents and types of glacial units and landforms.

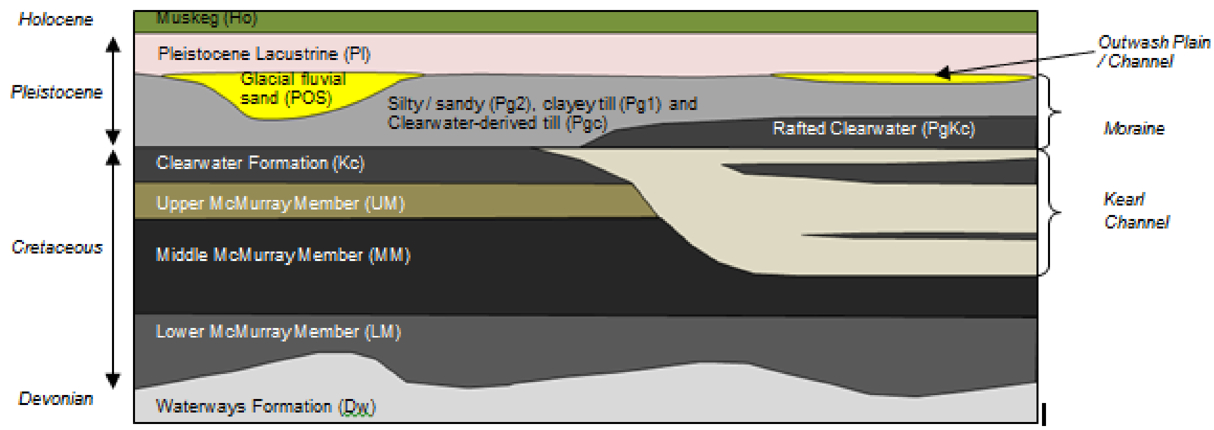


Figure 3. Generalized Stratigraphy for the Site (From Bayliss et al, 2014).

2 QUATERNARY GEOLOGY

2.1 Overview

The surficial geology of the SC2 study area and the surrounding region is summarized on Figure 2. This map was developed using the GIS datasets 2013-02 and 2014-22 from the Alberta Geological Survey (AGS) (2014; 2013). Dataset 2013-22 is a digital version of Map 601: Surficial Geology of Alberta (Fenton et al, 2013). Dataset 2014-22 is a digital version of the Map 604: Glacial Landforms of Alberta (Atkinson et al, 2014). Landforms mapped by Fisher et al (2009) and Andriashek and Atkinson (2007) have also been included in Figure 2.

The AGS (2013) currently characterize the surficial geology at the SC2 study area as an '*undivided moraine'.* This is described as '*Diamicton (till) deposited directly by glacial ice with a mixture of clay, silt, and sand, as well as minor pebbles, cobbles, and boulders; characterized by a lack of distinctive topography. Locally, this unit may contain blocks of bedrock, stratified sediment, or lenses of glaciolacustrine and/or glaciofluvial sediment'*.

The 'undivided moraine' (Figure 2) is bound to the south and west by glacial lacustrine units, associated with Glacial Lake McMurray and extends east to west from the Alberta-Saskatchewan border to the Athabasca river valley, where it was eroded or overlain by glacial-fluvial sands deposited by the Clearwater-Lower Athabasca Spillway (CLAS) Flood Event.

2.2 Regional Bedrock Geology

The matrix and clast composition of the glacial tills encountered at the SC2 study area are influenced by the regional geology. JPM is underlain by the Kc and Km. The younger Grand Rapids (KcG) and Westgate Formations have been eroded from the site but outcrop to the west on Birch Mountain and the east on Muskeg Mountain.

The Middle Devonian Waterways, Slave Point, Watt Mountain, Prairie Evaporite and Keg River Formations outcrop approximately 40 km north of the SC2 study area. The Canadian Shield outcrops approximately 60 km to the northeast of the SC2.

2.3 Previous Studies

The surficial geology of the Athabasca Plain, north of Fort McMurray, was summarized by Pawluck and Bayrock (1969) and McPherson and Kathol (1977). Recent AGS studies have focused on specific aspects such as buried channels (Andriashek and Atkinson, 2007).

The terminology used to classify glacial tills in the Fort McMurray region is confusing given the different oil sands operators and legacy nomenclature from historical AGS and Alberta Research Council (ARC)[1] studies. This is compounded by inherent difficulties in the interpretation of glacigenic units from borehole logs and the often incompatible objectives of resource and engineering boreholes. Historical ARC studies described the surficial geology at the SC2 study area as '*Unit 2: ground moraine'*, which was '*local relief less than 15ft'* (Bayrock, 1971) or '*low relief till'*, which has a '*local surface relief less than 20ft'* (McPherson and Kathol, 1977). The glacial tills to the east of the Athabasca River in the Waterways area (NTS 74D) were divided into the Kinosis and Gypsy Tills by Bayrock and Reimchen (1974). The Kinosis Till was correlated with Bayrock's (1971) Unit 2: ground moraine in the Bitumont area (NTS 74E). No later usage of the term 'Kinosis Till' has been identified.

McPherson and Kathol (1977) named the glacial tills within the Athabasca Plain, the *'Firebag Till'*. They described this as a brown to dark grey, sandy or clayey till with the composition influenced by the underlying Kc or Km bedrock. This was correlated to glacial tills mapped along the Firebag River by Fenton and Mougeot (1982) and Dufresne et al (1994).

Whilst aware of this nomenclature, oil sands mine operators use facies codes to describe the tills. SCE currently classify the glacial tills at JPM into four facies: granular till (Pg), clayey till (Pg1), sandy / silty till (Pg2) and Clearwater till (Pgc). Pg1 is interchangeable with Pgc at JPM. Suncor, Syncrude, Imperial Oil and Canadian Natural Resources Limited (CNRL) use their own variations.

[1] Renamed Alberta Innovates

Glacial tills, likely to represent the Firebag Till, have been encountered beneath other tailings dams in the Fort McMurray region[2]. At CNRL's Horizon Mine Dyke 10, they comprised clayey tills between 0.5 and 2.3 m thick. The liquid limits (LL) were between 20 and 60 % and Plastic limits (PL) were between 11 to 28 % (Sisson et al, 2010). At Suncor's South Tailings Pond, a maximum 26 m thick sequence of clayey, silty and sandy tills was encountered. The upper tills were sand-rich with the clay content increasing with depth. Lower tills were medium to high plasticity (Stephens et al, 2006). At Syncrude's Mildred Lake Settling Basin, they comprised clay- and sand-rich glacial tills (Nicol, 1994; El-Ramly et al, 2003). The clay-rich tills were up to 10 m thick and contained rafted bedrock. The average particle size distribution (PSD) and Atterberg Limits are summarized in Table 1.

Table 1. Average particle size distribution and Atterberg Limits for glacial tills at the Mildred Lake Settling Basin (from Nicol, 1994)

Property	Clay-rich till	Sand-rich till
Gravel (%)	0.1	0.6
Sand (%)	43.1	53.6
Silty (%)	50	43.9
Clay (%)	7	1.5
Liquid Limit	32	19.2
Plastic Limit	19.3	12.7
Plastic Index	12.7	2.6

Table 2. Composition of glacial tills from McPherson and Kathol (1977)

Property	Unnamed Till	Firebag Till	Fort Hills Till
Sand (%)	56	57	18
Silty (%)	29	32	69
Clay (%)	16	10	13
Liquid Limit	25	26	36
Plastic Limit	19	17	22
Plastic Index	6	8	14
Sand Mineralogy:			
Crystalline	42	12	14.2
Quartz	47	50	26
Limestone	0.4	6	5
Dolostone	2	20	32
Carbonate	2	27	41

Two other glacial till units, distinct from the Firebag Till by particle size distribution and sand mineralogy (Table 2) were mapped by McPherson and Kathol (1977). They identified an unnamed till, which was restricted to a small number of localities south of the SC2 study area and the Fort Hills Till, which was encountered north of the SC2 study area near the thrust moraine (Figure 2).

[2] Only published data is referenced in this study. The Mine Operators have collected large quantities of borehole and test data on the glacial tills but these are confidential and have not been used.

2.4 Glacial Landforms

Glacial landforms mapped by the AGS (Atkinson et al, 2014) are shown in Figures 2 and 4. These indicate that study area regularly cycled between sub-glacial and pro-glacial settings. Three sets of streamlined bedforms (red, yellow and green lines in Figure 4) are present within the region and provide an indication as to the general direction of the ice streams within the Laurentian ice sheet (LIS). Moraine and ice-thrust ridges (blue lines) are perpendicular to the ice stream direction.

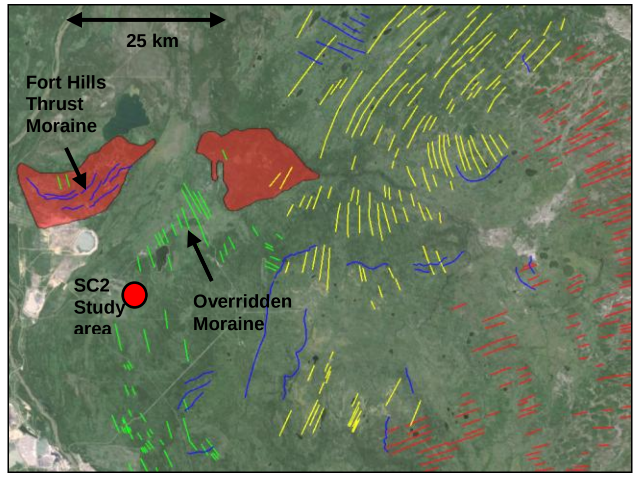


Figure 4. Streamlined bedforms within the Study area (mapped by Atkinson et al, 2014.)

This study has inferred that at least three ice-streams were active in the region. Ice-streams (yellow and red lines) advanced from the northeast and east. A probable later ice-stream (green lines) advanced from the northwest through the Athabasca Valley as far south as Fort McMurray. This overrode a pre-existing landform forming an elongate, transverse ridge 9 km north of the study area (AGS, 2014; Andriashek and Atkinson, 2007). The last ice-sheet advance in the Athabasca Valley overrode existing glacigenic units and formed the Fort Hills Thrust Moraine (Section 2.7) and the associated till.

2.5 Kearl Channel

The Kearl Channel is present beneath the JPM lease and generally extends northeast to southwest through adjacent mine leases (Figure 2). It is sinuous and contains numerous tributaries. The thalweg is between El. 273 m and El. 295 m. The channel has been infilled with sands, gravels and localized rafted bedrock. The side walls of the channel are formed from the Upper (UM) and Middle (MM) Members of the Km. The channel is capped by the moraine assemblage (Figure 3).

Atkinson et al (2013) suggested that this is a tunnel channel formed by the periodic release of sediment laden basal meltwater (jokulhlaups) beneath the LIS, using either a pre-existing valley system or incising a new one, followed by waning or periods of low meltwater discharge.

2.6 Proglacial Lakes

A series of proglacial lakes formed after the retreat of the LIS within northeast Alberta. Fisher et al (2009) indicated that Glacier Lake McMurray was present in the Fort McMurray-Athabasca Plain; Glacial Lake McConnell was present to the north, where the current Lake Claire and Athabasca are located; and Glacial Meadow Lake was located to the east in Northern Saskatchewan.

Glacial lake McMurray resulted in the deposition of lacustrine lake-bottom (Plb) and lake shore (Pls) units throughout the region. The AGS Map 602 does not show glacial-lacustrine units at JPM. However, borehole and mapping data indicate that up to 4 m thick unit is present in the SC2 footprint[3].

2.7 Fort Hills Thrust Moraine

Although located approximately 15 km to the north of the study area, the Fort Hills Thrust Moraine forms an important marker in the Pleistocene history of the region. This up-ice concave landform was formed by a north to south re-advance of the LIS through the Athabasca Valley. The advancing snout of the LIS would have deformed and thrust any pro-glacial lacustrine and outwash units deposited after the LIS had previously retreated. After the advance stopped and the LIS began to gradually retreat north back through the Athabasca Valley, this removed the pinch point for meltwater from the CLAS. This resulted in a significant flood event through the valley, depositing sands and gravels in the valley and partially eroding the moraine along the current alignment of the Athabasca and Muskeg Rivers (Figure 5). Deposits from the flood event underlay the Muskeg River, Aurora North, Horizon and Fort Hills Mines. Deposits from the flood event have not been mapped beneath SC2.

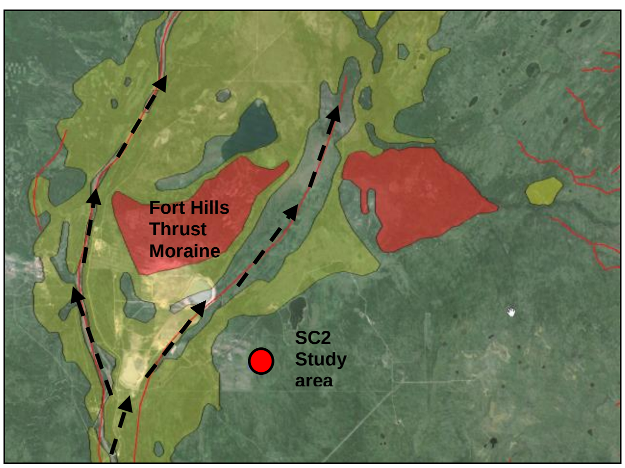


Figure 5. Extents of glacial-fluvial deposits (yellow) from the Clearwater-Lower Athabasca Spillway Flood Event.

[3] The AGS is recognized that inconsistencies may exist in Map 601 due to variation in published data and scale of the data sources (AGS, 2013).

3 FIELD INVESTIGATION

The shear key excavation, which is subsequently called Study Zone 1 (SZ1) within this paper, was 420 m long and 30 m wide at the base with 1H:1V side slopes. The depth ranged between 9.4 and 10.3 m with elevation of original ground between El. 324 m and El. 325 m. The excavation and backfilling occurred in a phased manner between January and April 2013. The extents of SZ1 on March 23, 2013 are shown in Figure 5. Study Zone 2 (SZ2) is a 2.5 km by 1.5 km area and included SZ1 (Figure 5b). It contains 119 boreholes drilled between 2009 and 2012. An adjacent excavation was also undertaken to the south of SZ1 but is not discussed in detail in this paper.

The geological units within the moraine assemblage were mapped using site-specific facies codes (Table 2) supplemented with a lithofacies classification system (Table 3), based on Evans and Benn (2004), for the recording of lithological, internal structures and contacts within glacigenic units. Notable features that could be observed safely such as rafted bedrock, imbrication, clast orientation, deformation and contacts, were recorded.

The field observations of the southern excavation face, in a west to east direction, are summarized in Figures 6a to 6e. The northern excavation face was used as a haulage road and the exposures were frequently reworked or exposed to heavy hauler traffic. To minimize the exposure to extreme temperatures and construction traffic, the mapping was undertaken in a rapid manner during downtime of the heavy haulers or away from active faces. Localized instability of the side walls limited access and snowfall often reduced visibility.

4 OBSERVATIONS

4.1 Moraine Assemblage

The moraine assemblage was formed from glacial tills and rafted bedrock. The glacial tills comprised two types of massive, matrix supported diamicton: a grey to dark grey, silty, sandy, clay with variable amounts of gravel (interpreted as Pg1/Pgc) and a brown, sandy, clayey silt, with variable amounts of gravel (interpreted as Pg2). These are shown in Figures 7a and 7b respectively. Weak clast orientation in a north-south direction was observed locally but could not be mapped in detail due to access and slope instability. The clasts in both tills were predominantly pink granite and limestone. The contact between the tills varied laterally, although the Pg2 was typically above the Pgc1/Pgc, where present. No fissures or slickensides were observed, although evidence of deformation such as silt stringers, folding and clast orientation was observed (Figure 7c).

The contact between the Kearl Channel and the overlying moraine assemblage was exposed at the eastern end of SZ1 (Figure 7d). The channel infill comprised cream to grey, fine to medium, planar-cross-bedded, silty sand. Distorted bedding within the sands was frequently mapped at the interface with the overlying glacial tills.

Glacially rafted Clearwater Formation (PgKc) was mapped in the eastern part of the excavation. This comprised dark grey to blue-black, medium to high plasticity, slickensided, silty clay. The slickensides were undulating, shiny, smooth and orientated in different directions. Further discussion of the PgKc can be found in Bayliss et al (2013, 2014). Rafted blocks of sandstone were observed locally within the glacial till (Figure 7c). It is likely that these were derived from the Grand Rapids (KcG) or Km, however, no testing has been undertaken to date to determine the origin.

The thickness of the moraine assemblage varied laterally between 0.5 m to 24.6 m within the SZ2 (Figure 8). Glacial till accumulation was greater above the Kearl Channel than above the bedrock plateau to the south of the channel. The thickness of glacial till also increased towards the western limit of SZ2. The elevation at the top and base of the moraine assemblage increased from west to east (Figure 9). The thalweg of the Kearl Channel did not reflect this elevation change. In the east, the moraine assemblage comprised PgKc overlain by glacial tills. No PgKc was observed in the western part of SZ1.

4.2 Glacial Outwash Sands

The glacial tills were locally interbedded and/or overlain by yellow to orange, or cream, fine to coarse sands (Pos) with occasional gravels (Pog). These were encountered as laterally continuous sheets, discontinuous lenses with pinch/swell geometry, discontinuous trapezoid-shaped ‘channels’ and elongated, inclined lenses. Bedding structures were frequently deformed (Figure 7e), contained silt stringers, rafted bedrock and lenses of black sand.

The distribution of the Pos within SAZ2 was mapped using the borehole data. The connectivity could not be proved across the shear key and adjacent excavations and it does not appear to extend south beyond the Kearl Channel, where the glacial tills are considerably thinner. The thickness of the Pos varied from 0.2 m to 13.5 m with an average thickness of 2 m. Yellow to orange sands were predominant in the eastern portion of SA1 whilst the cream-coloured sands were predominant in the western portion of SZ1.

4.3 Glacial-lacustrine Units

The Pos was overlain by glacial lacustrine units. This comprised two sub-units: grey to pink, soft, varved clay interbedded with fine-grained sand and silt (interpreted as Plb); underlain by brown to pinkish-brown, soft very fine to fine-grained sand and silt diamicton with occasional gravel and cobble-sized clasts (interpreted as Pls). The Pls typically fines upwards into the overlying Plb, although the boundary is gradational and often undulating. The thickness of the cumulative Pl is between 1.4 and 3.7 m. A section through the Plb and Pls is shown in Figure 7f.

Table 2. Site-specific facies codes used at Jackpine Mine

Facies	Code	Description and Diagnostic Characteristics
Lake bottom	Plb	Clay interbedded with fine grained sand and clay, minor gravel clasts, medium to high plastic (clay), often varved, grey and/or pink colour which is diagnostic
Lake Shore	Pls	Very fine- to fine-grained sand and silt, occasional gravel, yellowish brown to pinkish brown, shallow water deposits, limited extent.
Glacial outwash sands	Pos	Very fine to coarse grained sand locally with minor gravel (pebble beds, cobble/boulder), commonly silty with clay or sandy till lenses, thin beds of re-worked McMurray sediments, 'blanket' habit common, meltwater outwash and glacial Lake Agassiz spillway flood deposits.
Glacial fluvial sands	Pfs	Relatively clean channel sands and gravelly sands, sorted, graded bedding common, deposited as point bar 'inwash' in discreet channels that usually incise bedrock, by ASTM convention <50% > 4.75 mm.
Clearwater Till	Pgc	Clay till, grey to black, reworked Kc, may have undergone mixing with other units, silt, sand and gravel content may be variable, soft to hard, low to high plastic, till matrix, no bedding.
Granular Till	Pg	Grey to brown, often weathered and multi-coloured, usually dense granular matrix with heterogeneous assortment of grain sizes and shapes through to large boulder size, chaotic mix of sedimentary and igneous/metamorphic rock types common. Lack of bedding/sorting diagnostic, can be semi-lithified and very hard to dig, fine grained cohesive vary locally but typically non-plastic.
Clayey Till	Pg1	Light to dark brown, silty clay till, firm to stiff, low to high plastic, gritty with 2-8% gravel to cobble size clasts, till matrix, low permeability
Sandy / Silty Till	Pg2	Brown to grey black, high sand content, medium dense to firm, gritty with up to 8% gravel to cobble size clasts, bituminous odour, fluvial sand lenses common

Table 3. Lithofacies codes used for the recording of lithological information and sedimentary structures in stratigraphical cross-sections and vertical profile logs (Based on Evans and Benn, 2004).

Diamictons	**Very poorly sorted admixture with wide range of grain sizes**	**Silts and Clays**	**Particles of < 0.063 mm**
Dmm	Matrix-supported, massive	Fl	Fine lamination, often with minor fine sand and very small ripples
- - - (c)	Evidence of current reworking	Flv	Fine lamination with rythmites or varves
- - - (r)	Evidence of re-sedimentation	Fm	Massive
- - - (s)	Sheared	- - - (d)	with dropstones
		- - - w)	dewatering structures
Sands	**Particles of 0.063 – 2mm**		
Sh	Very fine to very coarse and horizontally / plane-bedded or low angle cross-lamination		
Sm	Massive		
Sd	Deformed bedding		

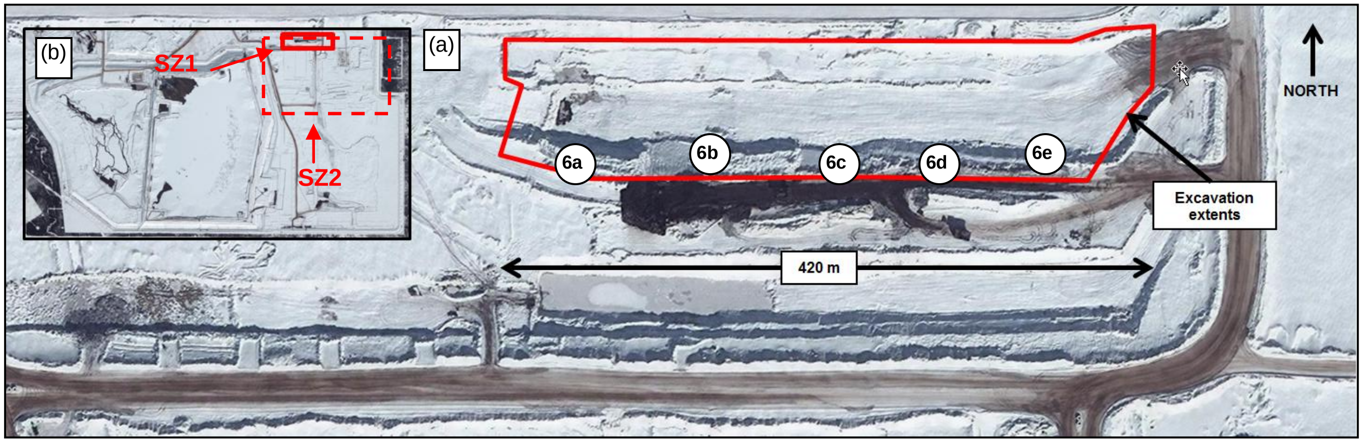
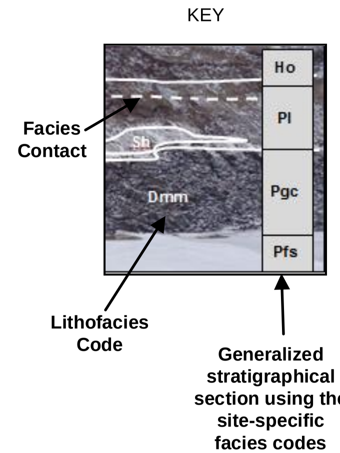


Figure 5. a) Satellite image of the excavation (SZ1) dated March 23, 2013. b) Location of SZ1 (red box) and SZ2 (dashed red box) in relation to SC2 tailings dam footprint.



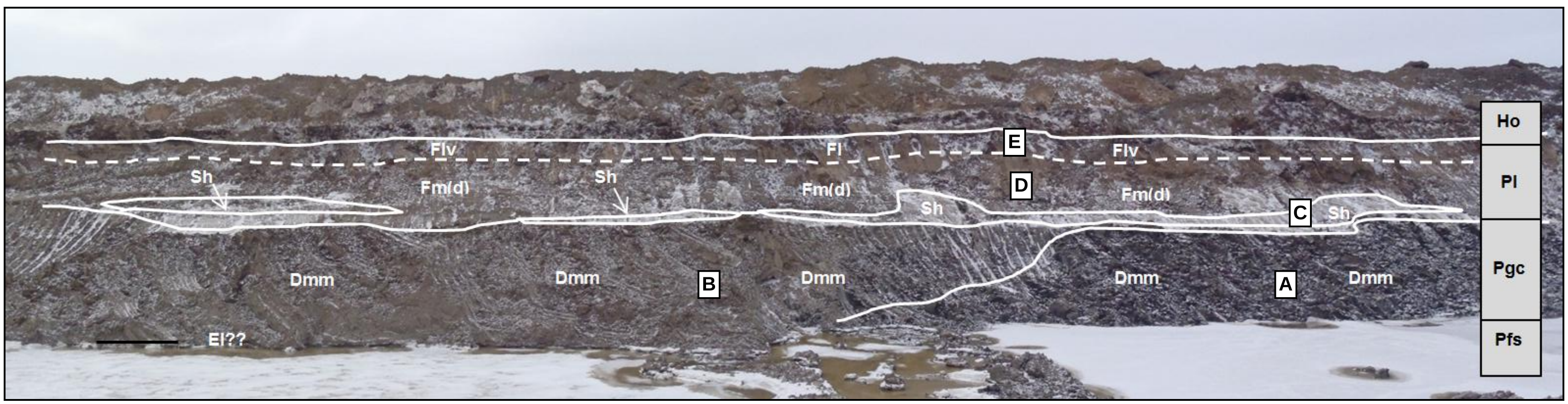


Figure 6a. West end of SZ1. (A) Dark grey, matrix-supported, clast-poor, massive, silty clay diamicton encountered between El. 313 m and El. 319 m. Interpreted as Pgc. Variable thickness, thinning towards the east with gradational contact with (B) brown, matrix-supported, clast-moderate, massive, sandy silty diamicton encountered between El. 313 m and El. 319 m. Interpreted as Pg2. (C) Both diamictons overlain by lenticular-shaped lenses of cream, fine to medium-grained sand. Seepage observed within the lenses. Interpreted as Pos. (D) Grey to pink, varved clay interbedded with fine-grained sand and silt. Interpreted as Plb. Underlain by (E) brown, very fine to fine-grained, massive, sandy silt diamicton with occasional gravel and cobble-sized dropstones. Interpreted as Pls.

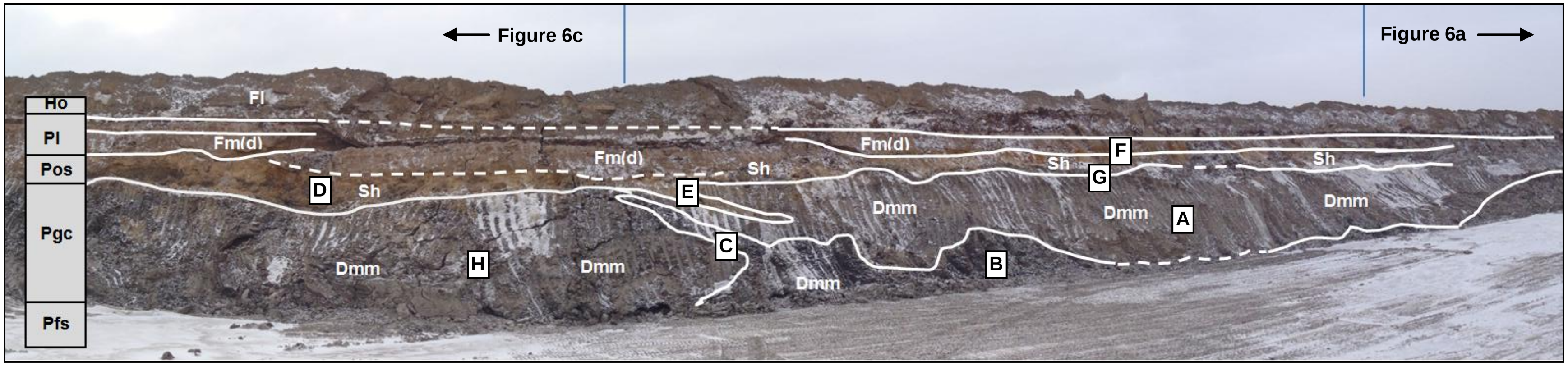


Figure 6b. (A) Brown to light grey, matrix-supported, clast-moderate, massive, sandy silt diamicton encountered between El. 313 m and El. 319 m Interpreted as Pg2. (B) Dark grey, matrix-supported, clast-poor, massive, silty clay diamicton observed beneath the brown to light grey diamicton. Interpreted as Pgc. (C) Loaded and irregular contact between the two diamictons. (D) Overlain by lateral, sheet deposit of yellow to orange, horizontal fine to medium sand. Interpreted as Pos. (E) Sand lenses locally deformed into the underlying diamicton (F). Grey to pink, varved clay interbedded with fine-grained sand and silt. Interpreted as Plb. Underlain by (G) brown, very fine to fine-grained, massive, sandy silty diamicton with occasional gravel and cobble-sized dropstones. Interpreted as Pls. (H) Localized slumping and slope instability observed due to over-steepened excavation face.

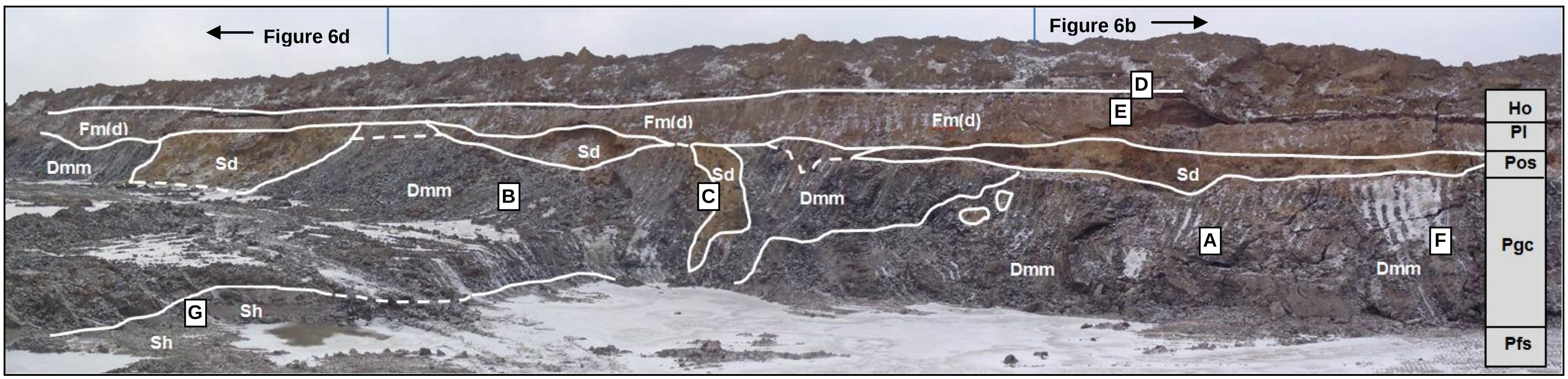


Figure 6c. (A) Brown to light grey, matrix-supported, clast-moderate, massive, sandy silt diamicton encountered between El. 314 m and El. 320 m. Interpreted as Pg2. Variable thickness, thinning towards the east with gradational contact with (B) dark grey, matrix-supported, clast-poor, massive, silty clay diamicton. Interpreted as Pgc. (C) Loaded and irregular contact between the two diamictons with sand lenses locally deformed into the underlying diamicton. Seepage observed within the lenses. (D) Grey to pink, varved clay interbedded with fine-grained sand and silt. Interpreted as Plb. Underlain by (E) brown, very fine to fine-grained, massive, sandy silt diamicton with occasional gravel and cobble-sized dropstones. Interpreted as Pls. (F) Localized slumping and slope instability observed due to over-steepened excavation face. (G) Kearl Channel observed beneath the diamicton. Comprised cream to light grey, cross-bedded, fine to medium sand.

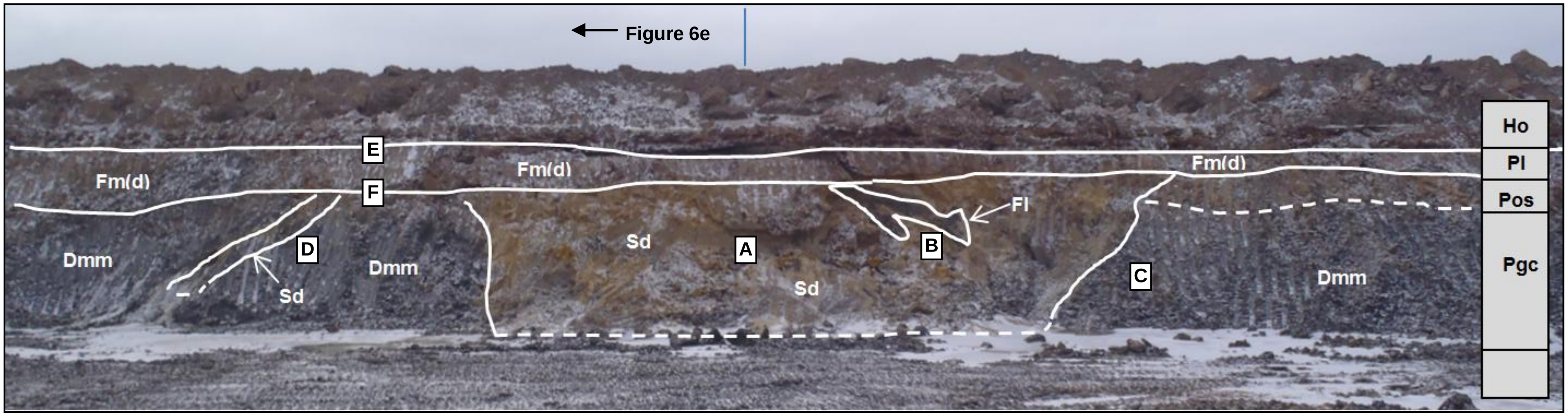


Figure 6d. (A) Trapezoid-shaped zone of orange/yellow to cream sands and gravels encountered between El. 314 m and El. 320 m. It was approximately 6 m high, 20 m wide at the base and 30 m wide at the top and contained (B) deformed raft of light grey, silty, clay surrounded by deformed sands and gravels. (C) Dark grey, matrix-supported, clast-poor, massive, silty clay diamicton. Interpreted as Pgc. (D) Sand lenses locally deformed into the underlying diamicton. Seepage observed within the lenses. (E) Grey to pink, varved clay interbedded with fine-grained sand and silt. Interpreted as Plb. Underlain by (F) brown, very fine to fine-grained, massive, sandy silt diamicton with occasional gravel and cobble-sized dropstones. Interpreted as Pls

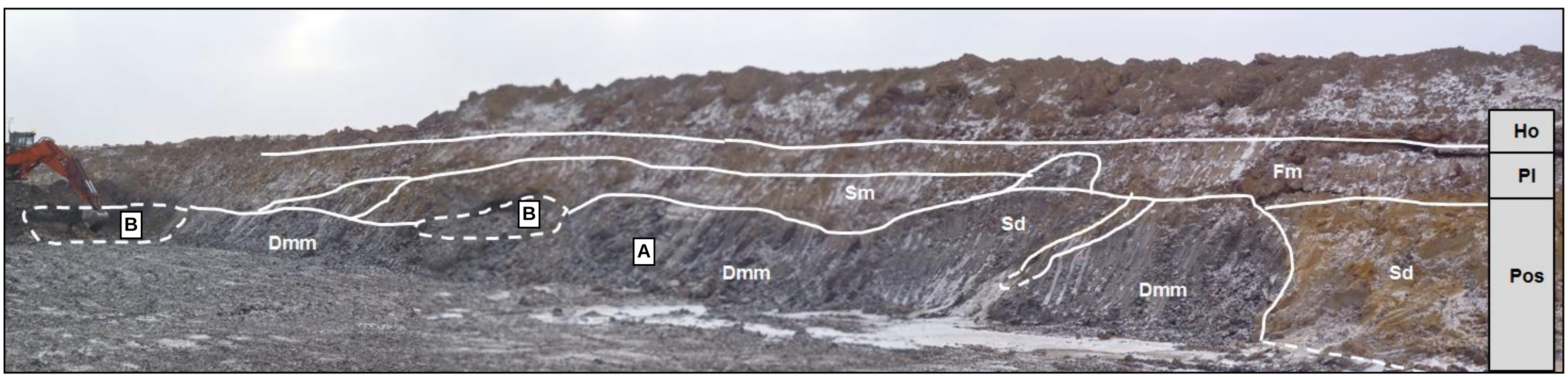


Figure 6e. East end of SZ1. (A) Dark grey, matrix-supported, clast-poor, massive, silty clay diamicton. Interpreted as Pgc. (B) Two rafts of Clearwater Formation emplaced within the Pgc. Both comprised dark grey to blue-black, medium to high plasticity, slickensided, silty clay. The slickensides were undulating, shiny, smooth and orientated in different directions.

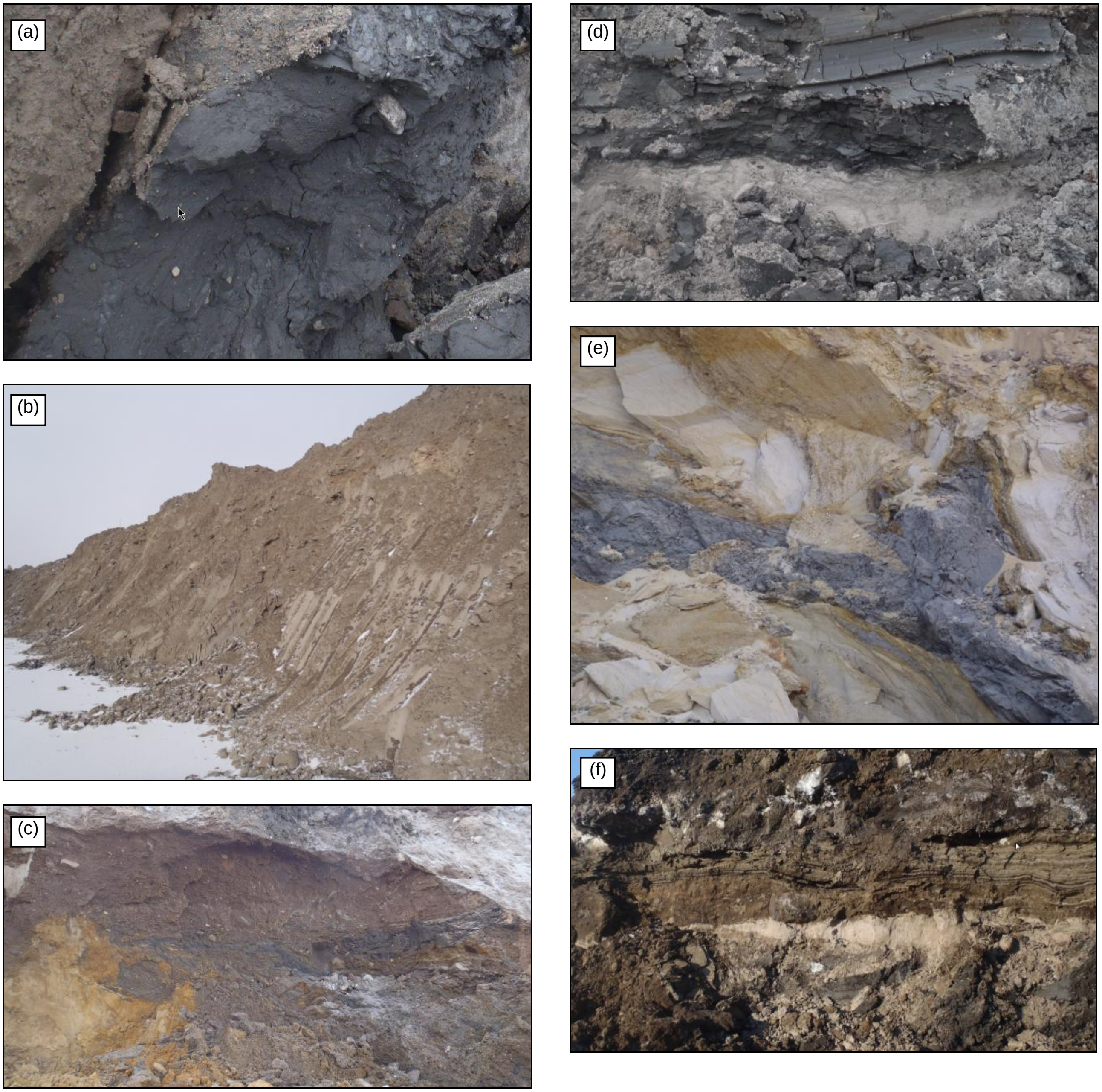


Figure 7. Sedimentary and structural features of glacigenic units exposed within SZ1. (a) Grey to dark grey, silty, sandy, clay diamicton with variable amounts of gravel. Interpreted as Pg1/Pgc. (b) Light to dark brown, sandy, clayey silt diamicton with variable amounts of gravel. Interpreted as Pg2. (c) Folded glacial till layers, silt stringers and rafted sandstone exposed within the moraine assemblage. (d) Basal contact between the glacial till and underlying sands that infilled the Kearl Channel. (e) Close-up of deformation observed within the trapezoid zone of sands and gravels in Figure 6d. Inclusion of light grey, silty, clay surrounded by deformed sands and gravels. The preserved bedding has been rotated between 45 to 90°. (F) Cross-section through glacial lacustrine, outwash and glacial till units. The uppermost unit is the Plb, which exhibits characteristic varved bedding. This is underlain by Pls, which has a diamicton appearance and contains cobble-sized dropstones. A cream coloured sand Pos layer is interbedded between the Pls and the underlying Pg1/Pgc layer.

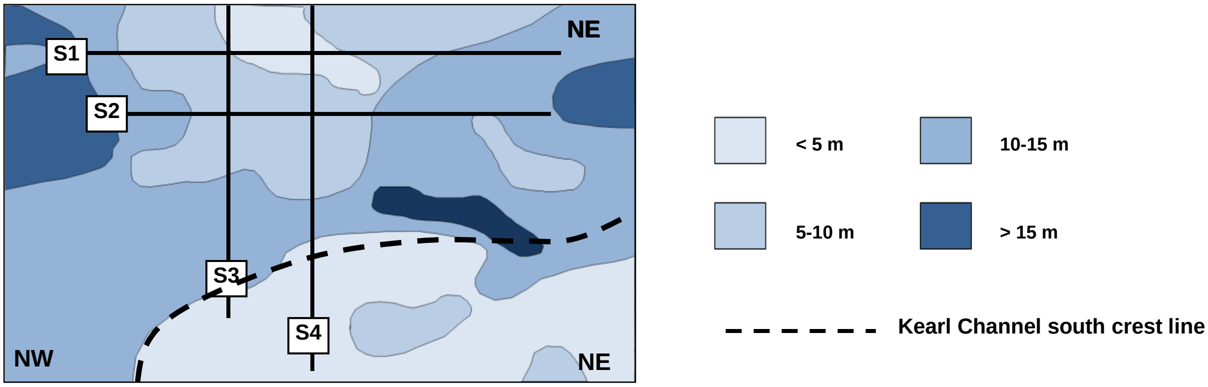


Figure 8: Isopach showing the thickness of the moraine assemblage within SZ2. Based on 119 boreholes from the study area

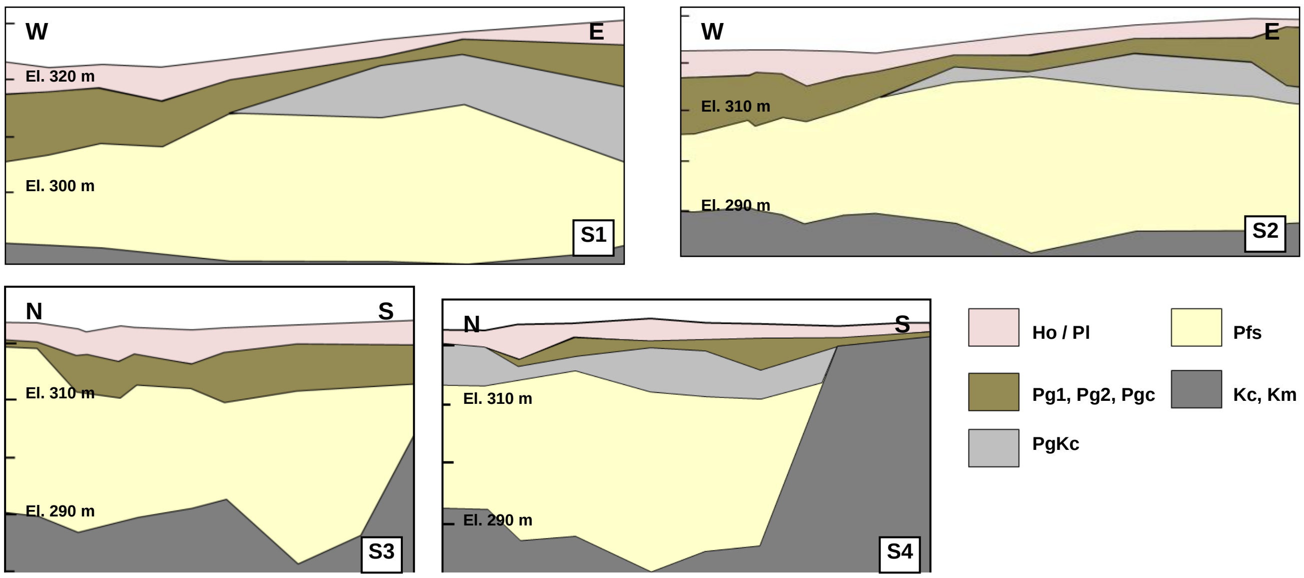


Figure 9: Schematic cross-sections through the moraine assemblage within SZ2

5 CLASSIFICATION TESTING OF GLACIAL TILLS

Geotechnical laboratory testing was undertaken on selected samples from the 119 boreholes within SZ2. To allow spatial analysis of the results, SZ2 is divided into W and NE zones with the S4 cross-section in Figure 8 dividing the two zones.

Given the scale of the investigations large number of samples and finite budget of the drilling programs, field personnel visually targeted materials that could be described as '*dark grey*' and '*silty or clayey tills*' for sampling and testing. It was hypothesized that these would represent the 'worse-case' glacial tills derived from Kc and would behave less favourably than granular tills largely derived from the Km.

5.1 Particle Size Distribution

27 PSD tests were undertaken on glacial tills within SZ2. The results of the PSD tests are summarized in Table 4, Figure 8 and a tertiary diagram (Figure 9).

Table 4. Particle size distribution of the glacial tills within SZ2

Statistic	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
Mean	0.3	38.2	36.6	24.8
Max	2.4	61.5	55.1	41.9
Min	0.0	3.0	25.8	12.6

The PSD results indicated that the fines content typically decreased with elevation in the NW zone compared to the NE. The clay content did not vary spatially within the NW and NE zones compared to the sand and silt contents. Higher sand contents were observed in the NW zone between El. 315 and 305 m. The % sand content became lower with increasing elevation and laterally towards the NE zone. In comparison, the silt contents were lower between El. 315 and 305 m and increased in % content with increasing elevation and laterally towards the NE zone.

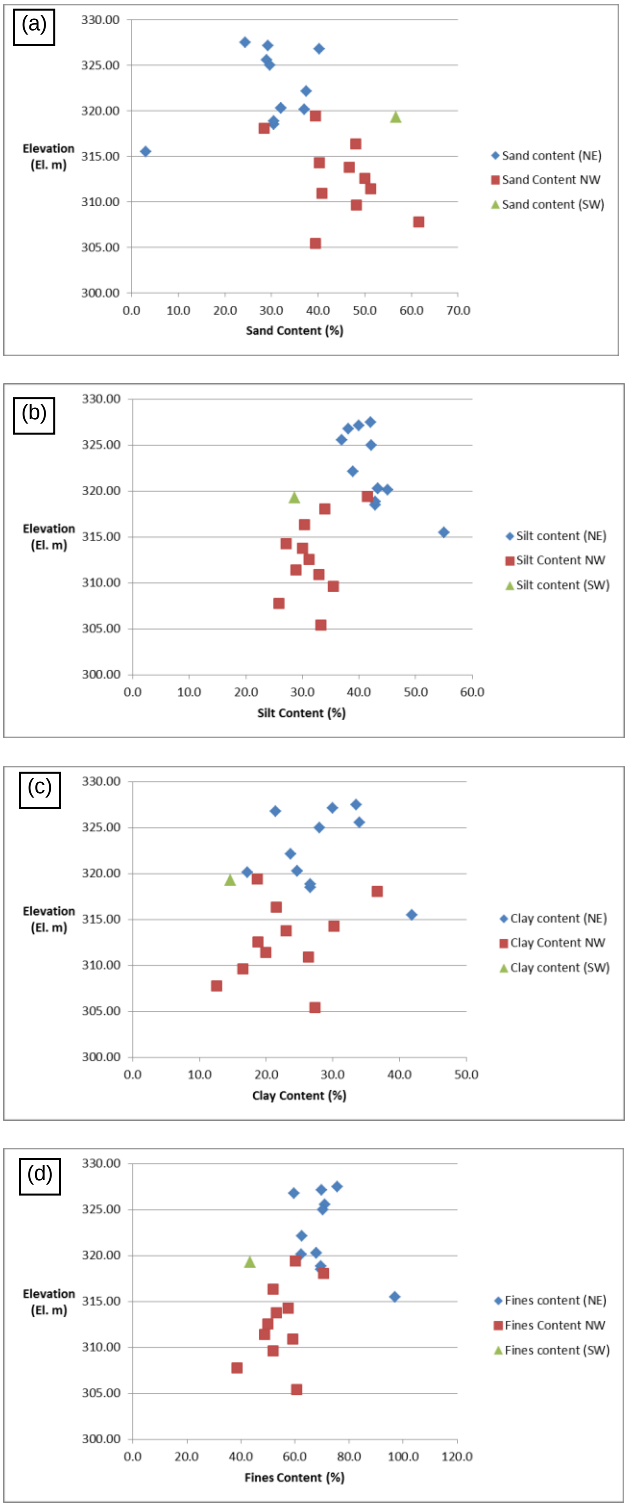


Figure 8: Distribution of (a) Sand content (b) Silt content (c) clay content (d) fines contents with elevation and location within the glacial tills within SZ2

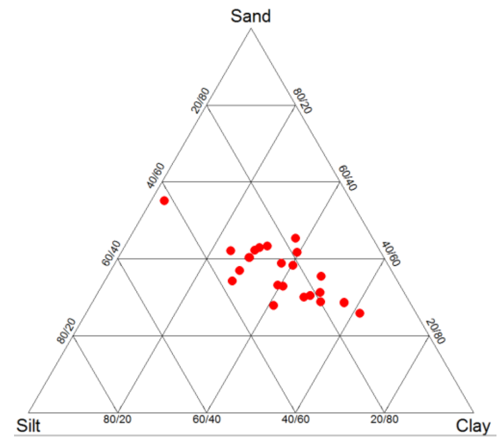


Figure 9: Tertiary diagram of the glacial tills within SZ2

5.2 Atterberg Limits

The results of 128 Atterberg tests are summarized in Table 5 and Figure 9. The distribution of PI and LL results with elevation are presented in Figures 10 and 11.

Table 5. Atterberg Limits of the Glacial Tills within SZ2

Statistic	Liquid Limit (%)	Plastic Limit (%)	Plastic Index (%)
Mean	39	14	25
Max	55	22	40
Min	18	11	3

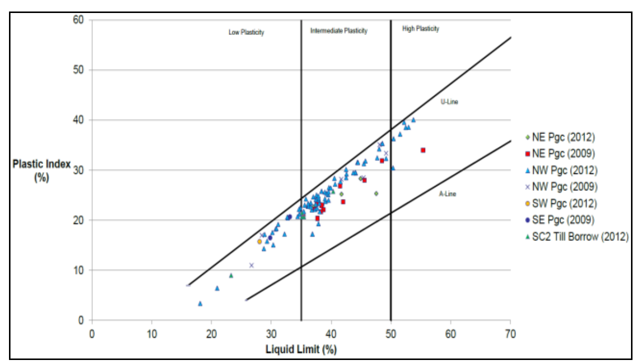


Figure 9: Atterberg Chart of the glacial tills within SA2

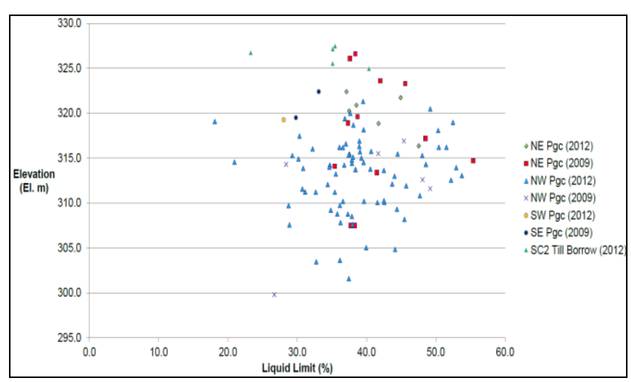


Figure 10: Distribution of liquid limits with elevation and location within SZ2

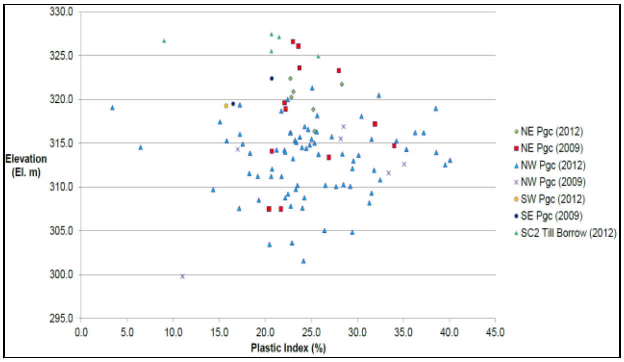


Figure 11: Distribution of plastic index with elevation and location within SZ2

The results displayed a high degree of scatter with only broad trends observed. These indicate that the glacial till broadly behaves as a low to high plasticity material but will behave predominantly as an intermediate plasticity clay. No conclusive relationship of LL and PL with elevation or lateral variation could be identified. Large variations in the plasticity of glacial tills over short distances are to be expected and have been documented by Denness (1974) and Anderson and McNicol (1989).

5.3 Strength Testing

Strength testing was undertaken on selected samples of glacial tills within the SC2 and adjacent Sand Cell 1 (SC1) footprints. These were selected on the degree of sample disturbance and whether clasts were present.

Two consolidated undrained triaxial tests (T1 and T2) and six direct shear tests (T1 to T6) were completed. The tests indicated that the glacial till exhibited a small post-peak drop in friction angle (Ø') at large strains. The results from these tests are summarized in Tables 6 and 7. The selection of strength parameters of glacial tills for the design of the SC2 Tailings Dam is not discussed in this paper.

Table 6. Consolidated undrained triaxial results for the Glacial Till

	T1	T2
Peak effective friction angle (°)	28	27
Effective friction angle at 28 % strain (°)	23	23
Plastic Index (%)	29	25
Liquid Limit (%)	43	38
Sand Content (%)	43.5	45.1
Silt Content (%)	34.6	30.8
Clay Content (%)	21.9	22.5

Table 7. Direct shear test results for the Glacial Till

	T1	T2	T3	T4	T5	T6
Peak effective friction angle (°)	21	26	23	28	23	24
Residual friction angle (°)	16	21	19	24	18	22
Plastic Index (%)	36	22	28	24	26	40
Liquid Limit (%)	49	37	46	38	44	53

6 DISCUSSION

This study concluded that the glacial tills at JPM have higher clay content than the glacial tills documented by McPherson and Kathol (1977) and Nicol et al (1994). The fines content decreased with elevation in the NW zone compared to the NE of SZ2. This possibly reflects the presence of PgKc in the eastern part of the SZ2. Tills overlying the rafts have higher clay and silt contents than the tills present in the west of SZ2, which contained no rafts. However, there may also be a degree of sample bias.

The glacial tills at SC2 'accumulated' in a complex subglacial setting, probably involving basal melting and debris release, deposition on the lee of the Kearl Channel, and through subglacial deformation. The variation in composition and colour over short distances indicate that the subglacial bed comprised a mosaic of deforming spots that varied temporally and spatially. Deformation structures were locally observed in the glacial till and comprised silt stringers and rafted bedrock, indicating that glaciotectonic processes were occurring.

The glacial tills could be described as lodgement or deformation tills using traditional nomenclature (*which also includes subglacial melt-out till, supra-glacial melt-out till and flow till*). However, this terminology has been challenged recently with the development of micro-morphological analysis of glacial tills (Bennett and Glasser, 2009). The internal architecture of subglacial tills indicate that they form through a combination of processes, involving lodgment (*deposition directly from sliding ice by frictional processes*); frictional retardation in a sub-glacial deforming layer; melt-out (*deposition due to the melting of stagnant or slowly moving ice*) and deposition by gravity. Given that no dominant process exists, the term '*sub-glacial traction till*' (Evans et al, 2006) could be used to describe the tills encountered at SC2.

The outwash sands were interrelated with the glacial tills and were encountered as lenses of variable thickness and distribution above the glacial tills or as inclined lenses or channels interbedded within the glacial tills. These are not deposits from the CLIS flood event and are interpreted as a braided canal outwash system that was present at the ice-till contact. These systems are common in regions where glacial till is derived primarily from underlying sedimentary and the subglacial till is relatively continuous, fine-grained and of low permeability and eskers are absent (Clarke and Walder, 1994). They are formed when meltwater discharges are too high to be excavated through the till and bed separation occurs. Subsequent recoupling of the ice-bed interface would result in the deformation of the sands and gravels.

ACKNOWLEDGEMENTS

The Author gratefully acknowledges the permission of Shell Canada Energy to publish the findings of this study and thanks Scott Martens for his comments in preparing the paper and Francis Belleville for his assistance in translating the abstract.

REFERENCES

Alberta Geological Survey. 2013. GIS Dataset 2013-02

Alberta Geological Survey. 2014. GIS Dataset 2014-22

Anderson, J.C.G and McNicol, R. 1989. The Engineering Geology of the Kielder Dam. Quarterly Journal of Engineering Geology, Vol 22(2), pp111-130

Andriashek, L.D. 2002. *Quaternary geological setting of the Athabasca Oil Sands (in situ) area, northeast Alberta*, Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report 2002-03, 286 p.

Andriashek, L.D. & Atkinson, N. 2007. *Buried channels and glacial-drift aquifers in the Fort McMurray region, Northwest Alberta*, Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report 2007-01.

ASTM. 2011. *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System*), D2478-11.

Atkinson, N, Utting, D.J. and Pawley, SM. 2014. Glacial Landforms of Alberta, Canada. Alberta Energy Regulator, AER/AGS Map 604, scale 1:1 000 000

Atkinson, N. Andriashek, L.D. & Slattery, S.R. 2013. Morphological analysis and evolution of buried tunnel valleys in northeast Alberta, Canada, *Quaternary Science Reviews*, Vol 65, pp53-72

Bayliss, A.I, Philip, L, Masterson, K, Wong, R, Rahman, M, Hepp, D, Clarke, M, Martens, S. & Elbanna, M. 2014. The Geological Influences of Glacially Rafted Clearwater Formation on the Design and Operation of an External Tailings Facility. *Proceedings-GeoRegina 2014. Canadian Geotechnical Society Annual Conference*. Regina. Saskatchewan. Sept 29–Oct 1, 2014.

Bayliss, A.I, Philip, L, Hepp, D., and Martens, S. 2013. A geotechnical study of glacially-rafted, weak, Clearwater Formation beneath a tailings dam, Fort McMurray region, Alberta, *Canadian Dam Association 2013 Annual Conference* Montréal, Québec, October 5-10, 2013.

Bayrock, L.A. 1971. Surficial geology: Bitumont (NTS 74E). Research Council Alberta, Map 34.

Bayrock, L.A & Reimchen, T.M. 1974. Surficial geology of the Waterways area (NTS 74D). Map 148.

Benn, D.I. & Evans, D.J.A. 2010. 2010. *Glaciers and Glaciation*. 2nd Ed. Hodder Education, London

Bennett, M.R and Glasser, N.F. 2009. Glacial Geology: Ice Sheets and Landforms. 2nd ed. Wiley-Blackwell

Clark, P.U & Walder, J.S. 1994. *Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets*, Geological Society of America Bulletin, Vol 106, pp 304-314

Denness, B. 1974. *Engineering aspects of the chalky boulder clay at the new town of Milton Keynes in Buckinghamshire*. Quarterly Journal of Engineering Geology, Vol 7(3), pp297-309

Dufresne, M.B, Henderson, B.A, Fenton, M.M. Pawlowicz, J.G. & Richardson, R.J.H. 1994. *The mineral deposits potential of the Marguerite River and Fort McKay areas, northeastern Alberta (NTS 74E)*, Alberta Geological Survey Open File Report 1994-9.

Evans, D.J.A, Young, N.P. and Ó Cofaigh, C. 2014. *Glacial geomorphology of terrestrial-terminating fast flow loves/ice stream margins in the southwest Laurentide Ice Sheet*. Geomorphology, Vol 204, pp86-113

Evans, D.J.A. and Benn, D.I. 2004. *Facies description and the logging of sedimentary exposures*. In *A practical guide to the study of glacial sediments*. Arnold, London.

Evans, D.J.A, Clark, C.D and Brice Rea, R. 2008. Landform and sediment imprints of fast glacier flow in the southwest Laurentide Ice Sheet, *Journal of Quaternary Science,* Vol 23(3), pp 249–272

Fenton, M.M., Waters, E.J., Pawley, S.M., Atkinson, N., Utting, D.J. and Mckay, K. 2013. Surficial geology of Alberta; Alberta Energy Regulator, AER/AGS Map 601, scale 1:1 000 000

Fenton, M, M, Pawlowicz, J.G; Paulen, R.C, Prior, G.J, and Olson, R.A. 2008. Quaternary Geology of Northern Alberta: Implications for Kimberlite Exploration, *8th International Kimberlite Conference - Selected Papers*.

Fenton, M, M and Mougeot, C. 1982. Overburden or Quaternary Stratigraphy Firebag River, Northwest Alberta: Preliminary Report. AGS/ARC Open File Report 1983-3.

Fisher, T.G, Waterson, N, Lowell, T.V, and Hajdas, I. 2009. Deglaciation ages and meltwater routing in the Fort McMurray region, northeastern Alberta and northwestern Saskatchewan, Canada, *Quaternary Science Reviews,* Vol 28, pp 1608-1624

Martens, S. N., Meyer, J.P and List, B.R. 2001. A Geotechnical Performance Review of the Mildred Lake East Toe Berm. *Canadian Geotechnical Conference, Calgary Proceedings*

McPherson, R.A. & Kathol, C.P. 1977. *Surficial Geology of Potential Mining Areas in the Athabasca Oil Sands Region*. Alberta Energy and Utilities Board / Alberta Geological Survey. Open File Report 1977-4.

Nicol, D. 1994. The Syncrude Mildred lake Tailings Dyke Redesign, *Transactions of the 18th International Congress on Large Dams,* Durban, South Africa, 7-11 November, ICOLD

Pawluk, S. and Bayrock, L.A. 1969. Some Characteristics and Physical Properties of Alberta Tills, Research Council of Alberta. Bulletin 26

Shell Canada Ltd. 2007. 2006 Annual Information Form

Sisson, R., Chan, W.K, and Fear, C. 2012. Horizon Dyke 10 Geotechnical Design, *GeoManitoba 2012 65th Canadian Geotechnical Conference Proceedings,* Winnipeg, Manitoba, Canada

Stephens, B; Langton, C, and Bowron, M. 2006 .Design of Tailings Dams on Large Pleistocene Channel Deposits: A Case Study – Suncor's South Tailings Pond, *Canadian Dam Association Conference.* Quebec City, Quebec, Canada