Quaternary geology and drift prospecting in the Mount Polley region (NTS 093A)

by

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Abstract

Drift prospecting studies were conducted in the Mount Polley Mine region, integrating surficial mapping, paleoflow measurements and Quaternary stratigraphy to infer glacial history. Eighty seven till samples were taken with the objective of determining the geochemical and mineralogical dispersal in till down-ice from Mount Polley. Surficial mapping identified till as the most abundant surficial material. Colluvium was mapped at high elevations and on steep slopes, and glaciofluvial and alluvial sediments are widespread in the river valleys. The stratigraphic record documents till associated with Fraser Glaciation followed by retreat phase glaciolacustrine and glaciofluvial sediments. Two distinct ice-flow movements have been identified; an initial west, southwestward flow during glacial advance, followed by a northwestward flow. The till sampling survey identified mineralized glacial dispersal up to 10 km to the northwest, Hg and Zn as pathfinder elements and apatite, andradite, chalcopyrite, epidote, gold grains and jarosite as porphyry indicator minerals (PIMs).

Keywords: Quaternary geology; Mount Polley; Surficial mapping; Ice-flow history; Till sampling; Drift Prospecting.

Dedication

This thesis is dedicated to my grandmother and parents.

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I would like to extend my sincerest gratitude to my senior supervisor Brent Ward for taking me on as a student, for always listening to my arguments, being generous with his time and pushing me to improve my work. I also couldn't thank enough my co-supervisor Alain Plouffe for giving me the chance to work on this project. Thank you for your kindness, encouragement, generosity and appreciation throughout the course of my degree. A big thank you to my co-supervisor Matt Leybourne for encouraging me to publish and for introducing me to fantastic people in Rotorua and Vancouver. Many thanks to Ray Lett for being an extremely supportive external and for many memorable discussions over the last few years. All of you made my MSc a brilliant experience and I was extremely lucky to have you all in my supervisory committee.

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1. Introduction

1.1. Overview

The Interior Plateau of British Columbia hosts several economic porphyry deposits such as Mount Milligan and Copper Mountain and holds potential for undiscovered deposits (Fig. 1.1) (Anderson *et al.* 2012). Located within the Interior Plateau of British Columbia is the Mount Polley Mine. It is an alkaline, silica-under saturated Cu-Au porphyry deposit owned and operated by Imperial Metals Corporation. The Interior Plateau of British Columbia has also been glaciated numerous times throughout the Pleistocene (Clague & Ward 2011). As a result, it is dominantly covered in glacial deposits, primarily till, that masks much of the bedrock, impeding mineral exploration. However, drift prospecting techniques, which guide mineral exploration in glaciated regions, can be used as an aid to detect porphyry mineralization in this region. An understanding of the glacial history is crucial to the successful application of drift prospecting techniques. However, the glacial history needs to be revised in the Mount Polley Mine region.

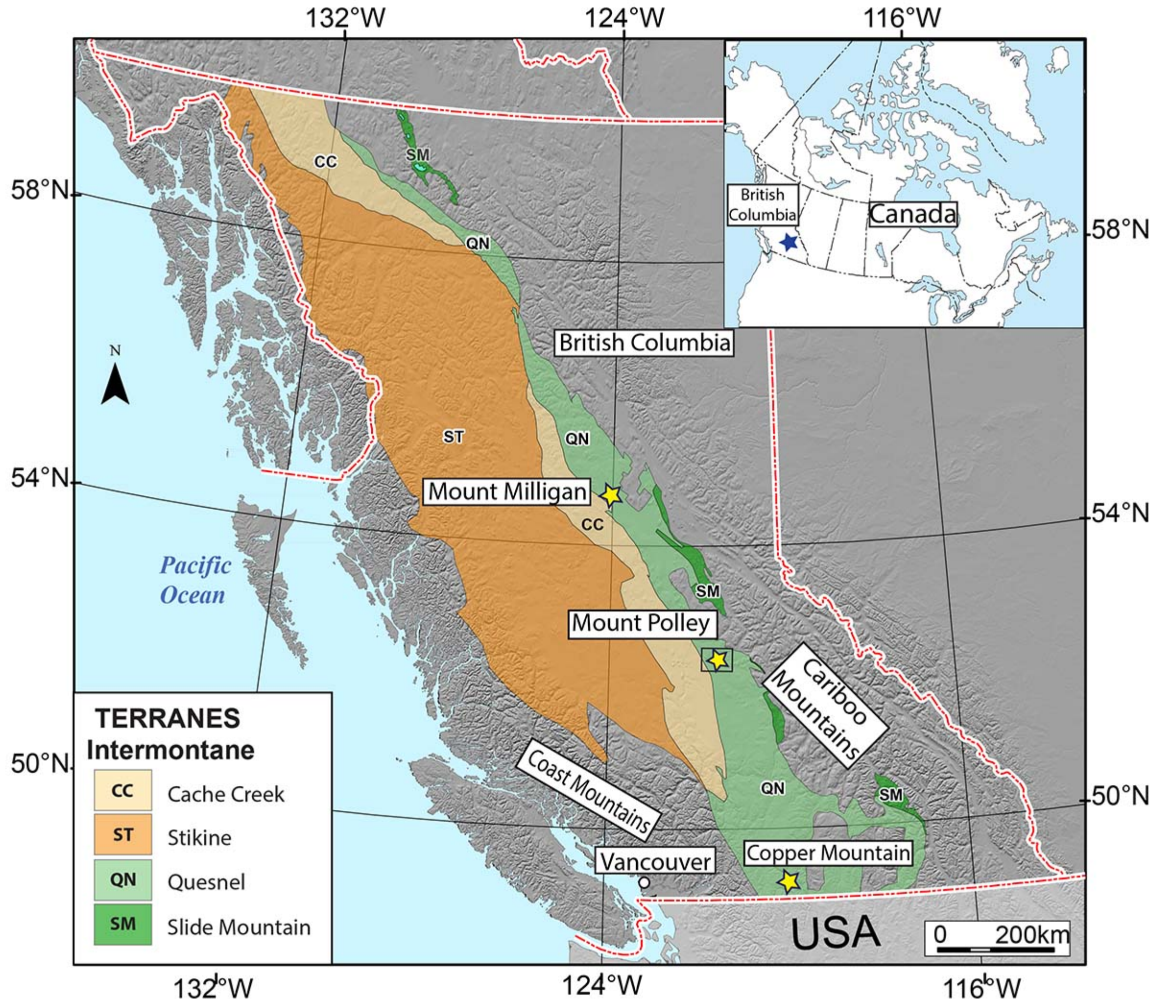

Figure 1.1: Location of the Mount Polley study area, including location of Cu-Au porphyry deposits Mount Milligan and Copper Mountain. Modified after Colpron & Nelson (2011).

This thesis project investigates one of four study sites, which are part of Natural Resources Canada's Targeted Geoscience Initiative-4 (TGI-4) program. The main objective of TGI-4 is to "provide geoscience knowledge and develop innovative techniques for effective targeting of buried mineralization" (Anderson *et al.* 2012).

1.2. Principles of drift prospecting

Drift prospecting is the process of locating mineralized ore in bedrock in glaciated terrain based on the anomalous geochemical, mineralogical and lithological patterns in till (DiLabio & Coker 1989). It is an ideal tool to explore for mineralization in areas where a thick cover of Quaternary sediments conceals the bedrock; till is the ideal sample medium (McMartin & McClenaghan 2001). Its value was first established in the Scandinavian countries and has been used successfully to discover economic deposits in Canada, such as the Lac De Gras kimberlites in the Northwest Territories (Paulen & McMartin 2009).

As glaciers flow, they erode bedrock, transporting and depositing the derived sediments down-ice (DiLabio 1990). Basal till is the first derivative of bedrock, deposited sub-glacially by glaciers, where it's geochemical, mineralogical and lithological signature is known as a "dispersal train" (DiLabio 1990). Dispersal trains are defined as three-dimensional patterns, characterized as having a high length to width ratio and are considerably larger than their original bedrock source; therefore, they are excellent targets for exploration as the anomaly is spread over a much larger area. The content decreases down-ice from the "head", which is a region of highest content to the "tail", where the anomaly signature becomes progressively diluted (Fig.1.2) (DiLabio 1990). Some of the most important factors that determine the shape and length of dispersal trains include size and orientation of mineralized bedrock available for erosion, its degree of erodibility and topography (DiLabio 1990).

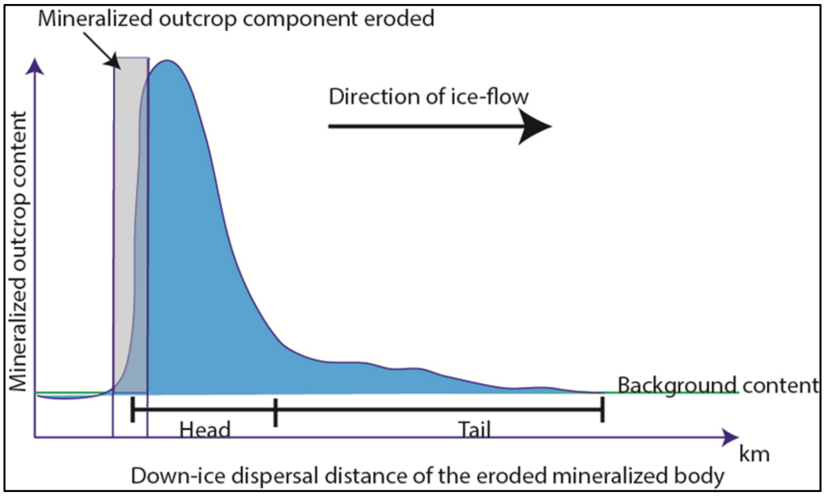

Figure 1.2: Dispersal train depiction, modified after DiLabio (1990).

In the case of limited availability of ore elements and ore minerals, examining till for pathfinder elements and indicator minerals is a useful approach. Pathfinder elements are elements associated with and indicative of the presence of a particular type of mineralization. These elements may be highly prevalent within the mineralization and can remain present in the till matrix over longer distances than ore elements (McMartin & McClenaghan 2001). Indicator minerals are coarse grained, high specific gravity minerals, resistant to weathering and associated with a particular deposit (e.g kimberlites, porphyries) (Averill 2011). These minerals have physical characteristics (colour, shape, size), which make them distinguishable in a sediment sample (Averill 2011; McClenaghan 2011).

Dispersal train shape is largely a function of ice-flow history. A single ice-flow movement produces “ribbon- shaped” dispersal (Parent *et al.* 1996). Multiple ice flows rework a ribbon-shaped dispersal into a fan shape and reversal in ice-flow may produce a stellate or amoeboid shaped dispersal pattern (Parent *et al.* 1996). “Palimpsest trains” is a term used to describe dispersal trains that are generated as a result of the reworking of an older dispersal train (Parent *et al.* 1996).

Drift prospecting utilizes a combination of field and laboratory methods including 1) surficial mapping to identify landforms and sediment distribution; 2) measurement of ice-flow indicators to identify ice-flow direction; 3) till sampling directed perpendicular to the direction of glacial transport (to intersect a potential dispersal train) and; 4) geochemical, mineralogical and lithological analysis of the till sample to determine element, mineral and lithic components. If mineralization is present, till within the dispersal train (down-ice from the deposit) carries a relatively high signal (compared to background/up-ice regions) of elements and minerals associated with the deposit (Grunsky 2010). These geochemical anomalies are then traced to their source rock. Drift prospecting is well suited to porphyry deposits, as porphyry ore bodies are fairly large and the associated alteration haloes are extensive, extending the geochemical and mineralogical signature of the deposit further compared to other styles of mineralization (Averill 2011; Anderson *et al.* 2012; Plouffe *et al.* 2013).

1.3. Overview of study area

1.3.1. Location

The Mount Polley study area lies ~55 km northeast of Williams Lake, within the township of Likely, British Columbia. It covers approximately 940 km^2 over NTS map sheets 093A 05, 06, 11 and 12 (Fig. 1.3).

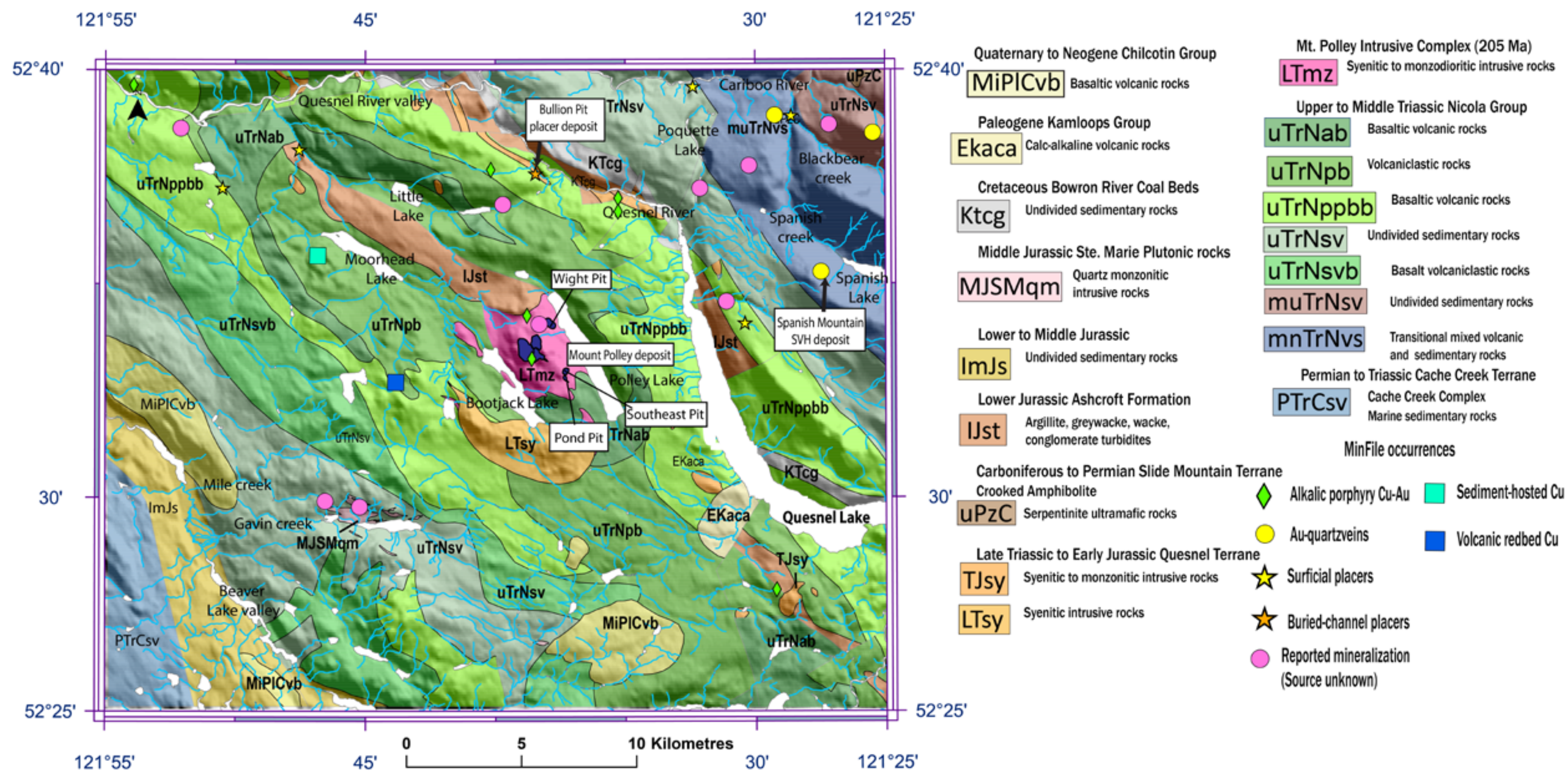

Figure 1.3: ***Bedrock geology, topography, hydrography and MinFile occurrences in the Mount Polley study area. Major hydrographic features and bedrock units are labelled in black. Pits are coloured in blue. Bedrock geology modified after Logan et al. (2007).***

1.3.2. Physiography

The Interior Plateau of British Columbia is a region of irregular relief, consisting of extensive plateaus, highlands and low-relief rounded mountains, bordered by the Coast Mountains to the west and the Rocky Mountains to the east (Tipper 1971a; b; Holland 1976; Church & Ryder 2010). The study area is of low to moderate relief and lies along the eastern margin of the Cariboo Plateau, within the Quesnel Highlands, which make up a part of the larger Columbia Highlands (Church & Ryder 2010). The Quesnel Highlands are bordered by the Shuswap and Okanagan Highlands and the Cariboo Mountains (in the Columbia Mountain Ranges) further east (McAndless 2006; Demarchi 2011). Highest elevation in the study area is 1585 m a.s.l. in the eastern portion of the study area (at Spanish Mountain; Fig. 3.1) and the lowest elevation is 650 m a.s.l. in the Quesnel River valley. Maximum elevation within the Mount Polley Intrusive Complex is at Polley Mountain, which stands at 1266 m (Rees 2013). The Quesnel and Cariboo river valleys make up the northern portion. Several small lakes occur in the study area but Quesnel Lake is by far the largest. It is also the deepest fjord lake in British Columbia at 512 m (Gilbert & Desloges 2012).

1.3.3. Climate and vegetation

The Mount Polley study region experiences long warm summers and cool wet winters with heavy precipitation from Fall to early Spring (Demarchi 2011). Climate data for this region was only available for 1974-1993 (Environment Canada 2013). The latest climate report available from 1993 indicates a maximum summer temperature of 30.5°C, minimum winter temperature of -30°C, annual rainfall of 535.8 mm and total snowfall of 108.3 cm (Environment Canada 2013). The study area falls within the “Interior Cedar-Hemlock” biogeoclimatic zone. It has Ponderosa and Lodge pole pine, hemlock, Douglas fir, spruce, and red cedar trees (British Columbia Ministry of Forests 1996). Dominant wildlife includes moose, grizzly and black bears, ruffled grouse, golden eagle, and the American robin (British Columbia Ministry of Forests 1996).

1.3.4. Regional bedrock geology

Extensive research on the bedrock, structural, alteration and deposit geology at the Mount Polley deposit was completed by Hodgson *et al.* (1976), Logan & Mihalynuk (2005), Logan & Bath (2006) and Tosdal *et al.* (2008). Detailed studies on the ore body, brecciation and alteration occurring within the deposit and present as halos around the deposit was reported by Fraser *et al.* (1993, 1995) and Fraser (1994). A detailed bedrock geology map of the region was generated by Imperial Metals Corporation in collaboration with the British Columbia Geological Survey (Logan *et al.* 2007). More recently, a detailed deposit geology map of the Mount Polley Intrusive Complex has also been released (Rees *et al.* 2014). Recent research has been focussed on the identification of potential porphyry indicator minerals (PIMs) in bedrock at a number of porphyry deposits in the Canadian Cordillera, including the Mount Polley deposit (Bouzari *et al.* 2011; Celis *et al.* 2013, 2014; Grondahl, 2014; Piziak *et al.* 2015).

The Mount Polley study area (Fig. 1.3) lies within Quesnel terrane, an accreted belt situated along the eastern margin of the Intermontane morphogeological belt (Rees 2013). The central Quesnel terrane is represented by Triassic mafic volcanic, volcaniclastic and sedimentary rocks of the Nicola Group, which dominate the middle of the study area (Logan & Mihalynuk 2005). Also associated with the Quesnel terrane are syenitic to monzodioritic rocks of the late Triassic to early Jurassic Mount Polley Intrusive Complex (Logan *et al.* 2007). The post accretionary, Middle Jurassic (165-167 Ma) monzonitic intrusive rocks of the Ste. Marie Plutonic group are present in the west central part of the study region. The oldest rocks are Permian to Triassic marine sedimentary and volcanic rocks of the Cache Creek terrane, a subduction accretionary complex, in the southwest part of the study area (Logan *et al.* 2007; Rees 2013). The youngest rocks in the area are Tertiary basaltic and calc-alkaline volcanic rocks of the Chilcotin and Kamloops groups, respectively (Logan *et al.* 2007).

1.3.5. Deposit geology

The Mount Polley deposit appeared as a magnetic anomaly during a regional aeromagnetic survey conducted by the provincial and federal governments in 1963 (McAndless 2006; Rees 2013). Rees (2013) explains that the magnetite rich hydrothermal alteration associated with the porphyry deposit is what was detected during the early regional geophysical survey. Mastadon Highland Bell Mines and Leitch Gold Mines Ltd. staked the first claims and the deposit was discovered by prospecting (Gillstrom 2004; Rees 2013). Exploration in the late eighties included B-horizon soil sampling and geophysical surveys followed by drilling (McNaughton 1987). The Mount Polley Cu-Au deposit is mined as an open-pit operation with estimated reserves (as of 2013) of 93 million tonnes grading 0.297% Cu, 0.299 g/t Au and 0.62 g/t Ag (Rees 2013). Other major deposit in this region includes the Spanish Mountain Au deposit, which is a sediment-hosted vein type Au deposit (Koffyberg *et al.* 2012).

The Mount Polley Intrusive Complex is a 5.5 by 4 km body, reaching a maximum elevation of 1266 m a.s.l (Rees 2013). The Complex formed during the last stages of Quesnellia island arc magmatism and has an U-Pb zircon age of approximately 205 Ma (204.7 ± 3 Ma) (Rees 2013). The Complex intruded into the mafic volcanic and volcaniclastic rocks of the Triassic Nicola Group (Hodgson *et al.* 1976; Logan & Mihalynuk 2005; Logan & Bath 2006; Logan *et al.* 2007; Celis *et al.* 2013). Mineralization at Mount Polley is hosted by alkaline, silica-undersaturated, multi-phase intrusions, which include syenites, diorites and monzodiorites as well as hydrothermal breccias (Fraser *et al.* 1993, 1995). The deposit includes a central potassic core (Core Zone), enveloped by spatially restricted sodic-potassic alteration and an outer propylitic alteration rim (Fig. 1.4) (Fraser *et al.* 1993, 1995; Fraser 1994; Tosdal *et al.* 2008).

The Cu-Au (-Ag) mineralization within the central potassic core is vein/fracture controlled as well as disseminated in igneous bodies including diorite, monzodiorite, monzonite, and plagioclase porphyry. However, most of the mineralization is present within the intrusion and hydrothermal breccias (Fraser 1994; Rees 2013). The Cariboo, Bell and Springer pits are hosted within the central potassic Core Zone (Fig.1. 4).

The sodic-potassic alteration zone, also referred to as the andradite garnet-epidote zone, envelopes the central potassic core (Rees *et al.* 2014). The main minerals in the sodic-potassic alteration zone include andradite garnet, epidote, albite, potassium feldspar and minor quantities of apatite (in the northern portion). The sodic-potassic alteration zone is characterized by breccia-hosted, coarse grained, Cu-Fe sulphides (primarily chalcopyrite, pyrite and bornite) (Rees 2013). The Wight open pit is situated to the northeast, within this zone (and also referred to as the Northeast zone) and has up to three times higher copper ore grades than the Cariboo-Bell-Springer pits located to the southwest (within the Core Zone) (Logan *et al.* 2007; Logan & Mihalynuk 2005; Tosdal *et al.* 2008). Silver also occurs in galena in this zone (Logan & Mihalynuk 2005).

The outer propylitic rim is weakly altered and includes epidote together with calcite and pyrite in veins and disseminated. The Southeast Pit occurs within the transition between the sodic-potassic and propylitic alteration. The style of mineralization within this zone is similar to the Wight Pit but the ore grades are lower. Minerals present in the Southeast zone (hosting Southeast Pit) include chalcopyrite, pyrite and trace quantities of molybdenite, which occurs within albite veins (Rees 2013). The Pond Pit is situated 400 m southwest of the Southeast Pit within a patch of skarn alteration, still within the outer propylitic rim (Fig. 1.4) (Rees 2013; Rees *et al.* 2014). Minerals in this zone include andradite garnet and disseminated chalcopyrite, as well as rare bornite (Rees 2013; Rees *et al.* 2014).

The primary ore sulphides consist of chalcopyrite, pyrite and minor amounts of bornite (Rees 2013). Chalcopyrite occurs as disseminations as well as coarser blebs and veins. Native Au is present as inclusions (micron-scale in the northeast portion of the sodic-potassic alteration zone) within chalcopyrite and pyrite (Rees 2013). Evidence of glacial erosion within the Mount Polley Intrusive Complex includes striations (oriented northwest and southwest) documented on bedrock surfaces of the potassic zone, the sodic-potassic zone and the propylitic rim (Fig. 1.4) (Rees *et al.* 2014).

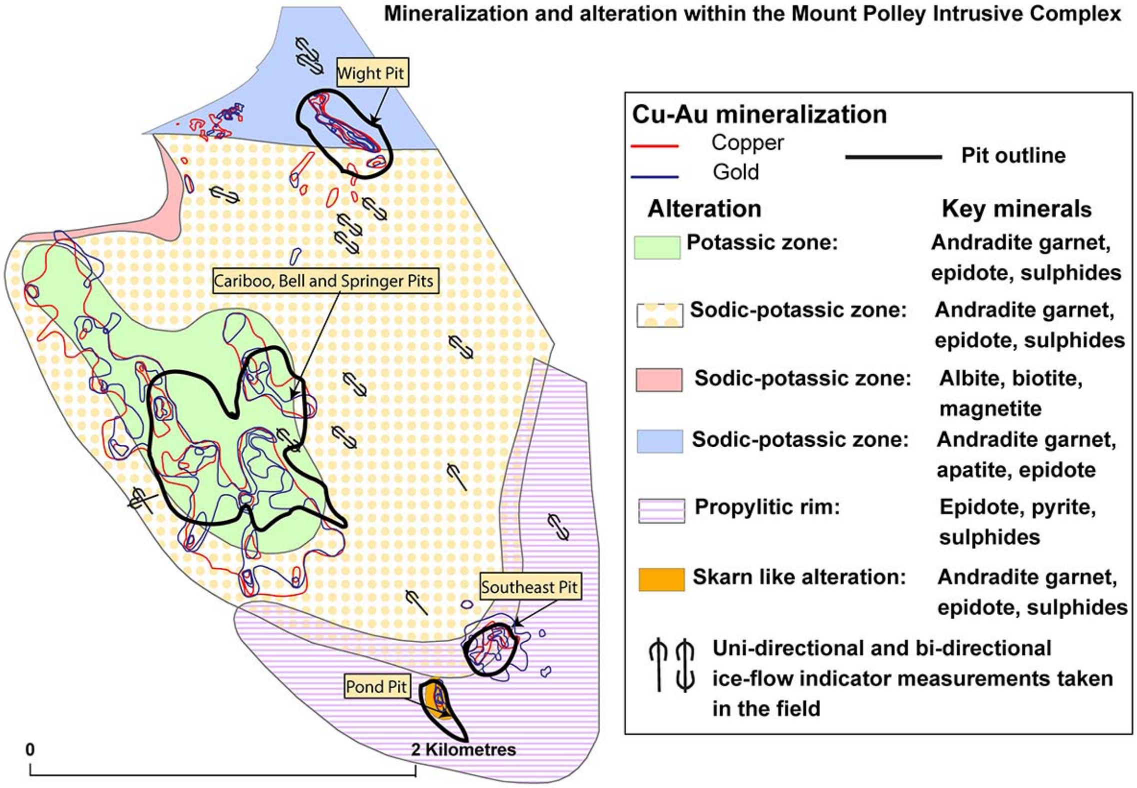

Figure 1.4: ***Mineralization outline and alteration zones within the Mount Polley Intrusive Complex. Black outline delineates the operating pits and the blue and red lines outline gold (grams per tonne) and copper (%) grades, respectively. Modified after and Rees et al. (2014) and Hashmi et al. in press.***

1.3.6. Regional Quaternary framework

British Columbia has undergone numerous glaciations by the Cordilleran Ice Sheet (CIS) during the Quaternary. At its maximum, the CIS extended from northwest Washington in the south to parts of Yukon and Alaska in the north. The Latest Wisconsinan glaciation, known as the Fraser Glaciation in British Columbia, may have started as early as 29 ^{14}C ka BP (Ryder *et al.* 1991). However, based on the radiocarbon dates of wood, peat and shells, significant portion of southern British Columbia remained ice free until after 19,000 to 20,000 year B.P. (Clague *et al.* 1980). During Fraser Glaciation, the Coast and Cariboo mountains served as the ice accumulation source regions for the glaciers that covered the study area (Tipper 1971 a, b; Plouffe *et al.* 2011a, b, c). Kerr (1934) and Davis and Mathews (1944) proposed a four-stage glaciation model to depict ice growth (Tipper 1971a, b; Ryder *et al.* 1991; Clague & Ward

2011). These include the alpine phase, intense alpine phase, mountain ice sheet phase and continental ice sheet phase.

During the alpine phase, ice began accumulating in the alpine regions (the Coast Mountains to the west and the Cassier, Omineca, Rocky, Cariboo and Columbia mountains in the east). Tipper (1971b) suggested that this initial build-up was comparable to present day glaciers in British Columbia. During the intense alpine phase, ice accumulation in high mountains intensified and alpine glaciers advanced into the valleys and coalesced to form piedmont glaciers; however, the flow was still highly influenced by topography. Ice advanced into the study area from the Cariboo Mountains in a west-southwestern direction (Plouffe *et al.* 2011a). Glacier advance was marked by increased sediment accumulation. During the mountain ice phase, glaciers flowed out of the mountains, advancing over and covering the Interior Plateau, but the flow was still largely controlled by topography. During the final continental ice sheet phase, ice domes formed in the Interior Plateau with ice flow radially away from their centres and this ice sheet was no longer topographically controlled. This ice sheet was suggested to have been similar to the present day Greenland Ice Sheet (Clague & Ward 2011). However, the final stage rarely occurred and does not appear to have developed over southern British Columbia during the Fraser Glaciation (Tipper 1971 a, b; Ryder *et al.* 1991; Church & Ryder 2010).

At the maximum extent of glaciation, north easterly flowing glaciers from the Coast and southwesterly flowing glaciers from the Cariboo Mountains coalesced along a northwestward trending front over south-central British Columbia (Tipper 1971 a, b). This coalescence formed an ice divide which caused the ice to flow to the north-northwest and south-southeast at approximately the 52° parallel (Tipper 1971). The glaciers flowing from the Coast and Cariboo mountains possibly coalesced along a trend oriented northwest and likely coalesced in the regions between Kamloops and Williams Lake. The Cordilleran Ice Sheet achieved its maximum extent in south-central British Columbia between 14.5 to 14 ^{14}C ka BP (Ryder *et al.* 1991).

Deglaciation in south-central British Columbia occurred mainly by down wasting and widespread stagnation (Fulton 1991; Clague & Ward 2011) and is suggested by Ryder *et al.* (1991) to have been underway by 11.5 ka. A glacial readvance from the

Coast and Cariboo Mountains onto the Interior Plateau is postulated by Tipper (1971a, b), based on his interpretation of landforms. Tipper (1971a, b) also suggests that the glaciers readvancing from the Cariboo Mountains did not coalesce with the glaciers readvancing from the Coast Mountains and that the ice had completely left the Interior Plateau before this late glacial readvance. However, this theory of glacial readvance needs to be reconsidered based on the new field data collected as part of this study.

Fulton (1967) proposed a four-stage model of deglaciation for central British Columbia. The first phase is the active ice phase. Ice flow continued through the valleys but lessened as ice thinned. The next phase is the transitional upland phase, where regional flow continued through valleys; however the highest peaks became ice free (Fulton 1991; Clague & Ward 2011). The third phase is the stagnant ice phase. During this phase ice still flowed but was confined to the valleys with adjacent uplands being ice free. The fourth phase is the dead ice phase where ice in the valleys became so thin, it no longer flowed and widespread stagnation occurred within the Interior Plateau (Fulton 1991; Clague & Ward 2011). This style of deglaciation resulted in upland areas becoming ice free before the valleys, blocking drainage and forming numerous glacial lakes (Fulton 1991). As a result, glacial retreat is marked by accumulation of glaciolacustrine and deltaic (clay, silt and sand) sediments (Clague 1987). The Interior Plateau was ice free by 9.5 ^{14}C ka BP (Stumph *et al.* 2000).

1.3.7. Objectives

This research project is part of the Geological Survey of Canada's Targeted Geoscience Initiative program (TGI-4). The main objective of this program is to provide the mining industry with tools for effective exploration for buried mineralization in central British Columbia (Anderson *et al.* 2012). The main objectives of this thesis are:

i) produce a 1:50,000 scale surficial geology map of the Mount Polley region to place the till composition (mineralogy and geochemistry) within a glacial geomorphological context;

ii) reconstruct the glacial history of this region based in part on the mapping of the surficial geology elements (sediments and landforms); and

iii) map and characterize the till geochemical, mineralogical and lithological signature of the Mount Polley deposit; in doing so, establish potential ore and pathfinder elements and porphyry indicator minerals (PIMs) present in till that are indicative of Cu-Au mineralization eroded and dispersed down-ice from Mount Polley.

This thesis will contribute towards the geoscience mandate of TGI-4 by defining the geochemical and mineralogical signature of Cu-Au porphyry mineralization in till. The 1:50,000 surficial geology map covers portions of NTS maps sheets 093A/05, 093A/06, 093A/11 and 093A/12. It was produced using aerial photo interpretation followed by ground truthing. The surficial geology map outlines the different types of sediment and their genesis in this region. It includes the following sediment categories: till, glaciofluvial, glaciolacustrine, lacustrine, alluvial, and colluvial sediments as well as organic and anthropogenic deposits. In terms of building material, till deposits can be used as bulk fill, glaciofluvial sediments are an aggregate resource and glaciolacustrine deposits can be used a lining for tailings ponds; this will be beneficial for future infrastructure development projects at the mine site or in the Likely region. The surficial geology map can also be used for slope stability studies and natural hazard potential in this region. Further, the glacial history presented in this thesis is reconstructed using information collected during surficial mapping and interpretation of the stratigraphic units. Reconstruction of the glacial history in this region will further improve on our understanding of the regional events of Fraser Glaciation. This thesis also includes a comprehensive study of glacial dispersal from the Mount Polley deposit based on the till geochemistry and mineralogy. The geochemical and mineralogical data derived from Mount Polley will improve our understanding of the signature of porphyry mineralization in till. Data from this research will establish potential pathfinder elements and PIMs at Mount Polley, one of which (epidote) has not been used previously in exploring for porphyries. In doing so, this study will provide improved techniques to the mining industry to explore efficiently for porphyries in British Columbia and other glaciated regions.

1.3.8. Thesis structure

The objectives presented in the last section will be addressed in the chapters that follow. Chapter 2 focuses on the surficial deposits and glacial landforms present in the study area. It briefly discusses previous mapping conducted in this region, followed by an outline of the methodology used for creating the surficial geology map. Chapter 3 reconstructs the glacial history of the study region. It incorporates information presented in chapter 2 on the surficial deposits as well as ice-flow measurements and Quaternary stratigraphic units to reconstruct the glacial history as well as the later Holocene environment. Chapter 4 focuses on the results of the till geochemistry, mineralogy and pebble lithology for the regional till sampling survey. Chapter 5 summarizes the main findings of the thesis. Lastly, recommendations on future follow up work that may be conducted in this region are also proposed.

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2. Surficial geology of the Mount Polley region

2.1. Introduction

This chapter presents the surficial geology of the study area. It begins with a summary of the previous work conducted, followed by the methodology used to identify the geomorphic and textural features, the units present and a summary of the mapping component. Information of interest (i.e. information useful pertaining to infrastructure development and hazard analysis) will be presented in chapter 5. This chapter is also incorporated into the reconstruction of the glacial history (chapter 3).

2.2. Previous work

Reconnaissance mapping was first conducted by Tipper in 1971 for central British Columbia. This mapping provided ice flow patterns based on drumlinoids visible on aerial photographs. An approximate distribution of till, glaciofluvial and glaciolacustrine deposits and limit of late glacial advances were also presented. As part of his MSc thesis work, A. Bichler produced a terrain map following the BC classification system for map sheet 093A12 (Bichler 2003; Bichler & Bobrowsky 2003).

2.3. Methods

Surficial materials and geomorphic expression were delineated on coloured air photos (1:15,000 and 1:30,000 scale) using a stereoscope. Google Earth® and DEM imagery (retrieved from Geobase.ca) were also utilized to aid interpretation. Ground truthing was conducted by truck and traverse during May and June, 2013, where road cut exposures were documented in Global Mappers™ and GanFeld (Shimamura et al. 2008).

2.4. Results

This section will present the results of the surficial mapping component. Units on the surficial geology map include unlithified surficial sediments and bedrock.

2.4.1. Map legend

The closed legend is prepared using the GSC's mapping protocol as outlined in Deblonde *et al.* (2014). Each polygon is described by a single map unit designator (Fig. 2.1).

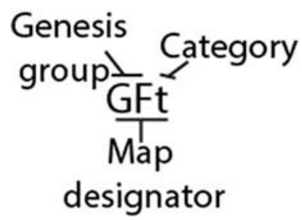

Figure 2.1: Single unit polygon label, modified after Deblonde et al. (2014).

Each map unit description is given starting with the map unit name, followed by the genesis, grain size, and morphology (Deblonde *et al.* 2014). The surficial geology map is included as Appendix A.

2.4.2. Pre-Late Wisconsinan bedrock

Exposed bedrock is denoted by “R” and is extremely rare in the study area (only 1 polygon mapped in the south-central portion of the map). An “R” polygon denotes a region dominated by bedrock outcrop with a rare thin cover (1 m max) of unconsolidated sediments, mostly present in depressions. The onsite symbol (x) is used in places where outcrops are visible on aerial photographs but are too small to be mapped as polygons. They were mapped at high elevations and at steep slopes adjacent to valley sides. Bedrock is predominantly volcanic with a few intrusive and sedimentary units (See bedrock geology map Fig. 1.3). The volcanic units are prone to failure as exemplified by several major landslide occurrences along the Cariboo River valley and Beaver valley and will be discussed under “colluvium”.

2.4.3. Late Wisconsinan deposits

Till

The till mapped in the study area is grey colored with a silty sand matrix and a pebbly to cobbly framework (clast component approximately 10-20%) with boulders present throughout. It has a massive, matrix supported structure, moderate to high compaction, weak to moderate jointing and moderate fissility. The till is identified as basal till (denoted by “T”). Only one stratigraphic unit of basal till is identified in the study area and it is representative of the Fraser Glaciation. It is usually directly overlying bedrock; however, close to the Quesnel River valley, the till is underlain by advance phase glaciolacustrine sediments.

Till blanket (“Tb”) refers to regions where the till cover follows and partly masks the underlying bedrock topography. In those areas, till thickness is generally greater than 2 m. Till blankets are mapped in valley bottoms and uplands at elevations up to 1200 m a.s.l. Till exposures, up to 20 m, have been observed in the study area (Fig. 2.2).

Till veneer (“Tv”) is less than 2 m thick, and completely reflects the underlying bedrock topography without masking the irregularities of the underlying substrate. It is mapped at high elevations and moderately steep slopes with abundant bedrock outcrops.

Figure 2.2: ***Till section 8 m high at sample site 12PMA092.***

Regions mapped as streamlined till (Ts) are underlain by till marked by a combination of streamlined landforms including flutings, drumlins and crag-and-tails. In those areas, till is generally greater than 2 m thick. Streamlined till is prevalent in the southern portion of the map sheet and indicative of a northwestward ice-flow. Flutings and crag-and-tail features, mapped in the southeastern portion of the study area provide evidence for a southwest and westward flow as well. Hummocky till (denoted by “Th”) is mapped in regions with hummocky to rolling topography and till thickness of at least 2 m. Only 2 polygons of Th have been mapped in the southeast corner of the map sheet and may include discontinuous lenses of glaciofluvial gravel. Ridged till deposits (denoted by “Tr”) are greater than 2 m thick, consist of till forming a ridged topography and consisting of moraines or crevasse fills,

Glaciofluvial erosional and depositional landforms

Glaciofluvial sediments are denoted by “GF” and represent deposition by glacial meltwater under, on top of, or in front of glacial ice. The resulting sediment deposition and geomorphic characteristics are dependent on the sediment flux, presence/absence of buried ice as well as deposition relative to the ice-margin (*cf* Bennett & Glasser 2003). Generally, glaciofluvial sediments include coarse sand and gravel as well as minor diamicton; however, the sediment composition varies between landforms. Glaciofluvial sediments in the study area are mapped as blanket, veneer, plain and hummocky. Glaciofluvial landforms include eskers (discussed under on site symbols), outwash and kame terraces, and ice-stagnation topography. Landforms within ice-stagnation topography include kame terraces (which are too small to map individually), deltas, kettle and kame topography and small eskers.

Glaciofluvial sediments, less than 2 m in thickness and whose surface expression is controlled by the underlying topography are mapped as a glaciofluvial veneer (GFv). Glaciofluvial sediments, greater than 2 m in thickness and forming an undulating to flat topography are mapped as a glaciofluvial blanket (GFb). Both polygons are mapped in regions where the sediment is associated with meltwater channels. Glaciofluvial plain sediments (GFp) were mapped at the mouth of 3 meltwater channels. Glaciofluvial plain sediments range 1 to 10 m in thickness and form a flat surface.

Hummocky glaciofluvial (GFh) is designated where the sediment forms hills (hummocks) and depressions, not influenced by the underlying unit (Fig. 2.3). Hummocky glaciofluvial, associated with deglaciation, form kettle and kame topography, i.e., hummocks and depressions resulting from the melting of buried ice, and ranging from 1 to 10 m in thickness.

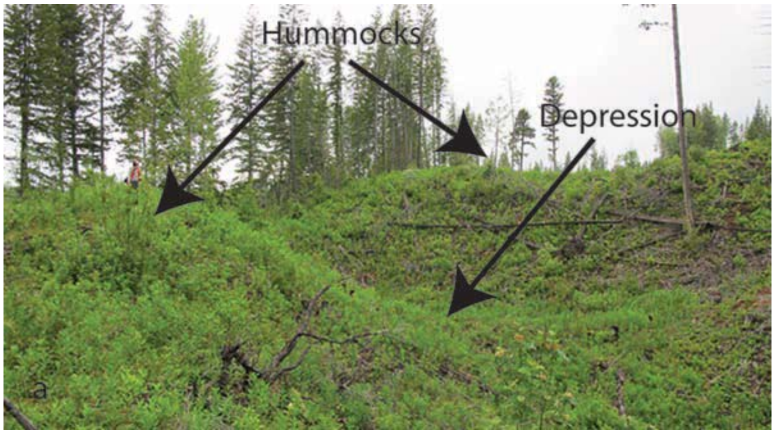

Figure 2.3: ***Hummocky topography. Relief is approximately 4 m.***

Glaciofluvial ice-contact deposits (denoted by “GFc”) include a complex of landforms which are too small to be mapped separately and include ice-contact/meltwater fed deltas, irregular kettle and kame topography, eskers, kame terraces and ablation till forming an irregular topography. The deltas and eskers are discussed under “on site symbols” and listed in Appendix A (surficial geology map).

Kame terraces (mapped as GFk) occur along valley sides and formed by glaciofluvial deposition between the glacier and the valley side. When the glacier melts, it leaves a perched, typically unpaired terrace. They have flat to gently sloping surfaces (Fig. 2.4a) with kettles and their slope steepness depends on the angle of the slope of the glacier against which the sediments were deposited (Bennett 2003; Carrivick & Russell 2013). The kame terraces mapped in the study area consist of poorly sorted coarse sand and sub-angular to rounded, cobbly to bouldery gravel as well as minor diamicton (Fig. 2.4b), ranging 1 to up to 45 m in thickness.

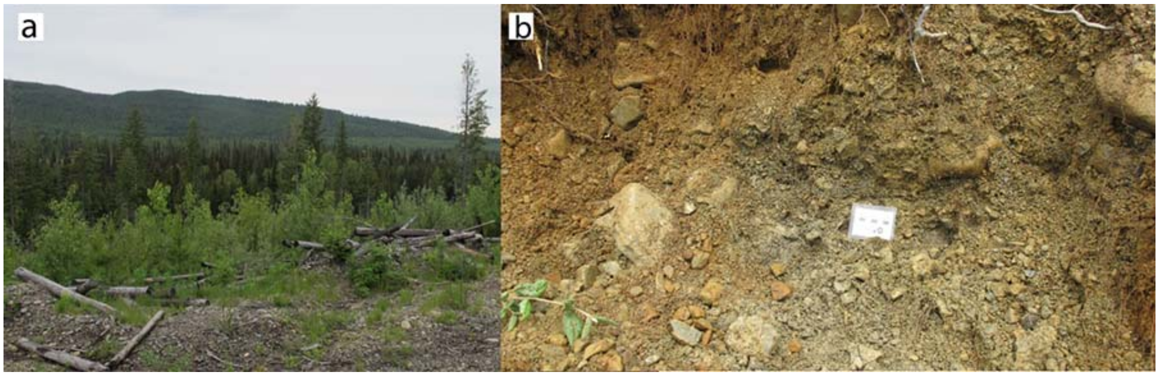

Figure 2.4: ***(a) Kame terrace with a flat surface. (b) Sediment includes poorly sorted coarse sand and sub-angular to rounded, cobbly to bouldery gravel, scale card is 5 cm.***

Ablation or melt out till results from the direct melt out of supra-glacial, en-glacial and sub-glacial sediments. The sediment deposited varies greatly ranging from coarse sand and gravel to diamicton and laminated fine sand and silt. The surface expression for melt out till is extremely variable, ranging from veneer to blanket, hummocky to rolling. Because it is only present in ice-stagnation areas, it occurs together with kettle and kame topography and is mapped under ice-contact glaciofluvial (GFc).

Glaciofluvial outwash terraces (“GFt”) are a constructional feature. These form when the ice-margin retreats and a consistent flux of sediment is deposited forming outwash plains, which are then cut by proglacial meltwater channels (cf Bennett & Glasser 2003). Glaciofluvial terraces in the study area have a paired terrace on the adjacent valley wall, a flat upper surface and form above modern alluvial terraces. Glaciofluvial terraces along the Quesnel river valley are mapped at elevations ranging between 580 m to 815 m a.s.l. Glaciofluvial outwash terraces are also mapped in the Cariboo river valleys as well as two major meltwater channels that join the Cariboo River valley in the northeast portion of the study area. A cross-section of a glaciofluvial terrace situated along the Cariboo River valley shows crudely bedded, coarse sand and gravel (Fig. 2.5a). Generally, the gravel is moderately to well-rounded and comprises pebbles to boulders (Fig. 2.5b).

Figure 2.5: ***(a) Cross-section of a glaciofluvial terrace (approximately 7 m high); (b) Sub-angular to rounded gravel.***

Glaciolacustrine

Glaciolacustrine sediments (“GL”) are composed of medium fine sand, silt and clay (Fig. 2.6). Glaciolacustrine sediments are deposited in front of or on top of the glacier by several mechanisms including suspension settling, underflow and melt out of sediment from icebergs (cf Bennett & Glasser 2003). Glaciolacustrine sediments are mapped as undifferentiated (GL), veneer (GLv) or blanket (GLb). Undifferentiated glaciolacustrine sediments (GL), mapped along Beaver valley are laminated. Of the few glaciolacustrine (veneer) polygons mapped, most of them are a result of localized ponding of meltwater in depressions. Glaciolacustrine sediments are observed overlying till units in many areas (e.g. GLv mapped adjacent to Little Lake and GLb mapped along Beaver valley), and therefore, provide evidence of the presence of glacial lakes formed during glacial retreat. Glaciolacustrine sediments have been observed to underlie till units in the Quesnel and Cariboo River valleys (Bichler 2003). The failure of the glaciolacustrine sediments in these valleys has resulted in large landslides, which will be discussed under “colluvium”.

Figure 2.6: ***Close view of the glaciolacustrine laminated silt and clay deposit adjacent to Beaver Valley. Knife is 21 cm.***

2.4.4. Holocene deposits

Colluvium

Colluvium (“C”), refers to all sediment deposited as a result of downslope movement under the influence of gravity. Colluvium mapped in this region is mainly associated with paraglacial sedimentation and landslides associated with advance-phase glaciolacustrine sediments. Paraglacial refers to the immediate post-glacial period where sedimentation is conditioned by glaciation (Church & Ryder 1972). It is a period of increased sedimentation with reworking of glacial sediments by alluvial and mass wasting processes, resulting in the formation of landforms such as paraglacial fans, colluvial aprons, etc. (cf Slaymaker 2009).

The composition of colluvium is directly dependant on the source material and varies throughout the study area. For example, rotational slumping of advance-phase glaciolacustrine sediments (adjacent to Quesnel River valley) overlain by till and glaciofluvial sediments result in colluviated till, glaciofluvial and glaciolacustrine deposits (Fig. 2.7). Post-glacial failure in volcanic and sedimentary bedrock result in a diamicton composed of angular fragments of the same bedrock unit (e.g. southern portion of Beaver lake valley).

Figure 2.7: ***Rotational slump resulting from the failure of underlying glaciolacustrine sediments.***

Colluvium veneer ("Cv"), is topographically controlled colluvium less than 2 m thick? It typically represents weathered bedrock accumulating on steep slopes and valley walls. Colluvial blanket (Cb) is greater than 2 m but still topographically controlled. Colluvial aprons are denoted by "Ca" and prevalent at valley bottoms. Landslide deposits from mass wasting events such as rotational and translational landslides are all mapped as "Cz".

Alluvial deposits

Alluvial sediments are denoted by "A" and refer to fluvially transported materials. These include primarily sand and gravel. Alluvial landforms mapped in the study area include plains, terraces and fans.

Alluvial fans (Af) are fan-shaped features, where increased sedimentation results from the change in gradient from the downslope water flow from the apex to the toe of the fan. Alluvial fans result from sediment input by modern drainage and occur along valley floors, in places, building out onto floodplains. Alluvial fans in the study area are composed of medium sand and gravel ranging between pebble to cobble and some boulders, all of variable roundness (Fig. 2.8). Alluvial fans are abundant within the Beaver valley, resulting from sediment transport by streams that were initially deeply incised meltwater channels. Alluvial fan sediments appear to have been utilized as a granular resource at least at one locality in the study area (Fig. 2.8).

Figure 2.8: Exposed sand and gravels from a cross-section of an alluvial fan along Quesnel Lake. Alain (1.9 m) for scale.

Alluvial plains (Ap) are floodplain deposits which accumulate in the river channel (Fig. 2.9). Alluvial plain deposits include sand, silt and minor granule to pebble sized, sub-rounded to well-rounded gravel. Alluvial plains present in the Cariboo and Quesnel river valley also contain minor organics. However, the alluvial plains mapped in Beaver Valley are fine-grained and have been cultivated into farmland.

Figure 2.9: Alluvial flood plain in Beaver valley.

Alluvial terraces (At) form adjacent to Quesnel and Cariboo rivers, Opheim and Poquette lakes (related to small creeks connecting the lakes) as well as two large meltwater channels present in the northeast (Fig. 2.10).

Figure 2.10: Alluvial terrace alongside Quesnel River valley.

Alluvial terraces form as a result of river incision of previous floodplain sediments and lie above the present floodplain and channel and lie lower than kame and glaciofluvial outwash terraces. Modern alluvial terraces range in elevation from 730 m to 870 m a.s.l along Quesnel River and between 640 m to 690 m a.s.l. along Cariboo River. Alluvial terraces exposed adjacent to Cariboo River valley show planar bedding consists of alternating layers of medium coarse sand and sub-rounded to well-rounded pebbles and cobbles (Fig. 2.11).

Figure 2.11: ***Alluvial terrace sediments; alternating layers of coarse sand and rounded gravel from an exposure along the Quesnel River valley. Scale card is 5 cm long.***

Lacustrine deposits

Modern lacustrine deposits (L) consist of medium to fine sand, silt and organics. Beach sediments (primarily sand) are mapped alongside Quesnel Lake near modern lake level. Lacustrine sediments surround a few other modern lakes, including Nina Lake (east of Quesnel Lake). However, they are extensive enough to be mapped in only a few areas.

Organics

Undifferentiated organic deposits are represented by “O” and mapped without any assigned surface expression and are dominated by fens with lesser bogs with shallow ponds. Regions mapped as organics are covered mainly by grasses, mosses and shrubs with sparse to no trees (Fig. 2.12). Organics mapped in the study occur in old meltwater channels and on low-lying, poorly drained sediments, i.e. till.

Figure 2.12: Fen.

Anthropogenic deposits

Undifferentiated anthropogenic deposits are designated as “H” and include active and inactive gravel pits, placer operations and the open pits and mine tailings. The four main anthropogenic occurrances include the Bullion pit, Miller pit, Ogden Mine placer operations and the Mount Polley Mine. Several other smaller placer operations do exist as well as active and inactive gravel pits and are denoted by onsite symbols (See Appendix A).

2.4.5. Onsite symbols

Ice flow indicators

Both large and small-scale ice-flow indicators have been mapped in the study area. Examples of large-scale indicators visible on aerial photographs include drumlins, flutings, crag and tail, drumlinoid ridges and fluted bedrock (known and unknown ice-flow direction).

Large scale ice-flow indicator features include uni-directional drumlins, crag and tail and fluted bedrock (Appendix A). Different line symbols were used to represent each one of these landforms. The line symbol was drawn on the aerial photograph to the length of the actual landform. In most instances, one line was drawn for each landform. In rare places, where the density of streamlined landforms was too high to be clearly depicted at the scale of mapping (1:50 000), one line was drawn to represent two landforms. Therefore, the length of the line symbols and their density on the map reflect their actual scale and abundance.

Crag and tail consist of a resistant bedrock knob making up the “crag” followed by the “tail”, which extends down-ice and is comprised of till (Benn & Evans 2010). Drumlins are uni-directional, elongate and streamlined “whaleback” shaped hills formed by the glacial erosion and deposition (Mickleson & Winguth 2013). Drumlins vary in length from tens to several hundreds of metres, where the stoss represents the up-ice and lee represents the down-ice direction of ice-flow (Rea 2007; Mickleson & Winguth 2013). Similarly, flutings are streamlined landforms, composed of till but with equal thickness and length on the stoss and lee sides, resulting in a bi-directional feature. They are also characterized by high length to width ratios.

Small-scale ice-flow indicator features include bi-directional striations and grooves as well as uni-directional rat tails and roches moutonneé (Fig. 2.13). A total of 19 stations with several ice-flow indicators have been recorded in the study area. At most sites, evidence for a single ice-flow has been recorded (i.e. to the northwest); however, at a few sites, evidence for an older southwestward and the transitional westward flow has also been recorded. At each outcrop (exposed along road cuts), the vegetation and topsoil were removed, the outcrop cleaned with water and brush, followed by identification and orientation measurement of any ice-flow indicator features present. At sites where 2 or more ice-flow measurements were recorded, cross-cutting relationships were established based on the position of the indicator. For example, at station 13PMA025, evidence for earlier southwestward flow was indicated by the presence of faint striations present on the protected side of the outcrop (i.e. protected from the later northwestward flow) (*cf* McMartin & Paulen 2009).

Striations are marks of abrasion eroded subglacially into the bedrock or large clasts embedded in till and therefore acting as substrate. Striations can also form on clasts during glacial transport within the glacier. These marks of erosion are made by hard rock fragments embedded at the base of the glacier (Fig. 2.13) (Benn & Evans 2010). Rat-tails are teardrop shaped linear features eroded down-ice from resistant rock and providing a uni-directional flow orientation (Fig. 2.13). Roches Moutonnée are erosional landforms where the up-ice side or stoss side is streamlined and the down-ice or lee side is plucked by glaciers (Ben & Evans 2010).

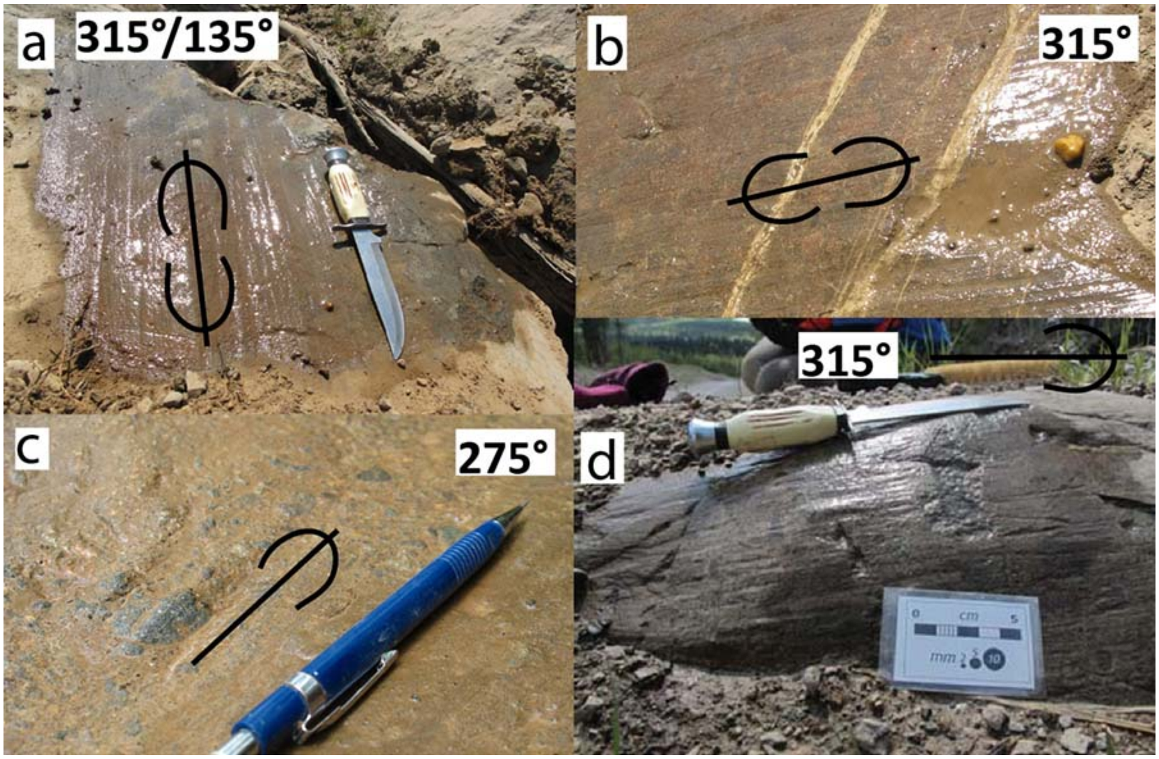

Figure 2.13: ***Ice -flow indicator features documented throughout the study area. (a) bi-directional striations and grooves; (b)bi-directional striations; (c) rat-tail; (d) mini roche moutonnee' with grooves and striations rat-tails on a boulder.***

Anthropogenic

Anthropogenic symbols include mine tailings, gravel pits, and open pits (bedrock quarry) (Fig. 2.14).

Figure 2.14: View of a gravel quarry.

Landslides

Landslides and slope movement have been observed in the field and on aerial photographs. They have been mapped at two broad scales: 1) large scale landslide occurrences are marked by the “landslide escarpment” symbol; and 2) smaller failures are marked by the “small landslide scar” symbol.

Glaciofluvial ice contact erosional and depositional features

Meltwater channels are an erosional feature cut by meltwater into the landscape. Three distinct types of meltwater channels are mapped in the study area: 1) sub-glacial (Nye) channels; 2) ice marginal channels; and 3) proglacial channels (Fig. 2.15). Meltwater channels cross-cut topography (mainly till but also bedrock), range several metres to a few kilometres and are oriented parallel to main ice flow direction (northwest) are interpreted as sub-glacial (Nye) in origin. Meltwater channels that form parallel to the valley walls are interpreted as lateral meltwater channels. Lateral meltwater channels forms as a result of meltwater draining along glacial margins adjacent to valley sides. They form “inset sequences” that document the gradual retreat of a glacier (Benn & Evans 2010; Kehew *et al.* 2013). Larger meltwater channels, ranging a few hundred metres in width and several kilometres in length which were cut through thick till cover and are now wide enough to form small valleys, are identified as proglacial meltwater channels. In some cases, these may have originated as Nye channels. Infact, some of the largest proglacial channels are now modern day lakes, for example, Poquette lake which has deposits of kame and alluvial terraces as well as fluvial and colluvial fans.

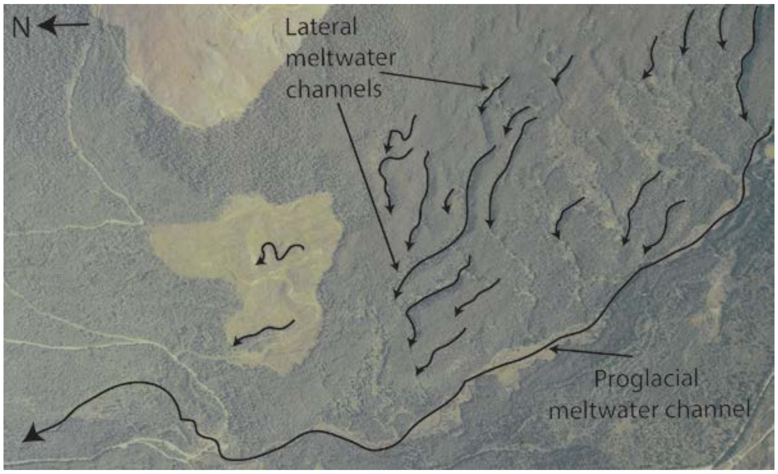

Figure 2.15: ***Aerial photo (1:15,000 scale) from the northeast portion of the study area with mapped proglacial and lateral meltwater channels mapped in the northeast portion of the study area.***

Two ice-contact deltas are mapped in the study area (Fig. 2.16). The first delta is mapped adjacent to Little Lake and the second delta is mapped along Beaver Valley. Overall, both deltas are composed of moderately to well-rounded, pebbly to cobbly gravel, with gently dipping foreset beds to the west southwest, at approximately 860 m and 740 m a.s.l., respectively.

Figure 2.16: Exposed forset beds of an ice-contact delta adjacent to Little Lake. Photograph taken looking north with C. Grondhal (1.9 m) for scale.

Eskers are sinuous ridges of moderately to well-sorted meltwater deposits consisting mainly of gravel (Benn & Evans 2010). Only one esker (with an unknown paleocurrent direction) is mapped in the northeast portion of the study area; however, small scale esker/ crevasse fill systems are prevalent in ice-stagnation topography.

2.5. Summary of the surficial geology

A 1:50,000 surficial geology map was created encompassing map sheets NTS 093A05, 06, 11, 12 as part of this thesis project with the aim of identifying surficial resources for infrastructure development, mineral exploration and to aid Quaternary geologic history interpretation. Of these, the only pre-Fraser Glaciation unit is bedrock (R). Till (T), Glaciofluvial (GF) and glaciolacustrine (GL) sediments are associated with the Fraser Glaciation. Alluvium (A) and Colluvium (C) are associated with post-glacial activity, whereas anthropogenic (H) is a result of human activity.

Bedrock is rarely exposed (mapped on extremely steep slopes) in the study area. It was eroded and moulded by glacial and post-glacial alluvial and colluvial activity. Till (T) is the most common surficial material mapped and was deposited during Fraser Glaciation. It occurs as streamlined till in the uplands, veneers on moderately steep slopes, and till blankets in lowlands. In many places, till is mantled by deglacial (glaciolacustrine, glaciofluvial) and post-glacial (alluvial and colluvial) sediments. Glaciofluvial sand and gravel is mapped as glaciofluvial terraces and as ice-contact deposits. Glaciofluvial terraces formed as a result of meltwater incision into outwash plains and are mapped in river valleys and meltwater channels. Landforms mapped as glaciofluvial ice-contact deposits include kame terraces and kettle and kame topography. Some thin glaciofluvial sediments are also associated with meltwater channels. Overall, ice-contact deposits are dominant at valley bottoms, where the ice-mass stagnated as is typical of the Interior Plateau of British Columbia.

Proglacial, lateral and sub-glacial Nye channels are mapped throughout the study area. Nye channels are abundant, cross-cutting topography and in most cases are parallel to the dominant ice-flow direction, i.e. to the northwest. In some cases, Nye channels were enlarged enough to form pro-glacial meltwater channels in valley settings. Poquette Lake and two meltwater channels mapped in the northeast portion are excellent examples of pro-glacial meltwater channels.

Glaciolacustrine sediments are mapped as veneer, blanket and hummocky and are composed of fine sand, silt and clay, exhibiting laminations at some exposures. Glaciolacustrine blankets are mapped in the valley bottoms of Beaver Valley. Glaciolacustrine veneers mapped in the study area may have resulted from local ponding of meltwater in topographic depressions underlain by non-permeable substrate.

Colluvium mapped in the study area is a result of post-glacial mass-wasting activity and failure of advance phase glaciolacustrine sediments near Quesnel River valley. Colluvium is mapped as a veneer at high elevations and on steep slopes. Mass-wasting, resulting from the destabilization of valley walls is mapped as landslide deposits, aprons, blankets and hummocky colluvium in the Quesnel and Cariboo river valleys and Beaver valley.

Alluvial sediments associated with Holocene activity are constrained to the river valleys and include landforms such as alluvial terraces, floodplains and fans. Lastly, undifferentiated organic deposits (including bogs, fens, marshes etc.) cover a small portion of the study area and are associated primarily with poorly drained till.

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3. Glacial history of the Mount Polley Mine region

3.1. Introduction

This chapter presents the inferred glacial history of the study area, based on the interpretation of stratigraphic sections, paleoflow measurements on bedrock outcrops and in aerial photographs, and the distribution of glacial landforms and sediments presented on the surficial geology map (Chapter 2). This reconstruction incorporates previous studies conducted within and adjacent to the study area as well as across south central British Columbia. This chapter begins with an overview of previous ice-flow and stratigraphic studies completed within or near the study area, followed by the methodology for measuring ice-flow indicators and description of the stratigraphic sections. Finally the stratigraphy and paleoflow measurements are integrated with the surficial geology map to interpret the glacial history of the study area.

3.2. Previous work

3.2.1. Ice flow

Extensive reconnaissance scale geomorphic investigations were conducted by Tipper (1971 a, b) within the Interior Plateau. Target regions included the McLeod (093J), the Prince George (093G), the Quesnel (093B), the Taseko (093O), the Nechako (093F), the Bonaparte Lake (092B), the Mount Waddington (092N), and the Anheim Lake (093C) map areas. Also the surrounding regions of Whitesall Lake, Bella Coola, Ashcroft, Kamloops Lake, Fort Saint James, McBride and Quesnel Lake (Tipper 1971b). Tipper's main objectives were to infer the glacial history of the Interior Plateau based on the interpretation of the geomorphic features mapped in the region. Ice-flow movement in the study region was determined based on the aerial photo interpretation of macro-scale landforms such as drumlins, and field measurement of striations. Deglaciation pattern was determined based on the mapped meltwater channels, eskers and ablation till (Tipper 1971 a, b).

Some of Tipper's most important findings included the pattern of glaciation and deglaciations as well as the suggestion of the occurrence of a short-lived late glacial readvance from the Coast and Cariboo Mountains. The pattern of glacial advance and retreat has been discussed previously in chapter 1. A summary of the readvance and retreat is presented here.

Tipper (1971 a, b) postulated that a late glacial readvance from the Coast and Cariboo mountains occurred which resulted in ice tongues extending from the mountains back onto the Interior Plateau. He also suggested that the ice had completely left the Interior Plateau before the late glacial readvance from the Coast and Cariboo Mountains occurred. Tipper further suggests that the glaciers readvancing from the Cariboo Mountains flowed westwards from Quesnel Lake. However, their extent was limited and a second coalescence did not occur, based on the terminus features mapped just west of Williams Lake. Deglaciation in these low relief regions was topographically controlled, resulting in thinning of the ice followed by isolated ice masses stagnating independently of the main glacier body. Deglaciation near the Cariboo Mountains proceeded with frontal retreat of the ice tongues in the valleys as the glacier retreated back into the mountain valleys (Tipper 1971 a, b).

Tipper's (1971 a, b) inferred glacial history of the Interior Plateau was incorporated into a study of the local glacial history of the Bonaparte map area, located approximately 120 km to the south of the Mount Polley region, by Plouffe *et al.* (2011). They demonstrated that at the onset of the last glaciation the Bonaparte Lake map area was covered by ice flowing in a westerly to southwesterly direction. This first phase of ice flow resulted from advancing glaciers from the Cariboo Mountains. This was followed by flow to the south derived from an ice-divide or a zone of coalescence between glaciers derived from the Coast Mountains to the west and the Cariboo Mountains to the east. This zone was located approximately around the 52° latitude and likely formed at glacial maximum (Tipper 1971 a, b; Plouffe *et al.* 2011). North of 52° latitude, the second phase of ice flow associated with glacial maximum was generally to the north to northwest (Tipper, 1971a, b).

Ice-flow features including striations, drumlins, flutings and crag and tails have also been mapped in part of the study area (map sheet 093A/12) by Bichler & Bobrowsky (2003). More recently Ferbey & Arnold (2013) published a compilation of ice-flow indicators documented in published and unpublished maps for British Columbia.

3.2.2. Stratigraphy

Several stratigraphic sections have been studied proximal to and within the study area. These include sections in the Fraser River valley region near Quesnel, approximately 85 km northwest of Likely (Clague 1988) and in Williams Lake, approximately 55 km south west of Likely (Clague 1987). The stratigraphic sections at both of these locations provide evidence for the last two glaciations (penultimate and Fraser) and the Olympia non-glacial Interval. Typical sequences at these exposures contain an older till unit, correlated to the penultimate glaciation, overlain by advance phase glaciofluvial and glaciolacustrine sediments associated with Fraser Glaciation (Clague 1987; 1988). These units are overlain by till deposited during the Fraser Glaciation, followed by retreat phase glaciolacustrine sediments (Clague 1987; 1988).

Other stratigraphic studies have been conducted by Clague (1991) to estimate placer gold potential in the Quesnel and Cariboo river valleys. These sections consisted of 7 units representing the penultimate and Fraser glaciations and associated non-glacial sediments. Sections included till associated with the penultimate glaciation, overlain by deglacial glaciolacustrine sediments. These sediments were overlain by organics representing the Olympia non-glacial interval, followed by an advance phase glaciofluvial fluvial sand and gravel unit that grades into glaciolacustrine sediments. This is overlain by till of the Fraser Glaciation. Deglacial glaciolacustrine sediments underlie the post-glacial Holocene sediments, primarily alluvium and colluvium.

Within the study area, a stratigraphic section at the Bullion pit, located a few kilometres northwest of Likely, provides evidence for the penultimate and Fraser Glaciations and the Olympia non-glacial interval (Clague *et al.* 1990). The sequence consists of a diamicton containing striated clasts, representing the penultimate glaciation. This is overlain by mud, sand and gravel indicative of deglacial ice-contact conditions. These ice-contact sediments are overlain by a 2.5 m thick unit of organic rich sand, silt and gravel containing twigs and branches. These provided ages of 46,300 +/- 1740 to 36,840 +/- 430 ^{14}C years BP. The interstadial organics were overlain by well-sorted glaciofluvial sand and gravel representing advance phase glaciofluvial outwash, followed by a unit of laminated mud indicating glacial lake settings. The glaciolacustrine sediments are overlain by a second diamicton, described as massive to weakly stratified and containing striated clasts, representing till of the Fraser Glaciation (Clague *et al.* 1990).

Stratigraphic sections within map sheet 093A/12 were described by Bichler (2003) with the objective of studying the surficial geology, glacial history and the landslide processes in the Quesnel River valley. Incorporating the work of Clague *et al.* (1990), Bichler described the local glacial history and identified six distinct units correlated with the penultimate and Fraser glaciations and the Olympia interstade. The oldest unit is a till consisting of a clayey silt matrix and 25-35% clasts and correlated to the penultimate glaciation. The overlying unit is a poorly sorted, irregularly bedded sand and gravel with pockets of fine-grained material, representing an ice-proximal setting. This is overlain by advance phase glaciolacustrine sediment at least 90 m thick and present at an approximate elevation of 730 m a.s.l. Bichler (2003), divides these glaciolacustrine sediments exposed along the Quesnel River valley into three distinct units (units D, E, and F). Within these units, unit D (lowermost) is a coarsening upwards succession of sub-horizontal, rhythmically bedded, sand, silt and clay. Within unit D is Unit E, a 20 m thick succession of intertonguing sands and gravel (ranging from pebble to boulder sized) interpreted as subaqueous gravity flow deposit). The third unit overlying unit D and E is unit F, a 10 m thick massive to laminated, silt and clay (Bichler 2003). This is capped by the till of the Fraser Glaciation. Unit F is a silty clay diamicton with 30% clasts. This unit is well compacted, shows moderate fissility and jointing. Finally, overlying the till unit is a moderate to poorly sorted, crudely stratified glaciofluvial gravel with lenses of sand. This retreat phase glaciofluvial unit is overlain by alluvial sediments consisting of a sandy matrix and imbricated cobbly gravel, associated with the Holocene period.

3.3. Methods

Ice-flow indicator measurements were taken during field work in May 2012 and May-June 2013. Exposed stratigraphic sections were documented during May-June 2013. Field work was conducted mainly by truck on a well-developed forest logging road network with limited foot traverse. Data collected for ice-flow indicator measurement and stratigraphy was recorded in Global Mappers® and GanFeld (Shimamura *et al.* 2008).

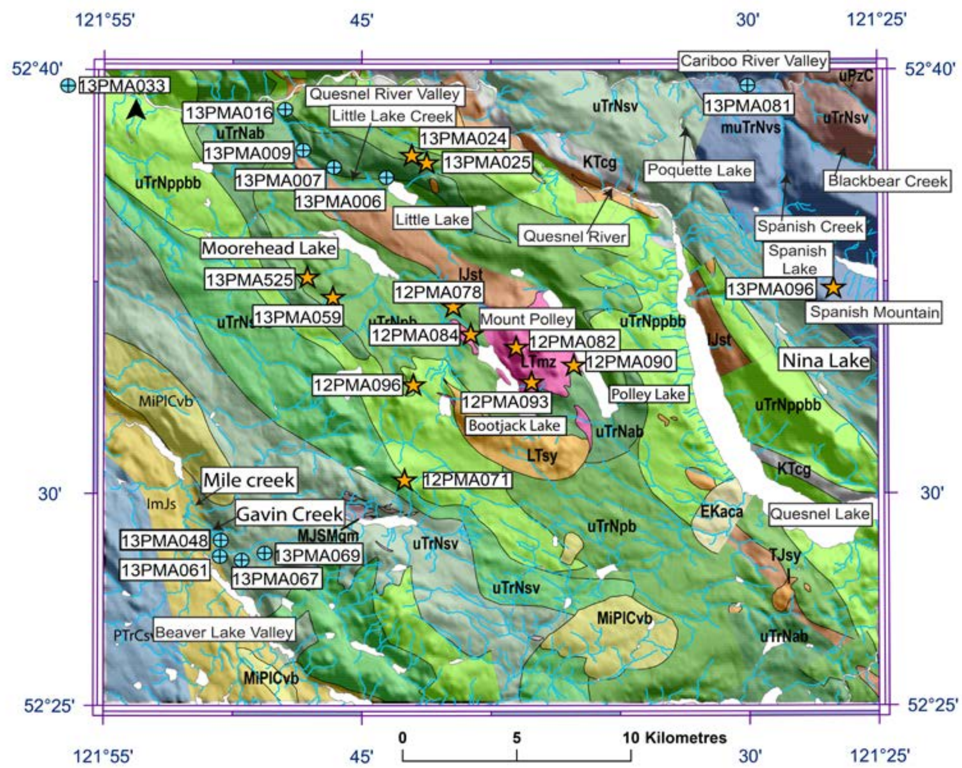

Figure 3.1: *Ice-flow measurements and stratigraphic sections documented in the study area. The orange stars indicate ice-flow measurement stations and the blue circle indicate stratigraphic section site.*

3.3.1. Ice-flow measurements

As indicated in Chapter 2, orientation of macro-scale landforms was determined on aerial photographs. Orientation of micro-forms was measured on 19 outcrops. Small scale landforms include striations, grooves, rat-tails and small roches moutonnées. At each site, any sediment, vegetation, roots or lichen was removed to increase the exposed area. The outcrop was then cleaned with a brush and sometimes water before the orientation of any preserved bi-directional striations and grooves as well as uni-directional rat tails and roches moutonnées were measured using a Brunton compass. In the case of rat tails, ice-flow direction is towards the “tail end” of the feature, whereas, in the case of roches moutonnées, ice-flow movement is towards the lee-side of the feature.

Information collected at each outcrop included elevation, GPS co-ordinates, types and abundance of erosional features, relative age relationship (in the case of multiple flow indicators), relative position on the outcrop as well as photographs. The complete data set is tabulated in Appendix B1.

At most sites, a single ice movement was determined based on the orientation of the most common ice-flow feature (striations). A few sites had indicators with two or three distinct orientations, i.e. with orientations differing by more than 10°. At these sites, the age relationship between the two or three sets of glacial flow indicators was based on the presence of older striations preserved in the lee side (protected faces) of bedrock surfaces striated by the younger ice movement (cf McMartin & Paulen 2009).

3.3.2. Stratigraphy

All stratigraphic sections described here were unconsolidated sediments exposed in road cuts and gravel pits. Exposures were located (latitude, longitude and elevation) with a GPS. Stratigraphic units were distinguish from each other and described according to sediment grain size, clast percent, thickness, lateral continuity, sedimentary structures, and contact relationship between adjacent units. Stratigraphic sections were sketched in a paper notebook and photographs were taken. Additional stratigraphic columns documented in the field are outlines in Appendix B2.

3.4. Results

3.4.1. Ice flow

Macro-scale landforms

Macro-scale landforms oriented east-west and southwest-northeast are mapped in a few topographically sheltered sites, which are indicative of ice-flow movement during glacial advance; however, they are rare and only preserved in the southeastern corner of the study area. Abundant northwest/southeast oriented macro-scale landforms, representing ice-flow movement during glacial maximum and early deglaciation are mapped in the region (See Chapter 2).

Micro-scale landforms

Ice-flow measurements were taken at 19 stations. From these measurements, two major ice-flow trends and their relative ages have been determined; an older west southwestward flow, followed by a younger northwestward flow. Grooves were observed at 16 sites, whereas rat-tails were observed at only 2 sites. At 3 sites, more than one set of glacial striations was noted with different orientations, indicative of ice-flow to the southwest and northwest. At one site (13PMA059), striations indicative of a southwestward, westward and northwestward flow were documented. At all of these sites, chronology of the ice movements was established using criteria identified in the “methods” section.

In summary, ice-flow indicators representative of the west, southwestward movement included striations, grooves and at one site, a rat-tail. Orientation of these indicators ranged 250°-275°. Indicators of this earlier ice-flow were measured off of side slopes and protected sides of the outcrop, i.e. protected from the later northwestward flow. At site 13PMA059, the westward indicators are interpreted to be an intermediate phase of ice movement between the southwest and northwest flow. Finally, all striated sites showed evidence of ice movement to the northwest, ranging approximately 290° to 330°.

Figure 3.2: ***Micro-scale ice-flow indicator features measured in the study area. (a) Several, well-defined striations and grooves preserved on the stoss slope. Knife is 23cm; (b) Rat-tail and several striations indicative of a westward flow. Pencil is 13 cm; (c) Striations and grooves oriented northwest. Scale card is 5 cm; (d) Several striations and grooves oriented west.***

3.4.2. Stratigraphy

As part of this study, a total of 16 sections have been logged. Out of those, nine sections expose key stratigraphic units that serve to interpret the glacial history. These include 13PMA006, 13PMA007, 13PMA009, 13PMA016, situated in the north central, 13PMA033 in the northwest portion of the study area, section 13PMA081 in the northeast and 13PMA061, 13PMA067, 13PMA69 and 13PMA048 in the southwest.

For each site, units are assigned a unit number, location, general site description and photographs followed by detailed unit description and inferred depositional environment. The unit numbers at each site relate to the regional stratigraphy presented in figure 3.3. Not all units may be present at a single section, so for example some sites may have stratigraphic sequence starting at Unit II or Unit III.

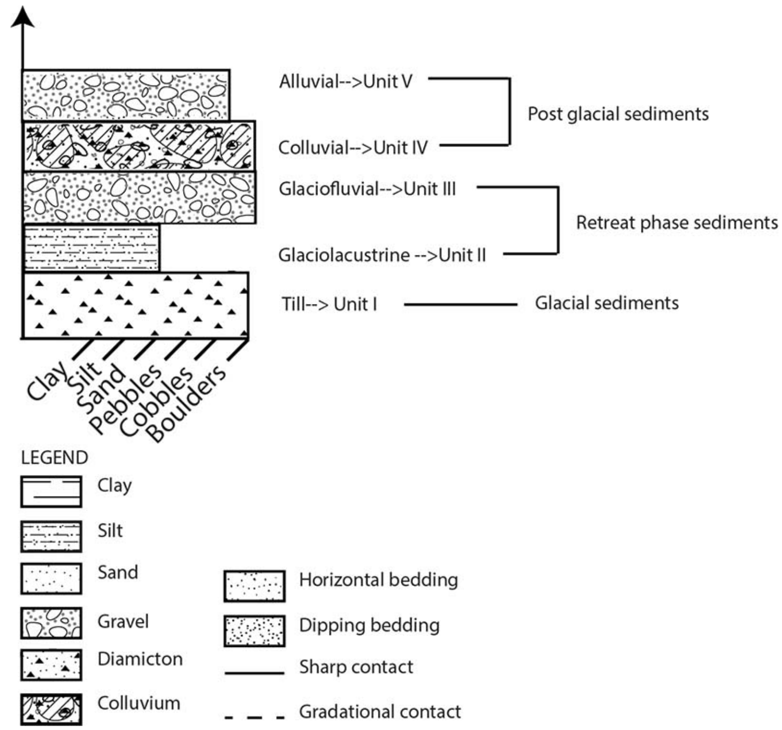

Figure 3.3: ***Idealized glacial and retreat phase sediment sequence. Units are shown in their relative stratigraphic position but their thickness is not drawn to scale.***

Site 1: 13PMA006

This station is located at the site of a large gravel pit adjacent to Little Lake, approximately 850 m a.s.l. (Fig.3.1, 3.4). The section is 30 m high, and comprises a clast supported, medium coarse sandy gravel. Clasts are dominantly sub-rounded and of pebble size with few cobbles and boulders. Exposed 11 m high foreset beds (photographed below) are striking 120°, dipping 30° and their dipping direction is 210° (southwest).

This landform is a Gilbert style delta. The meltwater feeding this delta may have been connected to an ice mass further east in the Little Lake valley. The elevation of the foreset beds suggest that lake levels at this area reached a minimum level of a least 875 m a.s.l. when this delta formed.

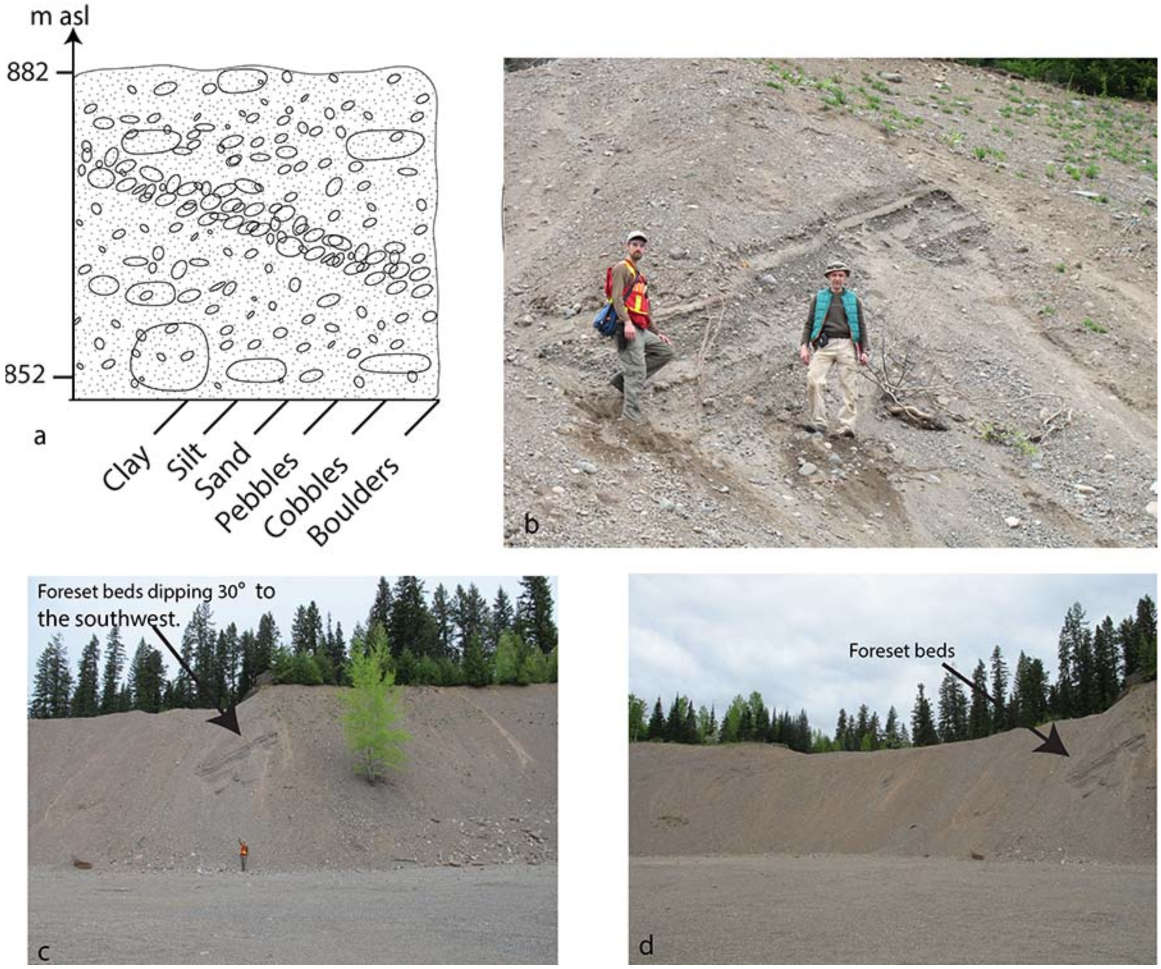

Figure 3.4: ***Cross section of the delta documented at site 13PMA006; (a) Stratigraphic cross-section reconstruction; (b) Exposed foreset beds, Alain (1.9 m) for scale; (c) View of the forest beds; (d) Bigger view of the gravel pit.***

Site 2: 13PMA007

This section is located approximately 840 m a.s.l. in a region of rolling topography. The ice-contact delta (site 13PMA006) is approximately 415 m to the northeast.

Unit I consists of a compact, massive, poorly sorted, matrix supported diamicton. This unit has a silty sand matrix. The clasts are pebble sized and exhibit striations. Unit I is estimated to be at least 3 m thick as the lower contact is not observed.

Based on the compactness of the diamicton and the presence of striated clasts, Unit I is interpreted as till deposited during Fraser Glaciation.

Unit II consists of a moderately sorted, very fine sand and silt of light brown color and no apparent bedding. Unit II varies 3 to 8 m in thickness. It has a gradational contact (5-10 cm) with Unit I, where the sediment transitions from silt and fine sand to silty sand matrix and granule and pebble sized clasts.

Based on the sediment composition, Unit II is interpreted as glaciolacustrine sediments. The lack of bedding may be due to the limited and poor exposure. The gradational contact between the till and glaciolacustrine sediments signifies a gradual change in deposition from sub-glacial to glacial lake environment.

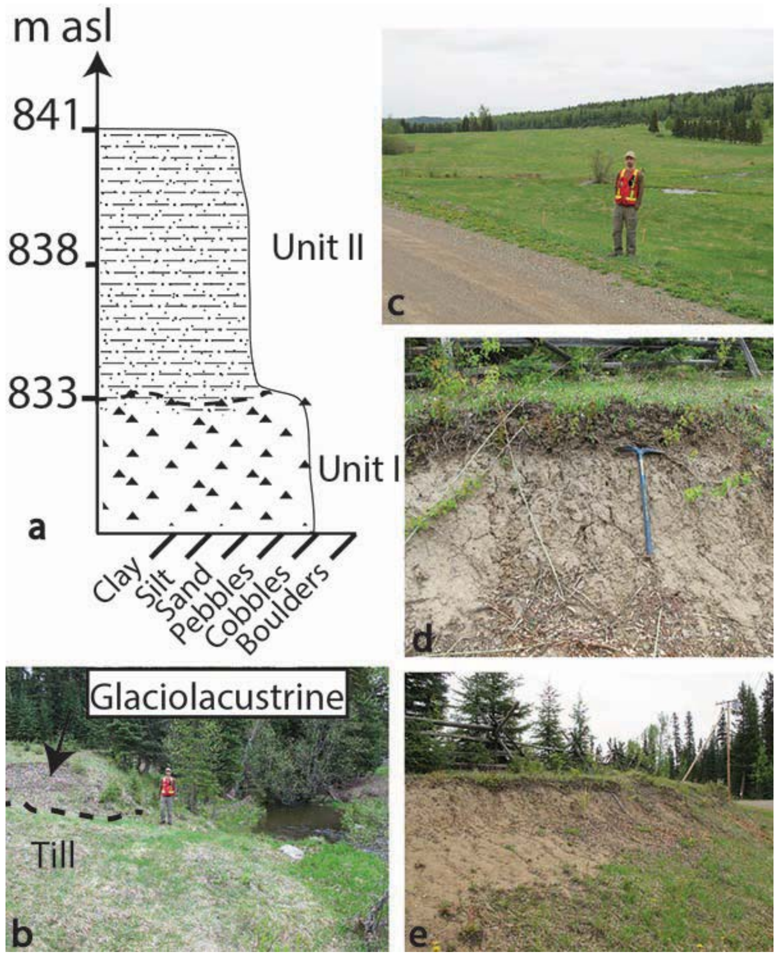

Figure 3.5: ***Cross-section of sediment exposure at site 13PMA007. (a) Reconstructed cross-section of the exposure; (b) Approximate divide between the glaciolacustrine and till sediments, person is 1.9 m tall for scale; (c) View of the surrounding rolling topography; (d) Glaciolacustrine sediments at the road cut exposure, pick (65 cm); (e) Larger view of the glaciolacustrine sediment exposure along the road.***

Site 3: 13PMA009

This exposure is at 820 m a.s.l., 1.5 km west of station 13PMA007.

Unit II consists of three distinct beds, including matrix-supported, laminated, fine sand and silt with a few sub-angular, granule to pebble sized clasts. It is well sorted and exhibits planar bedding.

Within the laminated fine sand and silt unit, there is a conformable, matrix supported, pebbly to cobbly gravel and sand unit. Exposed bedding varies 10's of centimetres to up to 2 m in thickness. This bed has parallel, crudely stratified and alternating layers of coarse sand and pebble rich, sub-angular to sub-rounded gravel, gently dipping in a general westward direction.

The upper most gravelly sand bed is discontinuous and pinches out within the laminated fine sand and silt unit. This gravelly sand bed consists of granular coarse sand, and 35-40%, sub-rounded to sub-angular, pebbly to cobbly gravel.

Based on the elevation, position relative to the till unit identified at the last station (13PMA007), matrix composition and bedding structure, unit II is determined as retreat-phase glaciolacustrine sediments, deposited pro-glacially in a glacial lake setting. The presence of alternating sand and gravel beds are interpreted as subaqueous outwash outwash sediment, deposited during high and low energy flow. This unit is interpreted as an ice proximal glaciolacustrine unit characteristic of the "grounding line zone". The glaciolacustrine sediments indicate glacial lake conditions, whereas the two gravel beds suggest high sediment load deposited by meltwater discharge as underflow deposits.

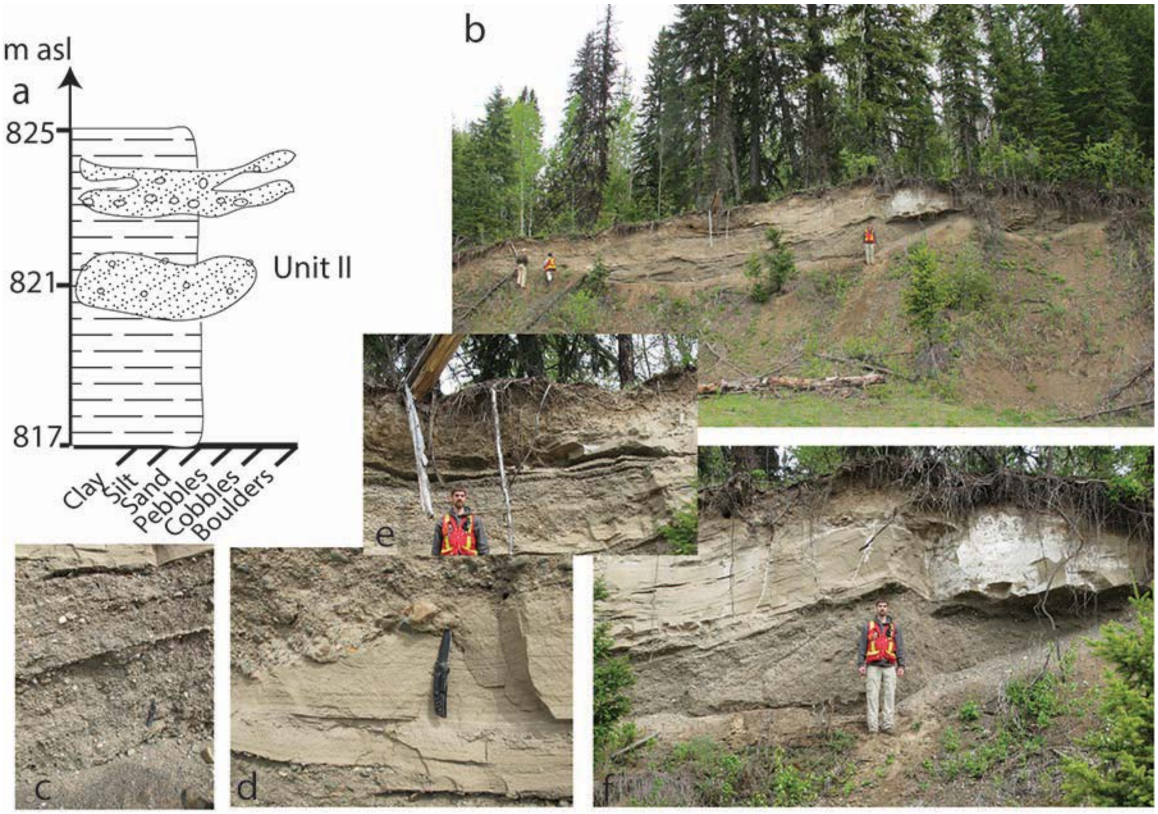

Figure 3.6: ***Site 13PMA009. (a) Reconstructed cross-section of the exposure, (b) View of the section, person (2 m) for scale; (c) Stratified gravel beds, gently dipping to the north; (d) Finely laminated glaciolacustrine sediments, knife (approximately 10 cm) for scale; (e) Interfingering glaciolacustrine and glaciofluvial beds; (f) View of the top of the section with exposed glaciolacustrine and glaciofluvial sediments, person (2 m) for scale.***

Site 4: 13PMA016

This station is located approximately one kilometre south of Quesnel River in the northwestern sector of the study area. This region consists mainly of glaciofluvial sand and gravel sediments, mapped at varying elevations to the east of a meltwater channel (Little Lake creek). The road cut section exposes two distinct units and is located at approximately 790 m a.s.l.

Unit I is a well-compacted, poorly sorted diamicton with a silt and fine sand matrix and a clast content of approximately 10%. The pebble sized clasts are sub-rounded and faceted. The unit thickness is estimated to range 4-6 m; however, the lower contact was not visible.

Based on the compactness, faceted clasts and stratigraphic position, unit I is identified as till deposited during Fraser Glaciation.

Unit II is a massive silt and fine sand unit, with a thickness ranging 2 to 3 m.

Based on the sediment composition, which indicates a low energy depositional environment, unit II is interpreted as glaciolacustrine sediments. Unit II has a gradational contact, 2-20 cm in thickness, across the dug exposure with unit I, where the sediment transitions from fine to coarse sand and pebbles, indicative a gradual change from basal till to glaciolacustrine sediments.

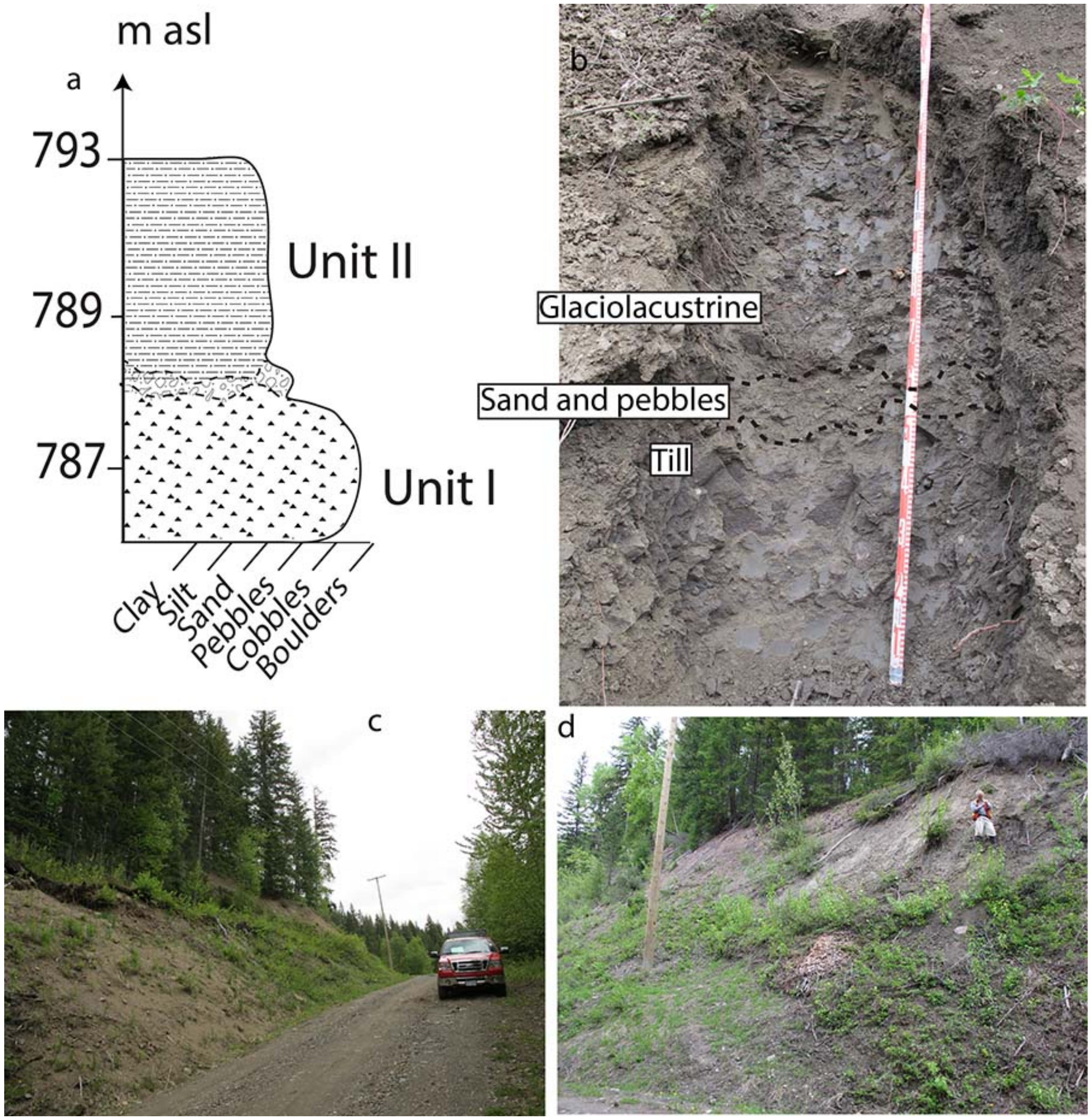

Figure 3.7: ***Site 13PMA016. (a) Reconstructed cross-section of the site; (b) Dug out exposure showing the diamicton (till), sand and pebble layer and the fine sand and silt unit (glaciolacustrine); (c) Road view of the section; (d) View of the dug site, Brent (1.7 m) for scale.***

Site 5: 13PMA033

This site is located along the Quesnel River valley, two kilometres due west outside of the study area. The road cut exposure is at approximately 795 m a.s.l., exposing three distinct units.

Unit IIa is a matrix supported, moderately compact diamicton. The matrix is silty sand with a pebbly framework, measures 3 to 5 m in thickness and has a clast content of up to 20%. Clasts vary from sub-angular to rounded, ranging in length from 3 to 10 cm.

Based on the lack of fissility and jointing and low compaction, this diamicton unit is interpreted to be a mass wasting deposit, most likely deposited as a sub-aqueous debris flow.

Unit IIb is an unconsolidated, clast-supported, coarse sand and gravel. The gravel is moderately sorted, ranges in size from pebbles to boulders but mainly cobbly. It is 1 to 2 m thick and forms gradational contacts with the underlying and overlying units. The gravel composes 90% of the section, and is on average sub-rounded; however, no bedding is observed.

Unit IIb is identified as a glaciofluvial sub-aqueous outwash. The gradational contact between the underlying and overlying unit signifies a transition in depositional environments.

Unit IIc is a matrix-supported, moderately sorted silt with minor sand and clay. This fine-grained unit exhibits crude stratification and is approximately 1.5 m thick.

Based on the matrix composition and structure, unit IIc is interpreted as retreat phase glaciolacustrine sediments with pebble sized dropstones.

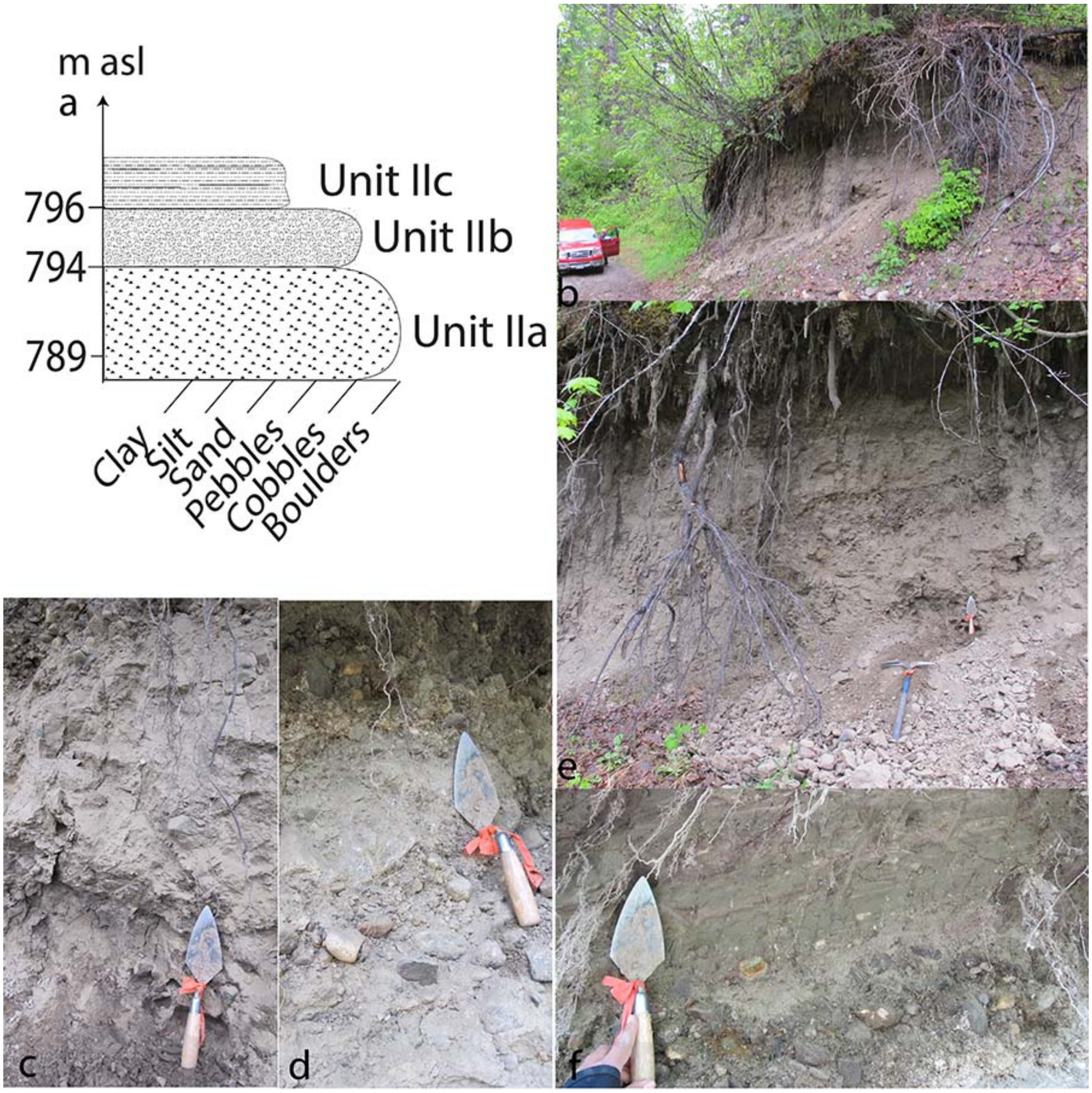

Figure 3.8: ***Site 13PMA033. (a) Reconstructed stratigraphy of the site; (b) View of the section; (c) Diamicton, trowel (17.5 cm) for scale; (d) Sandy gravel; (e) Closer view of the section; (f) Laminated silt with minor sand and clay sediments.***

Site 6: 13PMA081

This site was documented in the north, northeast section of the study area (Fig. 3.9). The topography is flat, and the exposure sits at approximately 920m a.s.l., 300 m due south of Quesnel River and in close proximity to Miller pit placer deposit.

Unit II is a grey brown, matrix-supported and massive, fine sand, silt and minor clay unit. It forms an erosive contact with unit III and is estimated to be approximately a metre thick.

Unit II is interpreted as glaciolacustrine sediment. The lack of bedding suggests that this unit was deposited as a grain flow deposit in a glacial lake setting (a low energy environment).

Unit III is massive, clast-supported, coarse sandy gravel, ranging two to three metres in thickness. The gravel ranges from granules to boulders, but is predominantly pebbly. The gravel is platy to bullet shaped, faceted and includes intrusive and volcanic rocks.

This sandy gravel unit is identified as a glaciofluvial outwash terrace which formed during deglaciation.

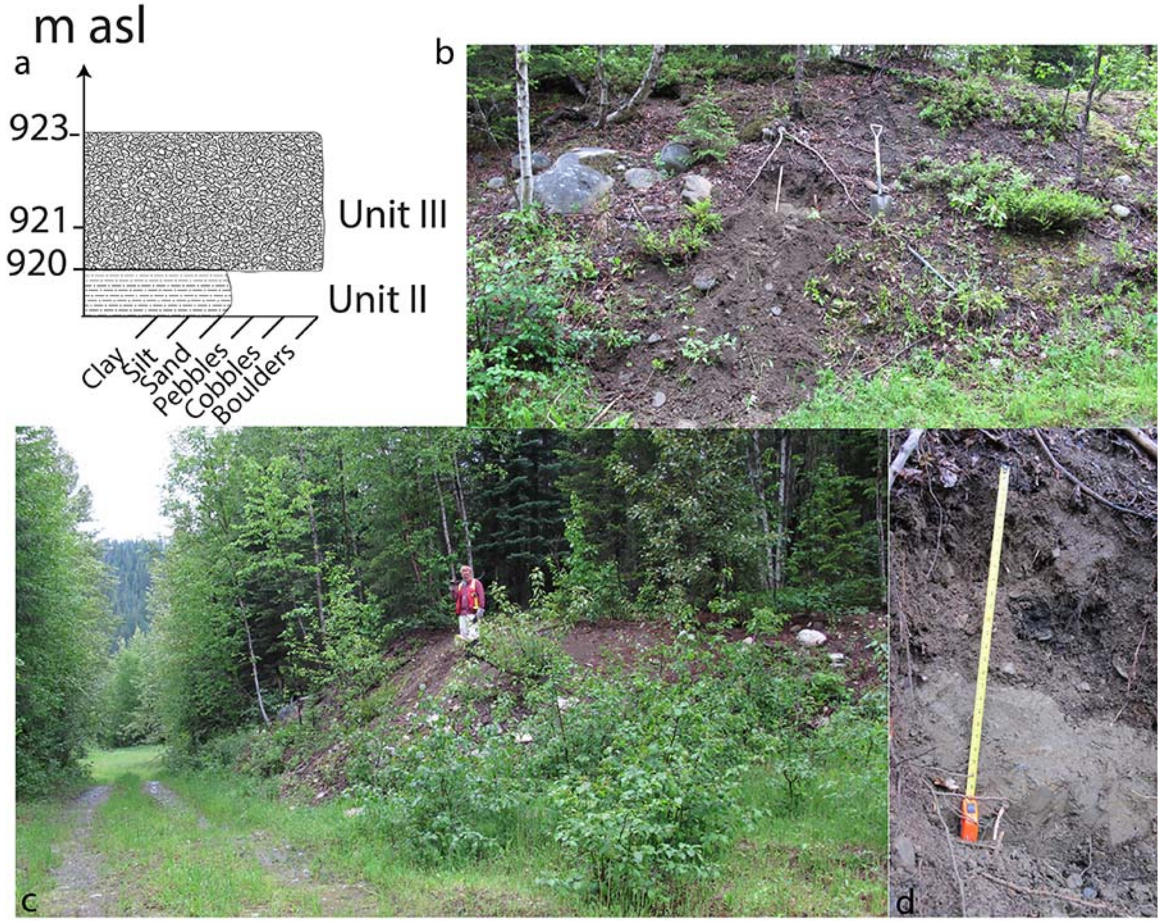

Figure 3.9: ***Site 13PMA081. (a) Exposure reconstruction; (b) View of the dug hole, shovel (1 m) for scale; (c) Larger view of the section, Brent (1.7 m) for scale; (d) Fine sand, silt and minor clay overlain by sandy gravel.***

Site 7: 13PMA061

This exposure is located at approximately 715 m a.s.l., roughly 750 m south, southeast of a meltwater fed Gilbert style delta (13PMA048).

Unit IIa is a sandy silt, exhibiting lamination and is at least 5 m thick. This unit consists of a repetitive sequence of 48-50 cm of silt and fine sand laminations, capped by 4 cm of clay, suggesting periods of low and very low energy environments, respectively.

Unit IIa is determined to be glaciolacustrine sediments associated with the formation of a pro-glacial lake during deglaciation in Beaver valley.

Unit IIb is a massive, matrix supported, moderately compact, diamicton with a sand-silt matrix and pebble to boulder sized clasts. It varies in thickness between 1-1.5 m, forming a conformable contact with the underlying glaciolacustrine unit.

Unit IIb is identified as colluvium, likely deposited in a sub-aqueous debris flow.

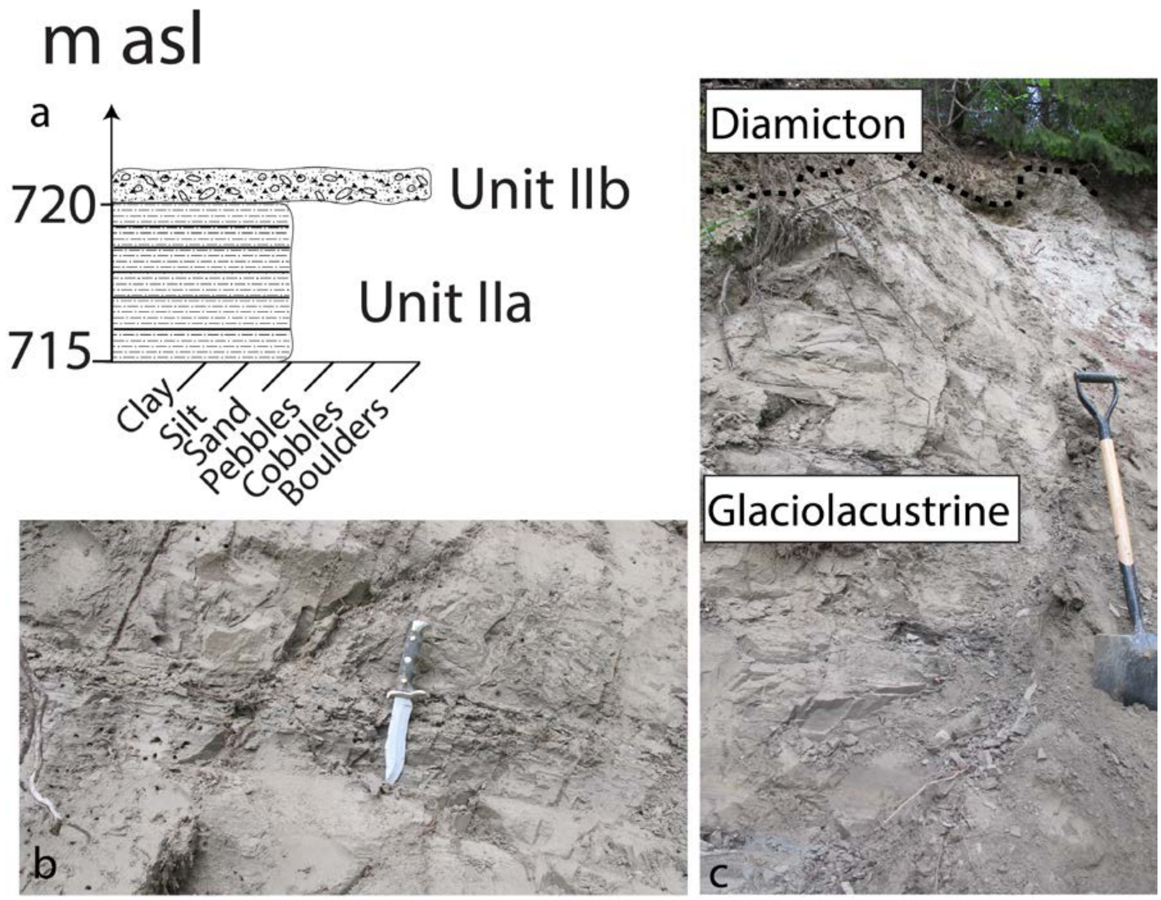

Figure 3.10: ***Site 13PMA061. (a) Stratigraphic reconstruction; (b) Laminated sandy silt sediments with knife (21 cm) for scale; (c) view of the exposure with shovel (1 m) for scale. The dashed line represents the division between the sandy silt unit and the overlying diamicton unit.***

Site 8: 13PMA067

This site is a road cut exposure along Likely highway at 760 m a.s.l. (Fig. 3.11).

Unit III is a clast supported, poorly sorted, sandy cobbly gravel. The unit is approximately 13.5 m thick and consists of alternating beds of crudely stratified fine and coarse gravels. The clast ranges 2-25 cm with an average size of 5 cm (pebble sized), mainly sub-angular with some striated faces.

Based on the flat surface (as mapped on the aerial photograph) and sandy gravel sediment composition, this unit is interpreted as a glaciofluvial terrace, formed in a proglacial setting. The fine and coarser gravels signify variable energy levels. The preservation of the striated clasts signify close proximity of the gravel to the glacier.

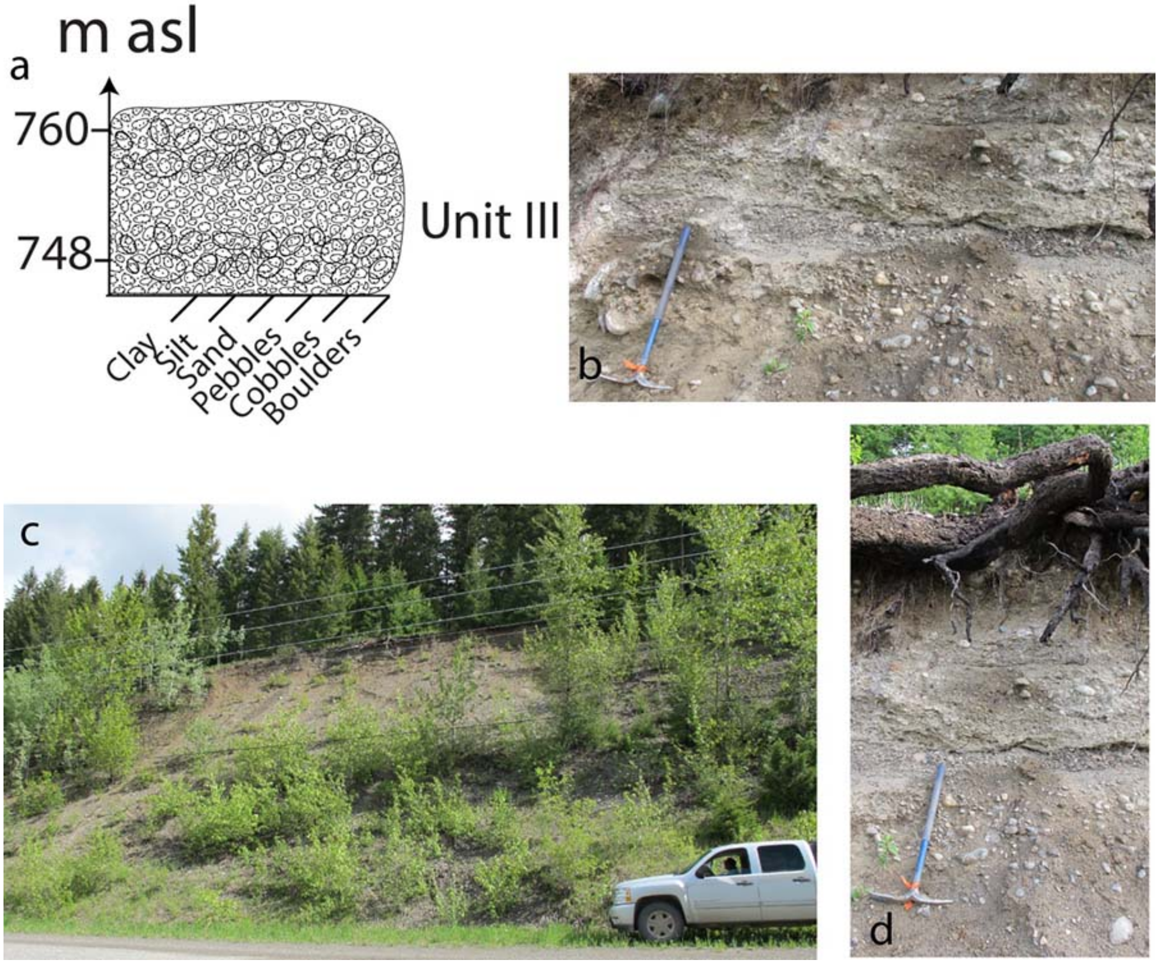

Figure 3.11: Site 13PMA067. (a) Exposed sediment reconstruction; (b) closer view of the sandy gravel sediments with pick (65 cm) for scale; (c) view of the section; (d) View of the top of the section.

Site 9: 13PMA069

This site is situated approximately 340 m northwest of the previous site (13PMA067) and lies at approximately 700 m a.s.l. (Fig. 3.12). Given the poor quality of this 3 m high exposure, three holes were dug at this site. They revealed two distinct units separated by a few centimetres of medium sand and pebbles.

Unit IIa consists of coarse sand and pebbly gravel. The gravel is sub-rounded and varies 1-5 cm (pebble sized), comprising approximately 45% of the unit. This unit is estimated to vary in thickness between 2-3 m and forms a fining upwards sequence with medium sand and granule sized gravel, indicative of a decreasing energy environment.

Based on the unit composition, lack of stratification or bedding, and roundness of the gravel, Unit IIa is determined to have been deposited as a subaqueous density underflow.

Unit IIb is a fine sand and silt with minor clay unit, exhibiting laminations. The unit ranges 1-2 m in thickness. This unit dips 30° towards Beaver Valley (dip direction 330°), most likely resulting from melting of ice resulting in the unit slumping.

Based on the sediment composition and laminations, Unit IIb is determined as glaciolacustrine sediments associated with the formation of a glacial lake in Beaver Valley. The laminations signify suspension settling.

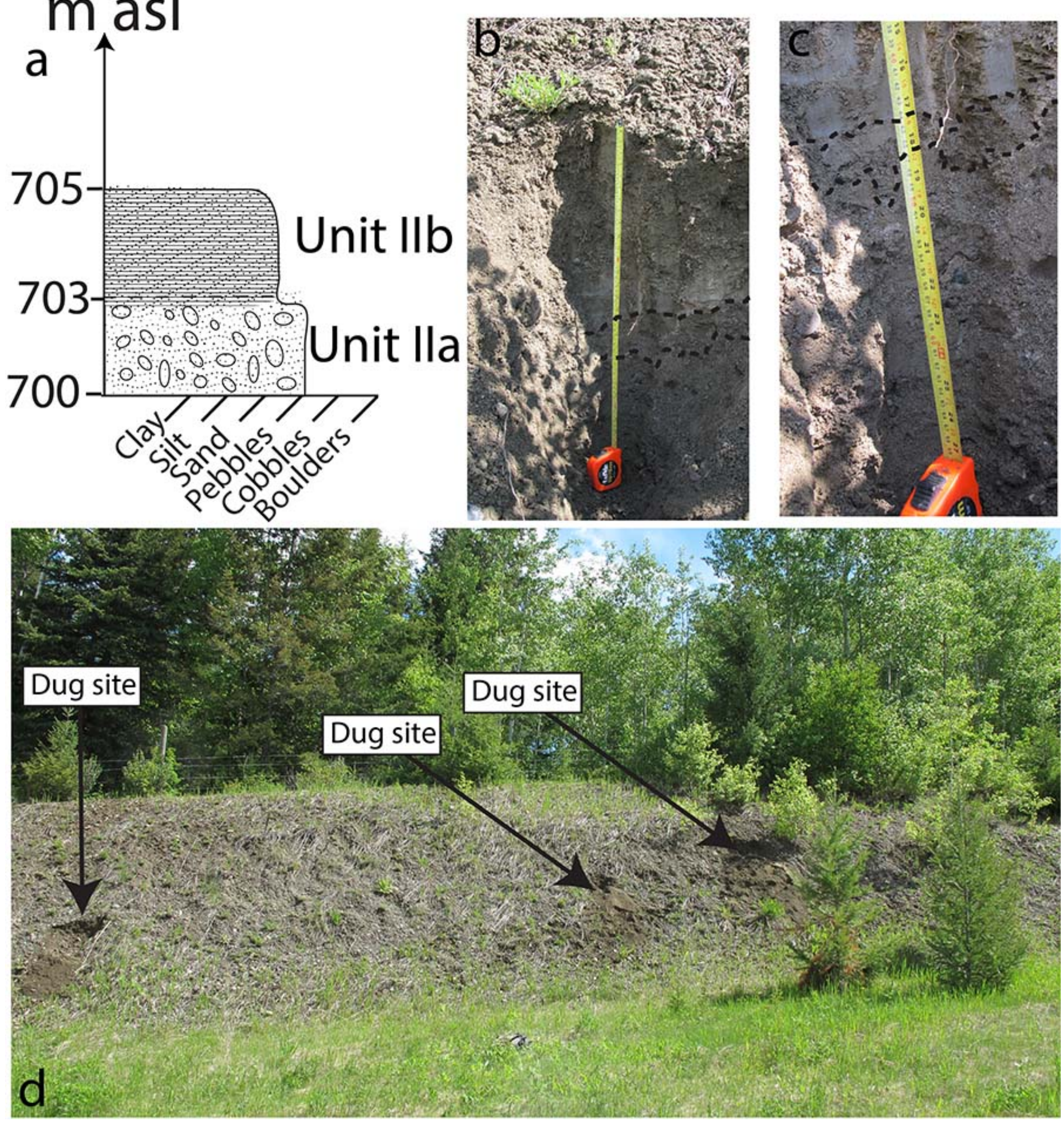

Figure 3.12: ***Site 13PMA069. (a) Stratigraphic reconstruction; (b) Dug hole with dashed lines representing the zone of mixing; (c) Closer view of the same dug hole; (d) View of the site.***

Site 10: 13PMA048

This station is located at the site of a large gravel pit adjacent to Beaver Lake valley at an approximate elevation of 705 m a.s.l. (Fig. 3.13). A 100 m high section of clast supported, sandy gravel is exposed in the gravel pit. Rounded to sub-angular clasts vary in size from pebble to boulder in a coarse sand matrix. Gravel beds are inclined, striking 185° and dipping 28° to the west.

These inclined gravel beds are interpreted to be part of foresets of a Gilbert type delta, formed as a result of sediment (and meltwater) input through meltwater channels (mapped 300 m east, southeast of this site) with a paleo-current to the west. Based on the height of the exposure, the top sets are estimated to be 805 m a.s.l. This elevation suggests that the glacial lake which formed in this valley was at least 805 m a.s.l high.

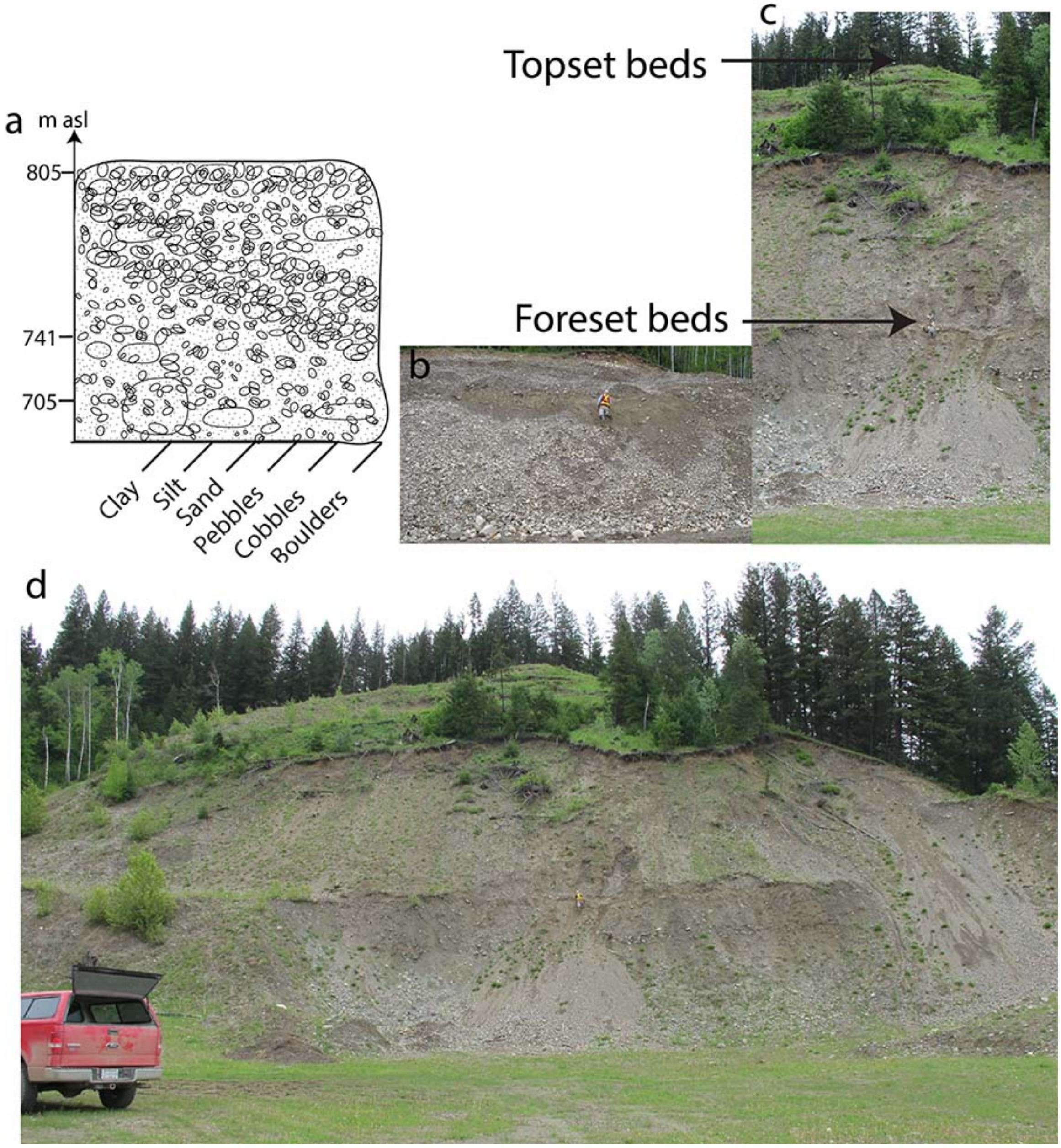

Figure 3.13: ***Site 13PMA048. (a) Delta reconstruction; (b) view of the forest beds with Brent (1.7 m) for scale; (c) View of the forsets and topsets; (d) Larger view of the site.***

3.5. Glacial history

The late Wisconsinan glaciation, known as the Fraser Glaciation in British Columbia, may have begun as early as 29 ^{14}C ka BP (Ryder *et al.* 1991). During the intense alpine stage, glaciers that developed in the Cariboo Mountains moved out towards the valleys and ice tongues formed piedmont glaciers and the ice movement was still topographically controlled (Tipper 1971a; Fulton 1991). Clague (1990, 1991) and Bichler (2003) indicate this glacial advance was marked by glaciofluvial sand and gravel aggradation. Advance phase glaciofluvial sediments are overlain by advance-phase glaciolacustrine sediments (characterized by laminated mud) within the exposed stratigraphy in the Bullion pit (Clague *et al.* 1990). Bichler (2003) noted these advance phase glaciolacustrine sediments as at least 90 m thick coarsening upwards sequence of rhythmically bedded sand, silt and clay. The presence of glaciolacustrine sediments (at a minimum elevation of 640 m a.s.l. along the Quesnel River valley) suggest a glacial lake environment as a result of blocked drainage in the Quesnel River valley (Bichler 2003). This obstruction of drainage may have either been due to glaciers advancing from the Coast Mountains or by the resultant outwash sediment aggradation (Ryder *et al.* 1991). However, the extent of this glacial lake is unknown.

During the intense alpine stage, glaciers advanced within the Mount Polley study area (oriented 250° to 255°) as indicated by the glacial striation record. It is likely that the first glaciers that reached the area were thin and therefore, their movements were controlled by topography (*cf* Clague, 1989). As ice thickness built-up, glacier movements became less influenced by topography. This can be seen from westerly and southwesterly oriented striations that cut across topographic obstacles (Fig. 3.14) and till (Unit I) was deposited during glacial advance.

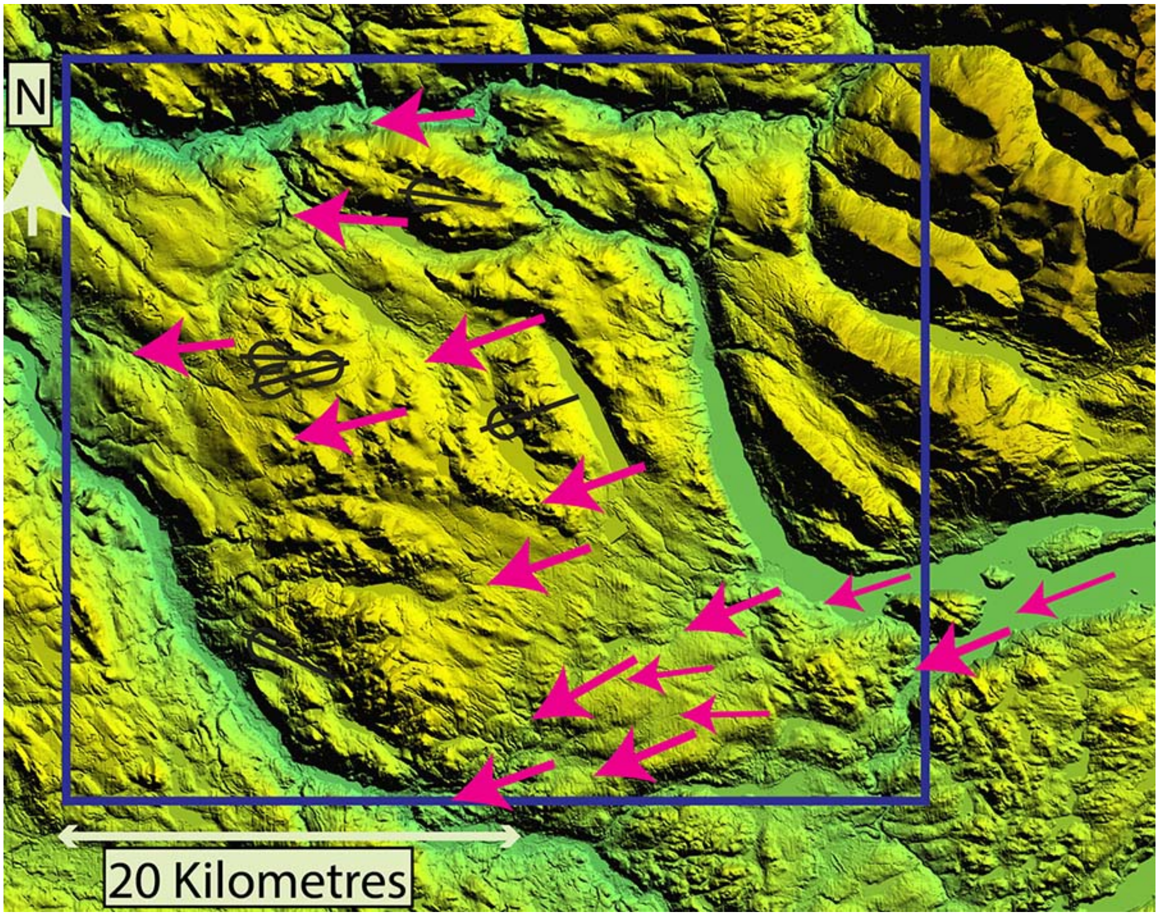

Figure 3.14: ***Ice-flow in the study area at the onset of Fraser Glaciation. The black arrows are on site paleoflow measurement indicators. The double ended striation symbols indicate bi-directional flow measurement and the single ended arrows indicate uni-directional ice-flow measurement. The pink arrows are the depicted ice-flow movement based on the onsite measurements and mapped features in the region.***

The intense alpine stage was soon followed by the mountain ice sheet phase (Tipper 1971b). During the mountain ice sheet phase, glaciers had completely covered the mountain ranges with only the highest peaks (nunataks) exposed (Tipper 1971a). As glaciation intensified, ice from the Cariboo and Coast mountains coalesced over the Interior Plateau; forming an east-west oriented ice-divide around the 52° latitude from which ice was generally flowing to the north and south (Tipper 1971a, b; Clague 1989; Ryder *et al.* 1991; Plouffe *et al.* 2011). At this stage, rugged topography underlying the ice sheet still exerted some control over the flow, resulting in movement parallel to major topographic features (Tipper 1971a; Fulton 1991). The second phase of ice flow, generally to the northwest (Fig. 3.15), identified in the study area is interpreted to be associated with the development of this ice divide or the zone of coalescence at the 52° parallel, south of the study area (cf. Tipper, 197a, b; Plouffe *et al.* 2011). Ice-flow indicators with an orientation of 290° to 325° correspond to this phase (Fig. 3.15). The range (varying from 255° to 330°) in ice-flow measurements suggests that the change in ice flow from southwest to northwest was progressive. Striations at sites 13PMA025 and 13PMA059 as well as flutings and crag and tails in the southeast sector of the study area oriented 270° +/- 5° are interpreted to be related to this transitional phase of ice movement. Lastly, the new set of ice-flow indicator data collected as part of this study is not suggestive of a late phase readvance as postulated by Tipper (1971a, b).

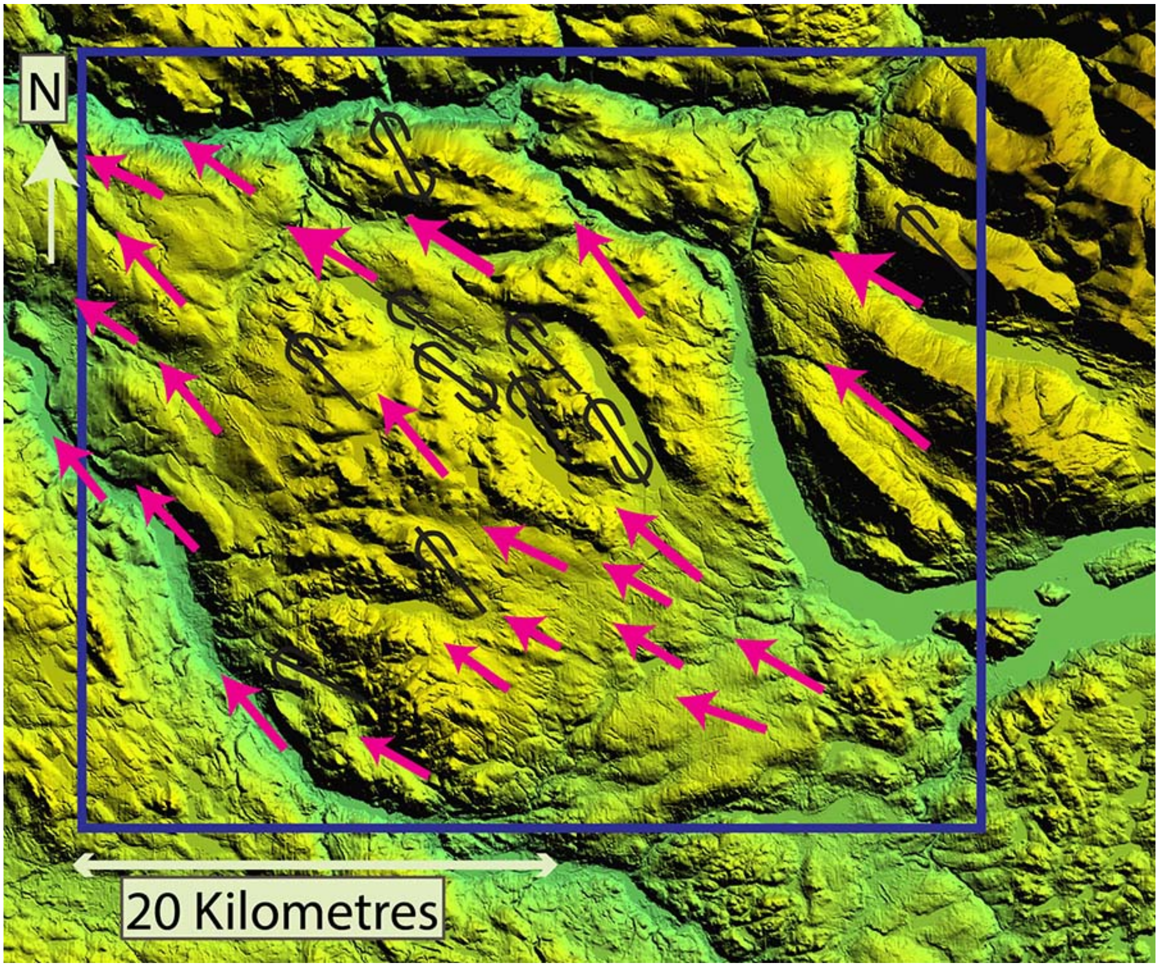

Figure 3.15: ***Ice-flow in the study area at glacial maximum. The black arrows are on site Paleoflow measurement indicators. The double ended striation symbol indicates bi-directional flow measurement and the single ended arrows indicate uni-directional ice-flow measurement. The pink arrows are the depicted ice-flow movement based on the onsite measurement and streamlined features mapped in the region.***

In summary, as part of this study, two distinct ice-flow phases have been identified in the Mount Polley area. These ice-flow phases correlate to the two phases identified by Plouffe *et al.* (2011) to the south and fit the regional ice-flow reconstruction presented by Tipper (1971a, b). The formation of the ice divide likely corresponds to the maximum phase of the Cordilleran Ice Sheet of the Fraser Glaciation. The Fraser Glaciation may have reached its climax between 14,500 to 14,000 years B.P. (Ryder *et al.* 1991).

Deglaciation began soon after the Cordilleran Ice Sheet reached its climax and may have proceeded as early as 13,500 years B.P (Ryder *et al.* 1991). The reconstruction of the deglaciation pattern in the study area is a modified version of the model proposed by Fulton (1967; 1991). In the Mount Polley study area, it is likely that glacial retreat followed a combination of: a) thinning of ice in the uplands followed by down wasting and stagnation of the broken ice masses; and b) east southeastward oriented frontal retreat of ice in Quesnel Lake (which terminates in the Cariboo Mountain Ranges).

The first phase of deglaciation was the active ice phase. Ice-flow movement similar to that of glacial maximum (i.e., northwestward flow) continued through the valleys but lessened as ice thinned and the highest ice-covered peaks became ice-free. Meltwater from thinning glaciers continued flowing throughout the region via subglacial (Nye) channels.

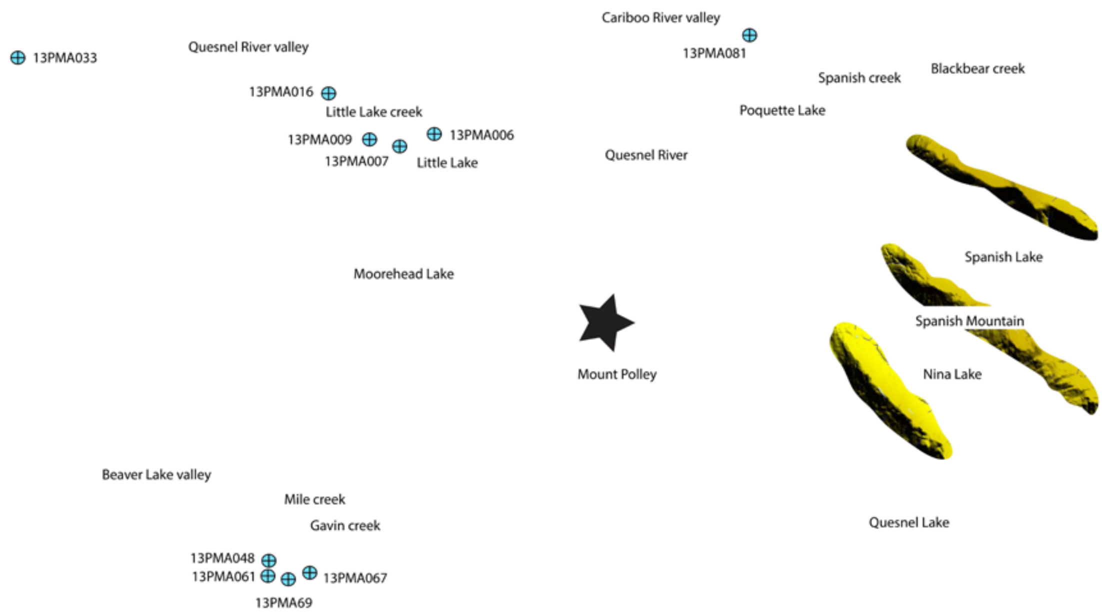

Figure 3.16: ***The first phase of deglaciation. There is near complete ice cover (shown in white) as ice-flow continued in the region; however, the highest peaks became exposed (represented by the darker shaded relief). The black star represents the Mount Polley deposit and the blue dots represent the stratigraphic sections noted through the region.***

The next phase is the transitional upland phase (Fulton 1991). While the regional flow continued through the valleys, the highest peaks and some of the uplands became ice-free. As deglaciation continued, the ice margin pulled back from the western regions of the study area and meltwater continually discharged into the lower relief regions and valleys (Fig. 3.17). Meltwater flowing through subglacial channels, now modern day valleys, creeks (Gavin, Mile, Blackbear, Little and Spanish) and lake (Poquette), flowed into the Quesnel and Cariboo river valleys and Beaver Lake valley. Continual down wasting of ice in the valleys is marked by the presence of lateral meltwater channels mapped between 1000 m a.s.l. and 1585 m a.s.l. along the valley walls in the Blackbear creek, and between 1000 m a.s.l. and 1430 m a.s.l. along the valleys walls of Spanish Lake valley and Spanish creek. Melting ice within valleys was also responsible for the formation of high kame terraces. Examples include kame terraces mapped at elevations ranging 915 m a.s.l. along Quesnel and Poquette Lakes and between 1000 m a.s.l. to 1070 m a.s.l. in Nina Lake to the east.

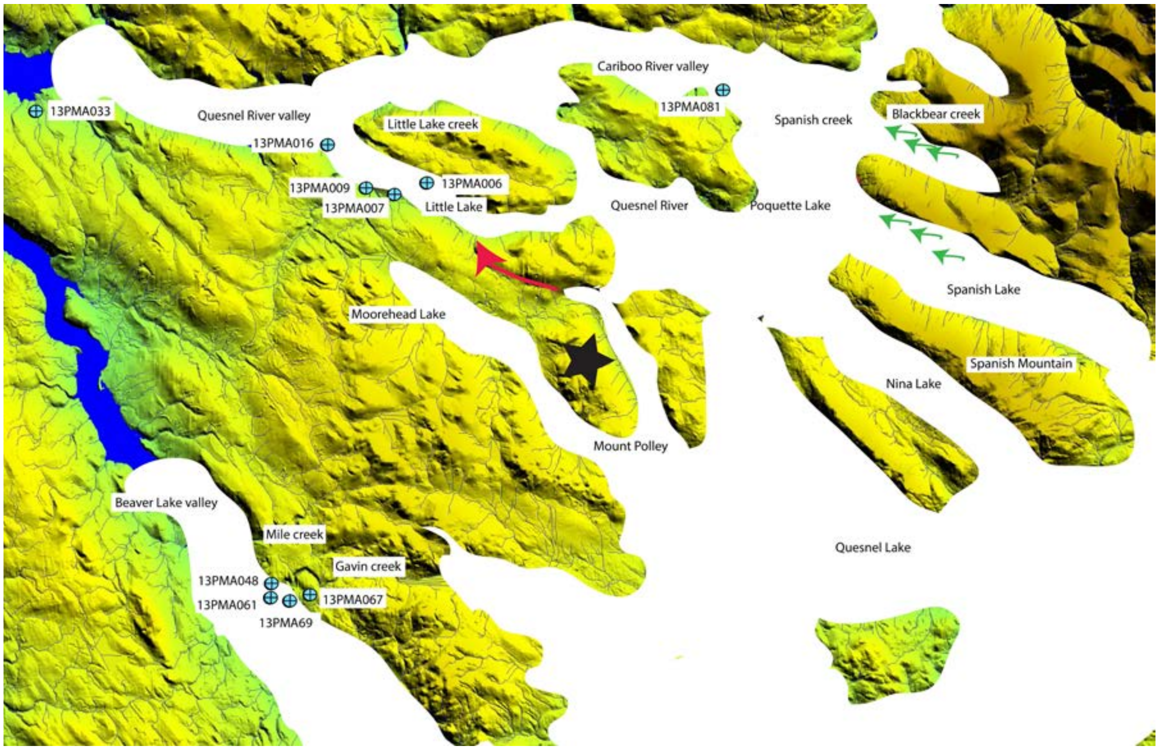

Figure 3.17: The transitional upland phase depicted in the study area. The highest peaks (darker shaded relief) and uplands became ice-free. The white shade represents hypothetical ice cover during this phase, the pink arrow indicates meltwater discharge. Down wasting of ice masses within valleys resulted in lateral meltwater channels carved alongside valley walls (represented by green arrows). The black star represents the Mount Polley deposit.

The third phase is the stagnant ice phase, where ice still flowed but was confined to the valleys while parts of the adjacent uplands were ice free. In other words, glaciers present in trunk valleys blocked the drainage of tributary valleys which resulted in the formation of glacial lakes (Fig. 3.18) (Fulton 1967, 1991; Clague & Ward 2011). During this stage, most of the Quesnel River and Beaver Creek valleys were deglaciated but their westward drainage (they are both part of the Fraser River drainage) was blocked somewhere west of the study area, resulting in the formation of glacial lakes (which may have been part of the Glacial Lake Fraser system) (Ryder et al. 1991). The nature and exact location of the dam west of the study area is not known.

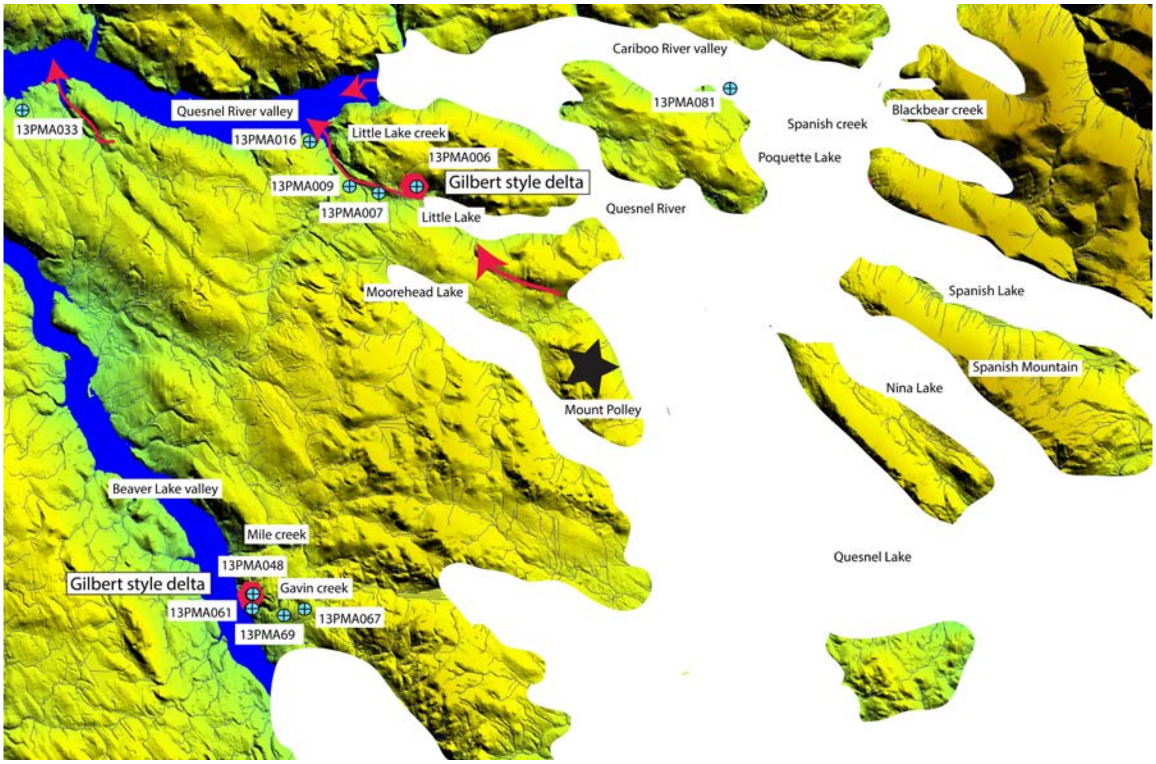

Figure 3.18: ***The stagnant ice phase (I), where pro-glacial lakes present in the study area are shown in navy blue. Ice (shown in white) at this stage has retreated further east in the Quesnel River valley and an ice-tongue (discharging meltwater) feeding a delta in the Little Lake creek has formed which is connected to glacier present in Quesnel Lake. The grey-blue lines represent drainage, the navy blue represents glacial lakes within the Quesnel River and Beaver Lake valleys and the pink hexagons represent Gilbert style deltas. The pink arrows represent continual meltwater discharge into Quesnel River and Beaver lake valleys.***

Laminated to crudely laminated sandy silt units in the Quesnel River valley (site 13PMA033 at 795 m asl) and in the Little Lake Creek valley (site 13PMA007 at 840 m asl and site 13PMA016 at approximately 795 m a.s.l.) are interpreted as evidence of glacial lakes in both of these valleys. While deglaciation continued and glacial lake conditions persisted, ice tongue present in Little Lake creek retreated back towards Quesnel Lake (drawn in Fig. 3.18, 3.19). The presence of multiple beds of glaciofluvial underflow sediment deposits (site 13PMA009) suggest that during glacial retreat, this site was likely an ice grounding zone, where a retreating ice tongue deposited subaqueous outwash glaciofluvial sediments (stratified, dipping sandy gravel beds in Unit II) via underflow as meltwater discharged into the lake. Based on the presence of glaciolacustrine sediments at similar elevations along Little Lake creek (13PMA016; 790 m. a.s.l.) and the Quesnel River valley (13PMA033; 795 m a.s.l.), it is likely that the glacial lake forming in the Quesnel River valley connected to the lake that developed in the Little Lake creek. As deglaciation continued, the ice tongue retreated further back towards Quesnel Lake. When site 13PMA006 was deglaciated, a delta formed there with topsets at approximately 875 m a.s.l., indicating the former glacial lake level.

The glacial lake in the Beaver Lake valley is identified by the presence of glaciolacustrine sediments and a delta. A meltwater fed, Gilbert style delta (site 13PMA048; Fig. 3.18, 3.19) is adjacent to Beaver Lake valley, with topset beds estimated at approximately 805 m a.s.l. suggesting minimum lake elevation.

The formation glacial lakes in the Quesnel River and Beaver Lake valleys is time transgressive and it is possible that glacial lake conditions may have persisted in this region as early as the upland ice phase (Fig. 3.17). An elevation difference of 125 m between the glaciolacustrine sediments in Beaver Lake valley (715 m a.s.l.) and Little Lake (840 m a.s.l.) suggest that these two glacial lakes were probably not connected within the study area. However, these lakes were probably part of the larger Glacial Lake Fraser system (Ryder et al. 1991; Plouffe 1997). Meltwater fed, smaller scale glacial lakes forming as a result of local ponding (e.g. Moorehead Lake (910 m a.s.l.), Little Lake (840 m a.s.l.), Spanish Lake (915 m a.s.l.), Polley Lake (920 m a.s.l.), Bootjack Lake (985 m a.s.l.)) are also mapped in the study area.

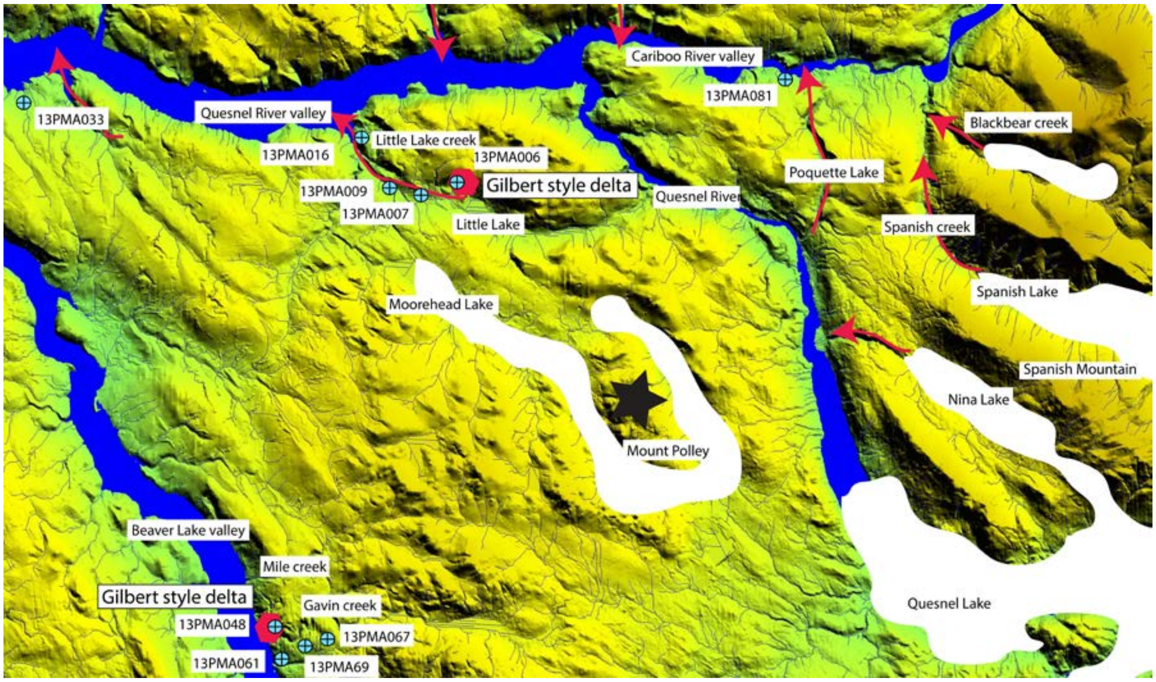

Figure 3.19: ***The stagnant ice phase (II). Ice (shown in light grey) at this stage has retreated as far back as Quesnel Lake and the Quesnel River valley is likely ice-free. The grey-blue lines represent drainage, the navy blue represents glacial lakes forming within the Quesnel and River and Beaver Lake valleys and the pink hexagons represent Gilbert style deltas documented. The pink arrows represent continual meltwater discharge into Quesnel River valley and the black star represents Mount Polley.***

Once the westward drainage in Quesnel River was established, glaciofluvial aggradation and degradation took place in the Quesnel and Cariboo river valleys, resulting in the formation of glaciofluvial terraces. The glaciofluvial terraces within the Quesnel river valley formed at elevations ranging from 730 to 875 m a.s.l. Similarly, meltwater flowing through the two meltwater channel systems (modern day Spanish and Black Bear creeks) draining into the Cariboo River valley also formed glaciofluvial terraces on either sides of the valley. At this stage, the ice sitting in Quesnel Lake had probably retreated further east, outside the study area.

The fourth phase is the dead ice phase, where isolated ice masses no longer flowed (Fig. 3.20) (Fulton 1991; Clague & Ward 2011). Only ice ablating in low relief areas remained. The location of stagnating ice is interpreted from the presence of ice-stagnation features including hummocky glaciofluvial sediment, kettle and kame topography, ablation till (till with a hummocky topography - Th) and kame terraces. These features are present in the southeastern, southwestern and northeastern sections of the study area.

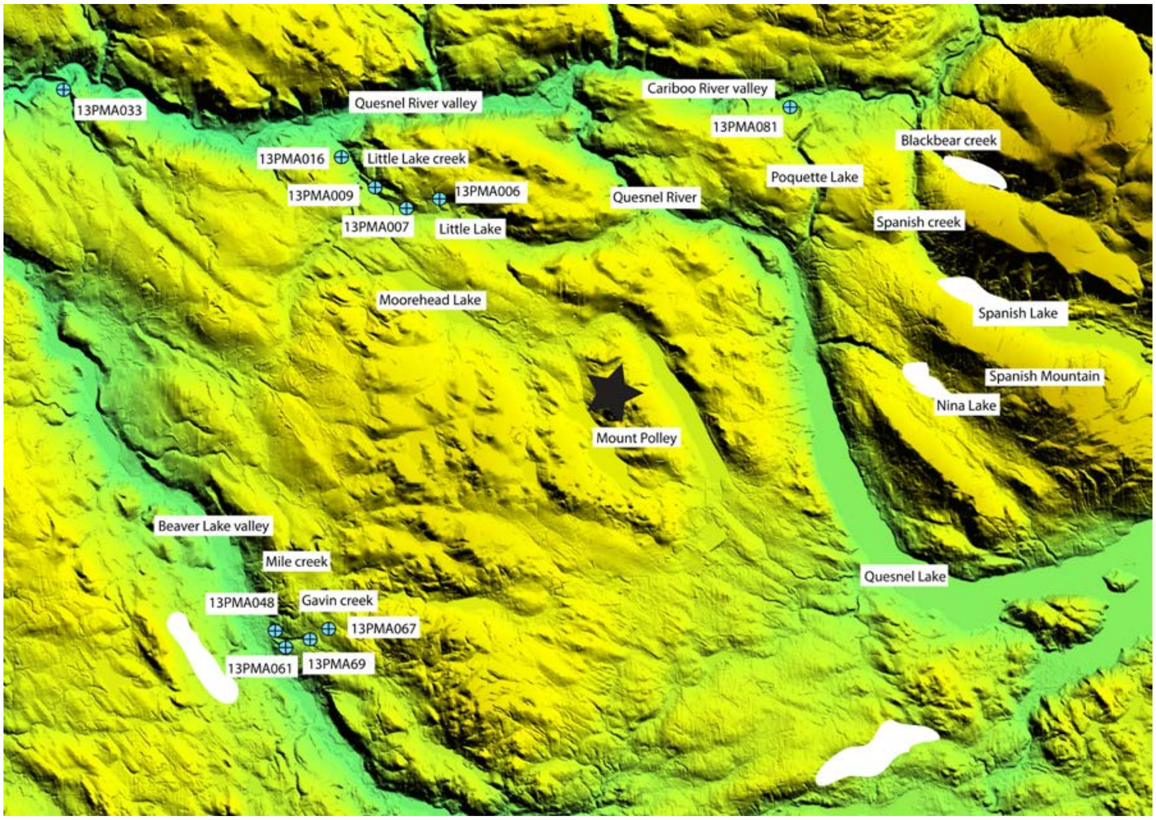

Figure 3.20: ***The dead ice phase is the final stage of deglaciation. The white patches represent the remaining ablating ice present in low relief areas, where ice stagnation topography is present. Features representative of ice-stagnation topography include hummocky glaciofluvial, hummock till, kettle and kame topography and kame terraces. The black star represents the Mount Polley deposit.***

The Interior Plateau was ice free by 9.5 ^{14}C ka BP (Ryder *et al.* 1991; Stumph *et al.* 2000). Following deglaciation abundant sediment (water saturated in many places), was left in unstable areas, including steep terrain. As a result, landslide and debris flows involving advance- and retreat-phase glacial sediments occurred, primarily in the Quesnel and Cariboo River valleys and Beaver valley. Postglacial streams went through a phase of aggradation and then degradation as indicated by alluvial terraces several meters above modern stream level, mapped in the Quesnel and Cariboo River valleys and Beaver valley. Post-glacial mass wasting continued (at a lessened rate) once forests and grasslands became established in the area by about 7 ka BP (Slaymaker 2004).

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4. Till geochemistry, mineralogy and pebble lithology

4.1. Introduction

This chapter presents the results of the till geochemistry, mineralogy and pebble lithology of the samples collected in the Mount Polley study area. The objectives of this chapter are: 1) to identify the elements and minerals that best define and characterize the anomalous dispersal originating at Mount Polley, and 2) determine the extent of the glacial dispersal of the Mount Polley Intrusive Complex lithologies in till. The chapter begins with a summary of the previous soil geochemistry surveys conducted in this region, followed by the methods used to accomplish the objectives stated previously. Finally, the results of the analysis, i.e., which elements and minerals work best as pathfinders and porphyry indicator minerals and how far the intrusive pebbles are dispersed down-ice of Mount Polley. Part of this chapter forms the content of the paper Hashmi et al. (in press).

4.2. Previous work

A surficial mapping and till geochemical survey was conducted within the Mount Polley claims block to determine aggregate potential as well as better assess the bedrock mineralization (McAndless 2006). Multi-element analysis utilizing Aqua Regia digestion followed by ICP-MS was used on 85 till samples taken within the Mount Polley claims block. Anomalous Ag, Au, Cu and Mo values were observed northwest of the deposit, parallel to the main ice-flow in this region. More recently, Blaine & Hart (2012) presented select compiled data including Cu values in B-horizon soil samples (Mount Polley, Mount Milligan and Galaxy porphyry deposits) and Au in lodge pole pine (Galaxy porphyry deposit).

4.3. Methods

4.3.1. Sample collection

A total of 87 samples of basal till were collected at 77 sites along a well-developed forestry road network and from exposures at the Mount Polley mine site. Samples were collected up-ice, overlying and down-ice from the Mount Polley deposit with the intention of defining both glacial dispersal from Mount Polley and regional background till composition. The till sampled in the Mount Polley region consists of a moderately to highly compacted diamicton with clasts of pebble to boulder size and varying lithologies derived from local bedrock sources in a silty sand matrix. Prior to collecting samples, the surface exposure was excavated to ensure the collection of *in situ* till and to avoid anthropogenic contamination from mine operations (e.g. dust). The samples were collected at depths ranging from 90 cm to up to 4 m deep depending on the height of road-cut section. All samples were C-horizon, surface, basal till samples (Fig. 4.1a, b). At each site, a small (2 kg) and a large (10 kg) till sample were collected following field procedures recommended by McClenaghan *et al.* (2013) and Plouffe *et al.* (2013a) for the sampling of glacial sediment for geochemical analysis and indicator mineral recovery. Care was taken to collect till samples well below the visible surface oxidation zone but some oxidation of the till might still have occurred. Samples were placed in clean plastic bags with multiple labels. Field data including site coordinates, sample description (texture, clast lithology, relative abundance and depth) and photographs were recorded digitally using a handheld computer (GanFeld) with a built-in geographic positioning system (GPS).

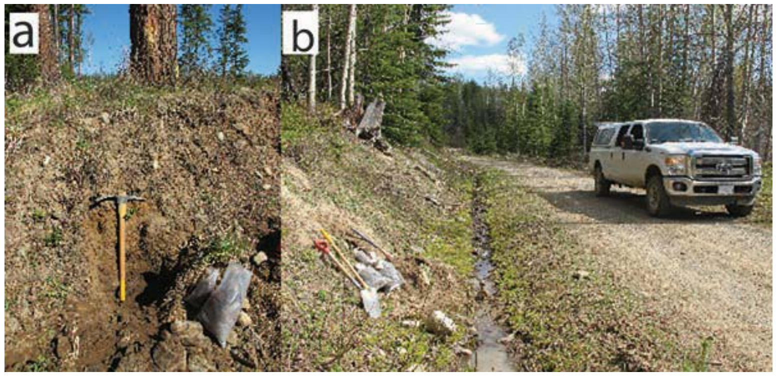

Figure 4.1: ***(a) Two and 10 kg basal till samples; (b) sample site along well developed forestry roads.***

4.3.2. Sample analysis

Till geochemistry

The clay- (< 2 µm) and silt plus clay-sized (< 63 µm) fractions from the 2 kg till samples were separated at the Geological Survey of Canada (GSC), Ottawa, Sedimentology Laboratory following procedures outlined in Girard *et al.* (2004), Spirito *et al.* (2011) (Fig. 4.2). The silt plus clay-sized fraction was analysed in this study because sulphide minerals and gold tend to be more enriched in this coarser fraction (compared to finer clay sized fraction) (Lett 1995; Sibbick & Kerr 1995). Also, the silt plus clay sized fraction is relatively easy and cost-effective to separate (Shilts 1984, 1995; McClenaghan *et al.* 2013). The clay-sized fraction, even though is more expensive to separate, can accentuate metal contents in till because of cation adsorption onto clay-sized particles (Shilts 1995; Spirito *et al.* 2011). Moreover, glacial entrainment and transport results in continual communition of bedrock fragments resulting in constituent elements being redistributed and concentrated in the finest (clay-sized) fraction (Dreimanis & Vagners 1971).

Geochemical analyses were completed on the clay- (0.5 g aliquots) and silt plus clay-sized (30 g aliquots) fractions, at ACME Analytical Laboratories, Vancouver, British Columbia, which included a digestion in a hydrochloric and nitric acid solution (ratio 1:1, modified aqua regia) followed by inductively coupled plasma-mass spectrometry (ICP-MS) determination (Fig. 4.2). Large silt and clay aliquots (30g) were submitted for analyses to reduce the gold nugget effect (Harris 1982) attributed to fine gold grains heterogeneously distributed in the silt-sized material of the till matrix, which generally result in low analytical precision. This procedure is part of the GSC protocols for till geochemical analyses (McClenaghan *et al.* 2013).

Till mineralogy

The 10 kg till samples were processed to recover indicator minerals at Overburden Drilling Management Limited, Ottawa following protocols used by the GSC (McClenaghan *et al.* 2013; Plouffe *et al.* 2013a) (Fig. 4.2). Bulk till samples were first wet sieved to < 2 mm and pre-concentrated with a shaking table (Fig. 4.2). Gold grains were panned from the table concentrates, counted, measured and classified by morphology (pristine, modified, reshaped; cf DiLabio 1990*a*). Shaking table concentrates were then separated in mid (2.8-3.2) and high specific gravity (s.g. > 3.2) fractions with a heavy liquid (methylene iodide). Magnetic minerals were removed from both density fractions. Both non-ferromagnetic density fractions were sieved to 0.25-0.5 mm, 0.5-1.0 mm and 1-2 mm. Only the 0.25-0.5 mm fraction with s.g. > 3.2, was submitted to electromagnetic separation to facilitate mineral identification based on magnetic properties of minerals (McClenaghan 2011; Plouffe *et al.* 2013a). All size fractions were examined for indicator minerals. The indicator minerals herein reported were dominantly present in the 0.25-0.5 mm fraction. Throughout this chapter, indicator mineral results are reported as either grain counts (normalized to a 10 kg weight of the < 2 mm bulk fraction processed on the shaking table) or as percent observed, in a specific size and density fraction (e.g. 0.25-0.50 mm; 2.8 to 3.2 s.g.). Abundance of gold (0.015-0.425 mm; panned from shaking table concentrate), chalcopyrite (0.25-0.5 mm, > 3.2 s.g.), jarosite (0.25-0.5 mm, 2.8-3.2 s.g.) and andradite garnet grains (0.25-0.5 mm, > 3.2 s.g.) are reported as grain counts. Apatite (0.25-0.5 mm, > 3.2 s.g.) and epidote (0.25-0.5 mm, > 3.2 s.g.) are reported as percent observed in the grain size and density fraction indicated above in parentheses. The percent observed is used for minerals that are abundant and for which an exact grain count cannot be completed.

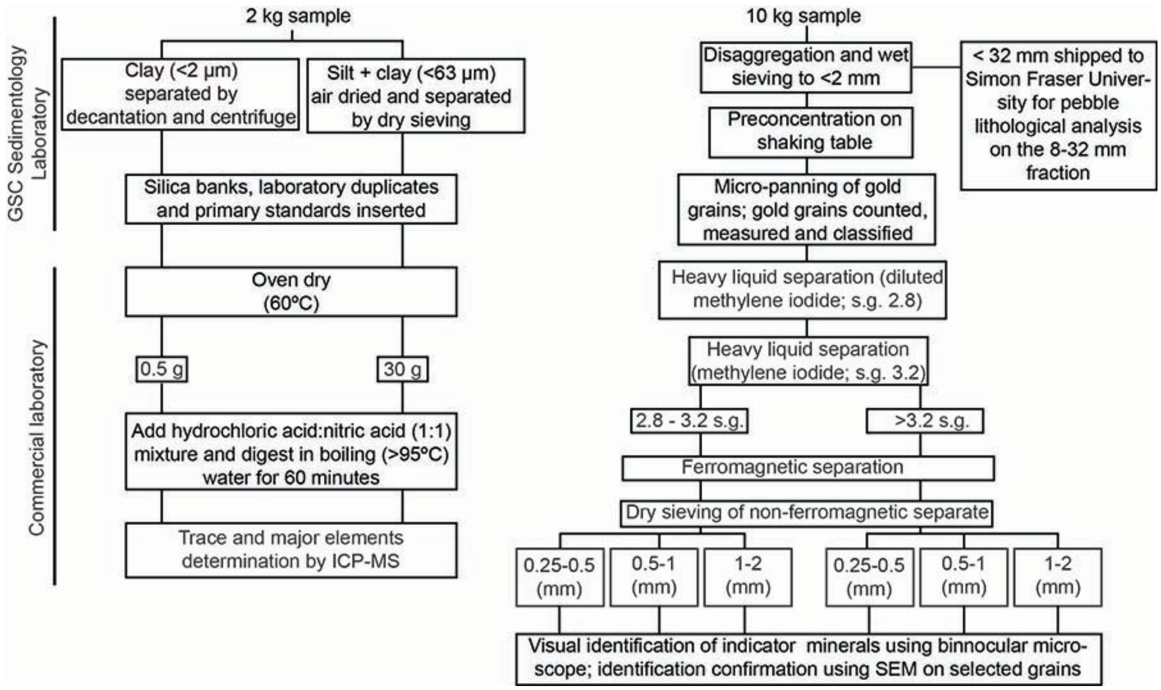

Figure 4.2: ***Geochemical, mineralogical and lithological analysis on the 2 kg and 10 kg samples.***

Pebble lithology

Of the 87 till samples, 21 were analyzed for clast identification at Simon Fraser University (Fig. 4.3). The pebble fraction (> 8 mm) was recovered from the 10 kg samples to determine the lithic component in the 8-16 mm and + 8 mm fractions. Pebble lithology was determined for the 8-16 mm size fraction where abundant pebbles were recovered from the samples, where the + 8 mm fraction was determined in samples where very few pebbles were recovered from samples (smaller sample size to examine). Larger samples were randomly split to half the volume for lithic analysis. The categories used were 1) intrusive rocks; 2) fine-grained volcanic and sedimentary rocks; and 3) metamorphic rocks. The volcanic and sedimentary categories were combined due to the difficulty in distinguishing between the two types in such small sized gravel. These samples were chosen up-ice, overlying and down-ice from Mount Polley to determine the spatial variation in the percent of intrusive clasts. The pebbles were examined with a Nikon dissecting microscope. The complete data set of the results of the pebbly lithology exercise is tabulated in Appendix C4.

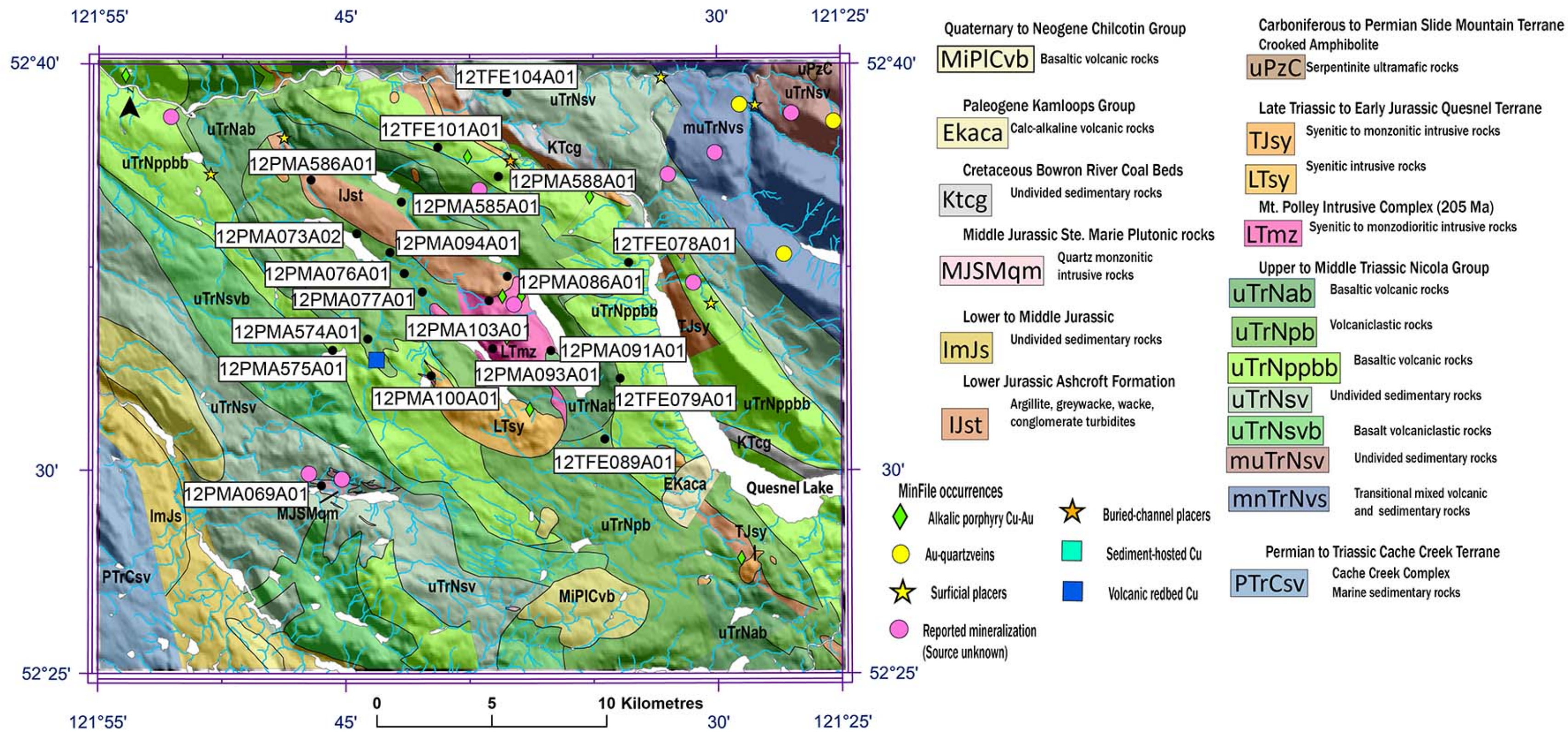

Figure 4.3: Bedrock geology with pebble lithology sample stations represented by black dots (modified after Logan et al. 2007).

4.3.3. *Quality assurance/Quality control*

Before the samples were shipped for geochemical analysis, silica blank (to detect cross-contamination), field duplicates (to determine site variability) and laboratory duplicates (to measure analytical precision) as well as primary standards (to determine analytical accuracy) were inserted as per the protocols described in McClenaghan *et al.* (2013). Blank, field duplicate and spiked (i.e. samples spiked with known quantities, sizes and type of indicator mineral to assess the efficiency and accuracy of mineral recovery) samples were also inserted into the sample set sent for indicator mineral processing as described in Plouffe *et al.* (2013a).

The analytical precision of geochemical analyses is estimated from the relative standard deviation calculated with the analytical results of laboratory duplicate samples (duplicate samples prepared in the laboratory and are considered homogenized) (Garrett 2013). The analytical precisions are estimated at ±14% for Ag, ±5% for Cu, ±8% for Hg, ±9% for Zn, and ±48% for Au. The RSD (%) for Au is relatively higher because of the heterogeneous distribution of fine gold particles in the sediment (or nugget effect) (Harris 1982). All QA/QC results of samples processed for indicator minerals will be presented in an upcoming GSC Open File report. In summary, results from blank samples indicate that cross-contamination is not detected. Chalcopyrite and gold grain recovery is estimated at approximately 90% based on results from spiked samples; 8 grains of chalcopyrite recovered out of 9 spiked grains and 11 gold grains recovered out of 12 spiked grains from two spiked samples.

4.4. Results

4.4.1. Data plotting

Ice-flow trend and distance of glacial transport

Glacial transport direction and dispersal distances were measured along a trend of 315° and 265°, which is based on the average respective northwestward and southwestward ice-flow directions measured in the field. Both the minimum and maximum dispersal distances are reported in this study. The minimum dispersal distance is defined as the down-ice distance measured (i.e. northwest or southwestward) from the edge of the source, i.e., the Mount Polley Intrusive Complex (Fig. 1.3 and 1.4), to the farthest sample with anomalous element and mineral content. The maximum dispersal distance is defined as the distance measured from the anomalous sample overlying the Mount Polley Intrusive Complex, to the farthest sample down-ice with anomalous element and/or mineral content.

Element, mineral and pebble data

Elemental threshold (i.e. values above which the element content is anomalous) was determined by plotting the geochemical data on cumulative probability plots (created in MATLAB). Threshold values were determined based on the “inflection points” or breaks in slope resulting in the division of population densities (Reimann *et al.* 2005). These element population densities were then divided into the categories “background content”, “anomalous content” and “very anomalous content”. Further, the proportional dot plots were created in ArcGIS (10.1) for both the element and mineral data. Both the routine sample (e.g. 12PMA092A01) and the duplicate sample (e.g. 12PMA092A02) were plotted. This approach ensures that no anomalous element or mineral content is eliminated in the evaluation of the distance of glacial transport. In the case of anomalies, the higher value (obtained in either the routine or the duplicate sample) is discussed.

The geochemical results presented in this thesis are for the size fraction that produced the highest background to anomaly contrast in cumulative probability distribution plots. Therefore, results for Cu, Ag, Hg and Zn are presented for the < 2 µm size fraction, using the ICP-MS analyses following a partial leach ($HCl:HNO_3$ 1:1).

Results for Au are presented for the <63 µm size fraction, using ICP-MS analyses following the same leach ($HCl:HNO_3$ 1:1).

Elements in till which reflect glacial dispersal from Mount Polley mineralization include Ag, Au, Cu, Hg and Zn. Results for ore and pathfinder elements show variations in content in till up-ice, over-lying and down-ice from the Mount Polley deposit.

4.4.2. Ore elements: Ag, Cu and Au

Copper content in the < 2 µm fraction of till ranges from 108 to 1548 ppm (Fig. 4.4). The Cu threshold is at 380 ppm, at approximately the 60th percentile (Fig. 4.5). Anomalous Cu contents (> 380 ppm) are observed in samples overlying the Mount Polley Intrusive Complex, extending at least 2.6 km down-ice (northwest) from mineralization. The highest Cu content of 1548 ppm (Table 4.1) is observed in one till sample (13PMA501A01) approximately 840 m down-ice from the Mount Polley deposit. Copper contents in till progressively decrease northwestward to 525 ppm, 2.6 km down-ice (13PMA521A01). All samples further to the northwest of sample 13PMA521A01 have a Cu content below 380 ppm. The minimum and maximum dispersal distances for Cu down-ice (northwest) of Mount Polley are approximately 2.6 km and 5.7 km, respectively. One anomalous value of 443 ppm in till is observed 4 km east southeast of the deposit (12TFE080A01) and may reflect glacial dispersal from an unknown mineral occurrence.

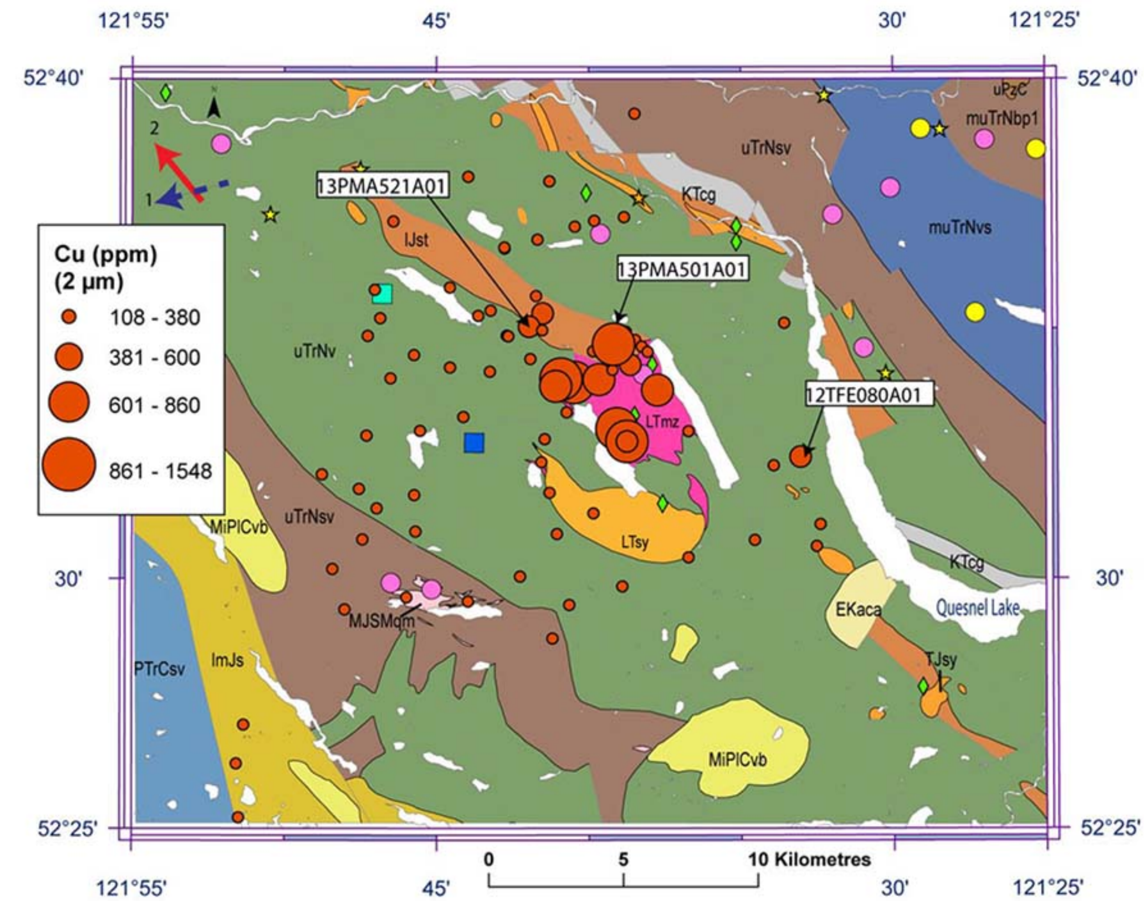

Figure 4.4: ***Proportional dot plot for Cu. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.***

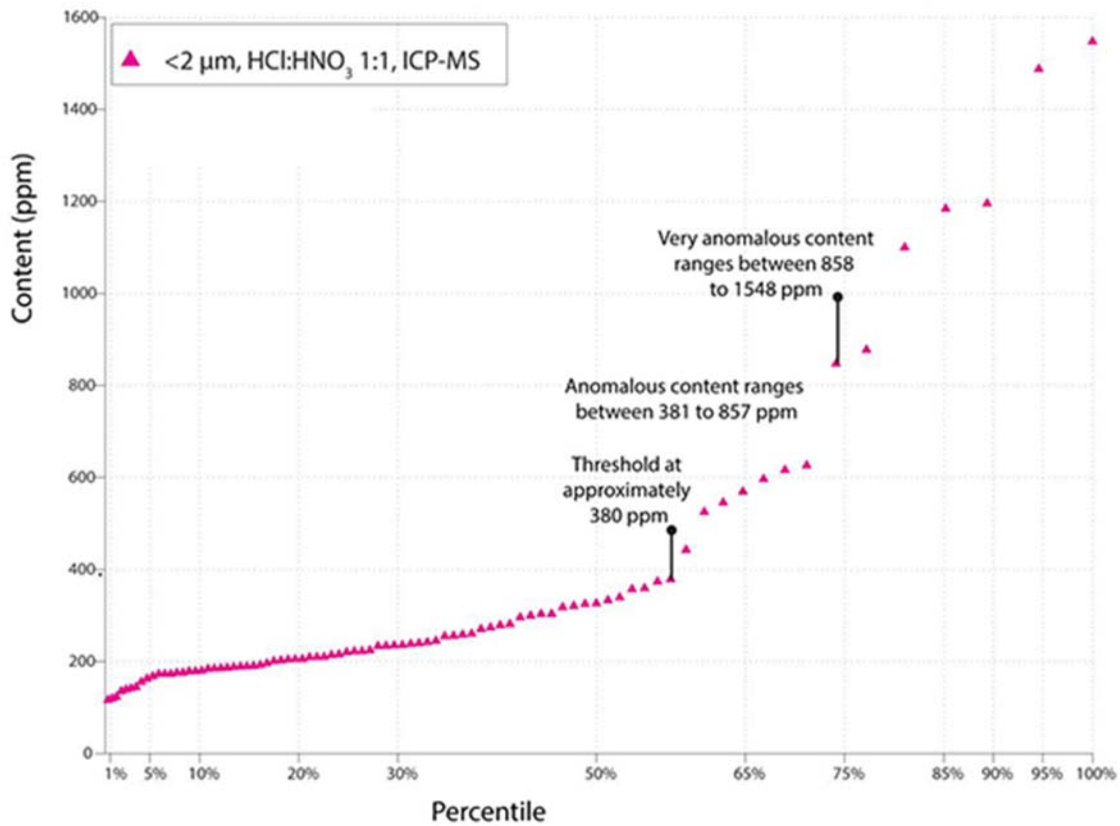

Figure 4.5: ***Cumulative frequency plot for Cu in the clay-sized fraction (< 2 µm).***

Gold contents in the < 63 µm fraction of till range from 0.4 to 90.2 ppb (Fig. 4.6). The Au threshold is 15 ppb, which occurs at approximately the 57th percentile (Fig. 4.7). Gold contents in till immediately down-ice (northwest) from the deposit range from 5.3 to 41 ppb, and generally decrease to 20.4 ppb (12PMA073A01), approximately 8.5 km northwest of the pluton (minimum distance). Anomalous Au content also occurs in till samples overlying the deposit. The highest gold content (90.2 ppb) is in sample 12PMA093B01, collected over the mineralization within the Core Zone. The maximum dispersal distance for Au down-ice (northwest) of Mount Polley is approximately 8.7 km. Anomalous Au content (30.6 ppb) is observed in sample 12TFE104A01, 9 km due north of Mount Polley. This anomaly coincides with elevated gold grain counts in the same sample (see gold grain results below) and likely represents another source of Au.

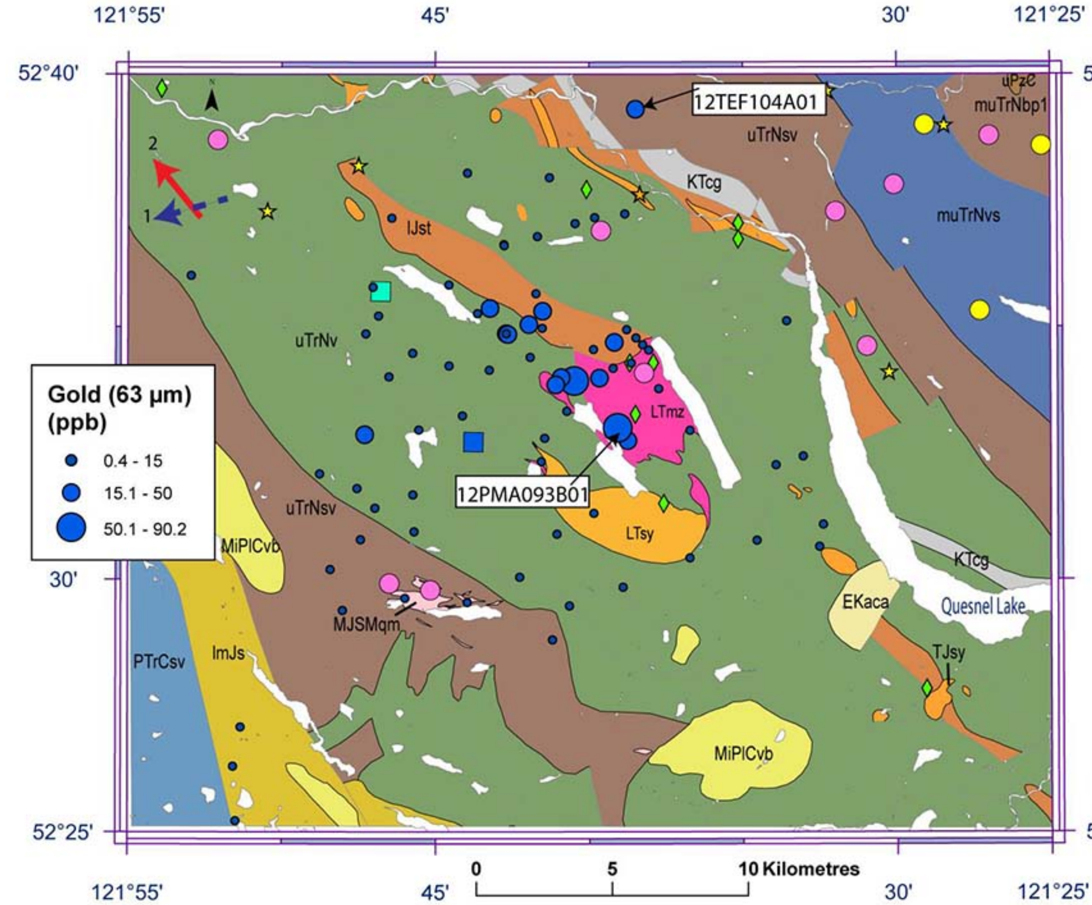

Figure 4.6: ***Proportional dot plot for Au. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.***

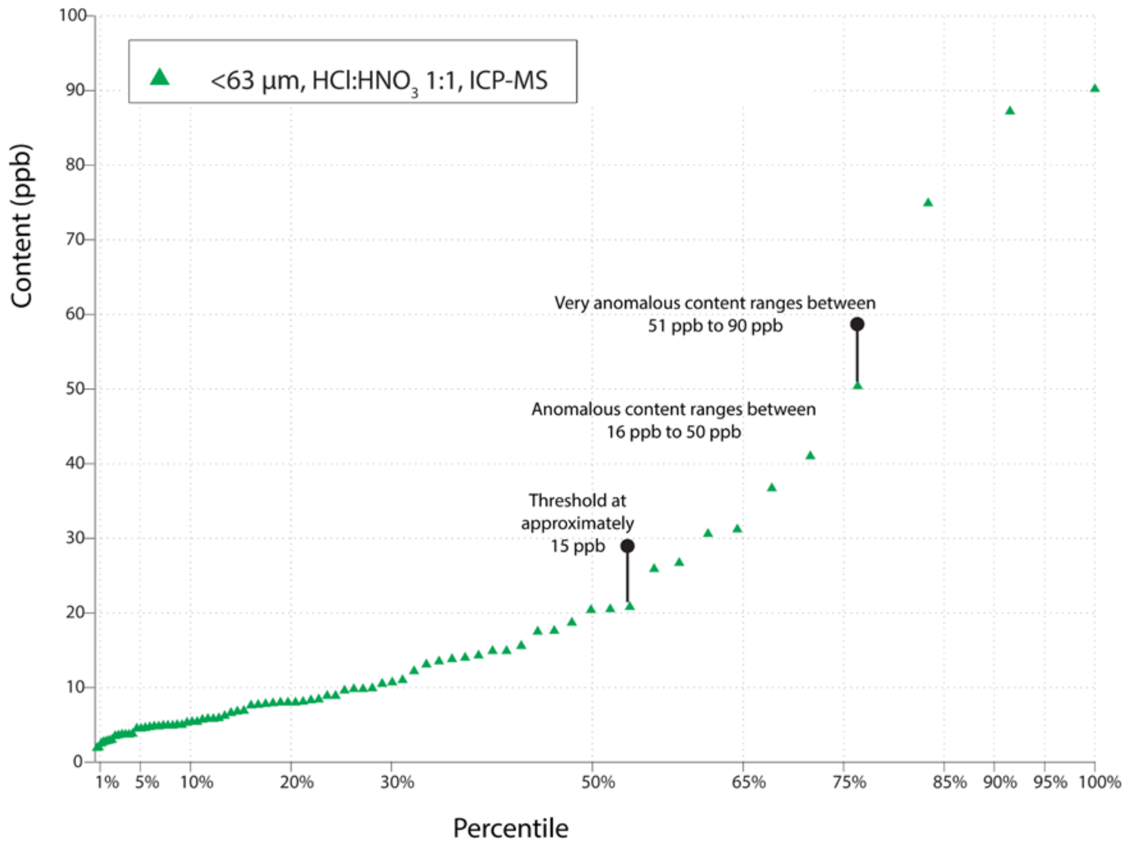

Figure 4.7: ***Cumulative probability plot for Au in the silt+clay-sized fraction (<63 µm).***

Silver contents in the < 2 µm fraction of till vary from 27 to 503 ppb (Fig. 4.8). The Ag threshold is estimated to be 190 ppb, which occurs at the 52nd percentile (Fig. 4.9). Samples containing anomalous Ag values of 285 ppb (12PMA586A01) occur as far as 10 km down-ice (northwest). The minimum and maximum dispersal distances for Ag down-ice (northwest) of Mount Polley are approximately 10 km and 12 km, respectively. Samples as close as 500 m contain as little as 154 ppb of Ag. Silver distribution in till down-ice (northwest) of the deposit is variable, but clearly enriched when compared to the background levels.

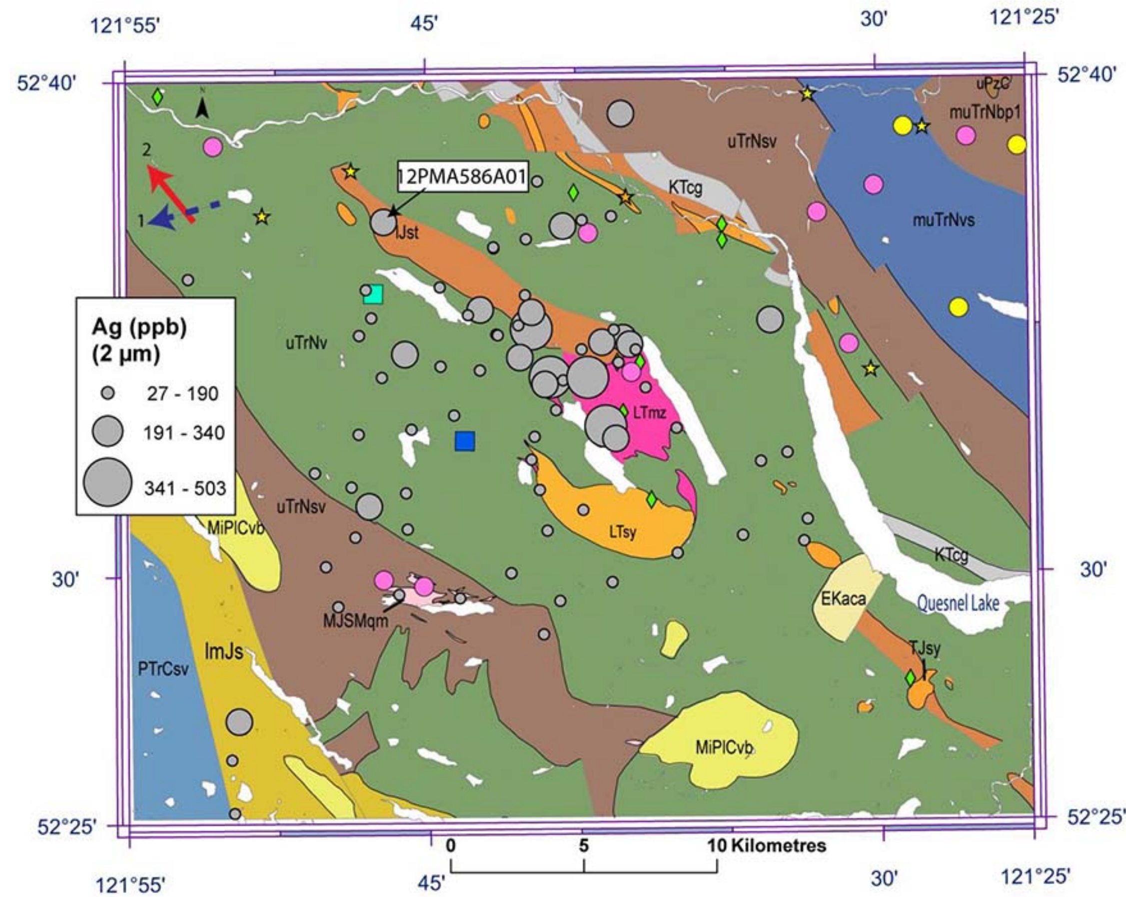

Figure 4.8: ***Proportional dot plot for Ag. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.***

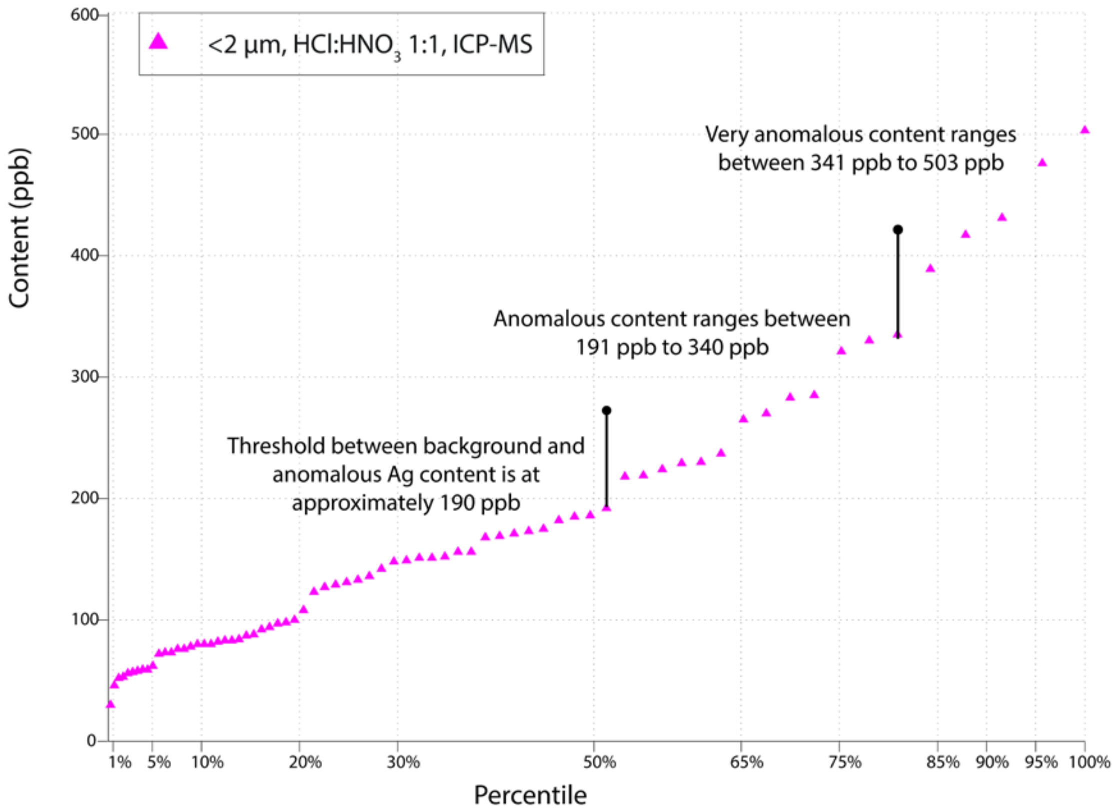

Figure 4.9: ***Cumulative probability plot for Ag in the clay-sized fraction (<2 µm).***

4.4.3. Pathfinder elements: Hg and Zn (< 2 µm fraction)

Mercury contents in the < 2 µm fraction of till range from 141 to 1954 ppb (Fig. 4.10). The Hg threshold is estimated to be 490 ppb, which occurs at the 78th percentile (Fig. 4.11). Samples overlying the deposit range between 193 to 822 ppb Hg, and anomalous Hg content (of up to 724 ppb) were measured as far as 2.6 km to the northwest. The minimum and maximum dispersal distances for Hg down-ice (northwest) of Mount Polley are approximately 2.6 km and 3.5 km, respectively. The maximum Hg value of 1954 ppb (12PMA095A01) was measured in sample that was taken 1.7 km down-ice (northwest) of the ore body.

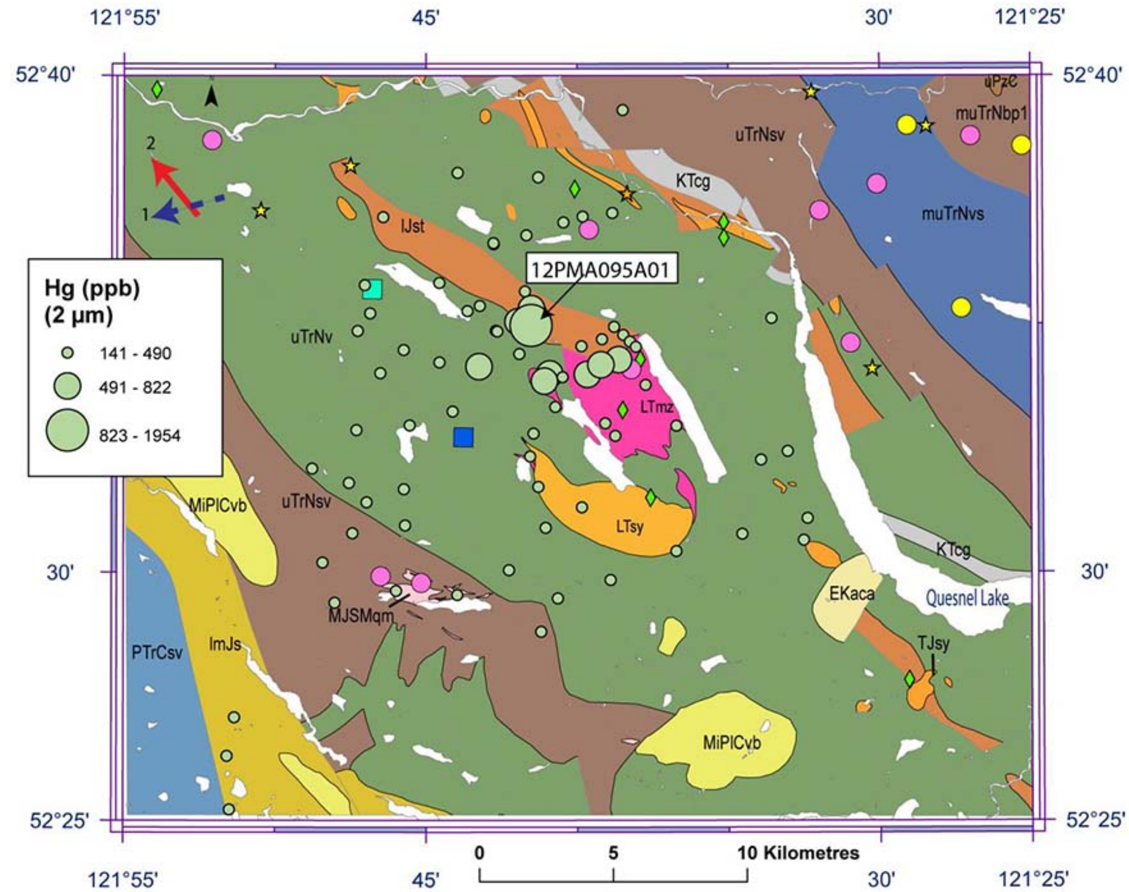

Figure 4.10: ***Proportional dot plot for Hg. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.***

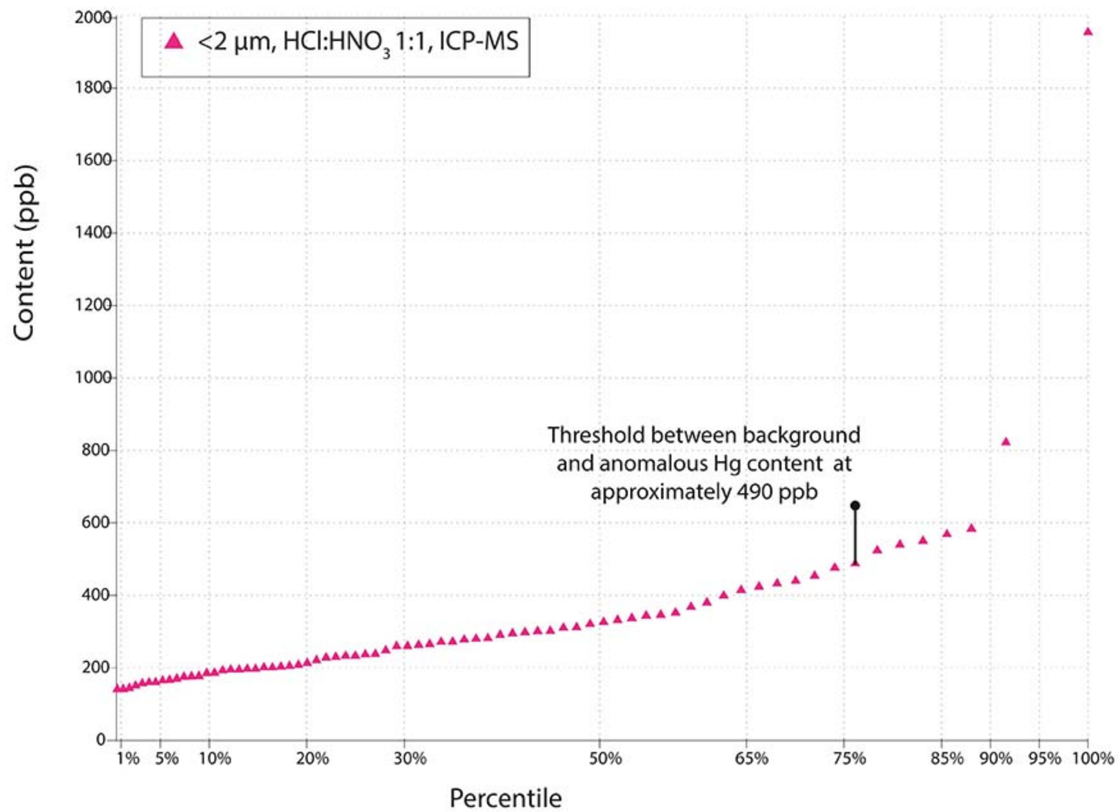

Figure 4.11: Cumulative probability plot for Hg in the clay-sized fraction (<2 µm).

Zinc contents range from 70 to 219 ppm, with the threshold determined as 150 ppm (Fig. 4.12), occurring at approximately the 75th percentile (Fig. 4.13). Samples overlying the intrusion range from 116 to 212 ppm Zn. Till samples immediately down-ice of mineralization contain 87 to 210 ppm Zn with the farthest sample at 1.9 km (minimum distance) (12PMA084A01; 184.3 ppm). The highest content of 219 ppm is observed in sample 12PMA080A01, which was collected 330 m down-ice (northwest) of the deposit. Including the anomalous Zn samples overlying the Mount Polley deposit, the maximum down-ice (northwest) dispersal distance is estimated as approximately 3.4 km. One isolated sample located further to the northwest (12PMA585A01) contains anomalous Zn value (171 ppm). This anomaly coincides with a chalcopyrite anomaly (see chalcopyrite below).

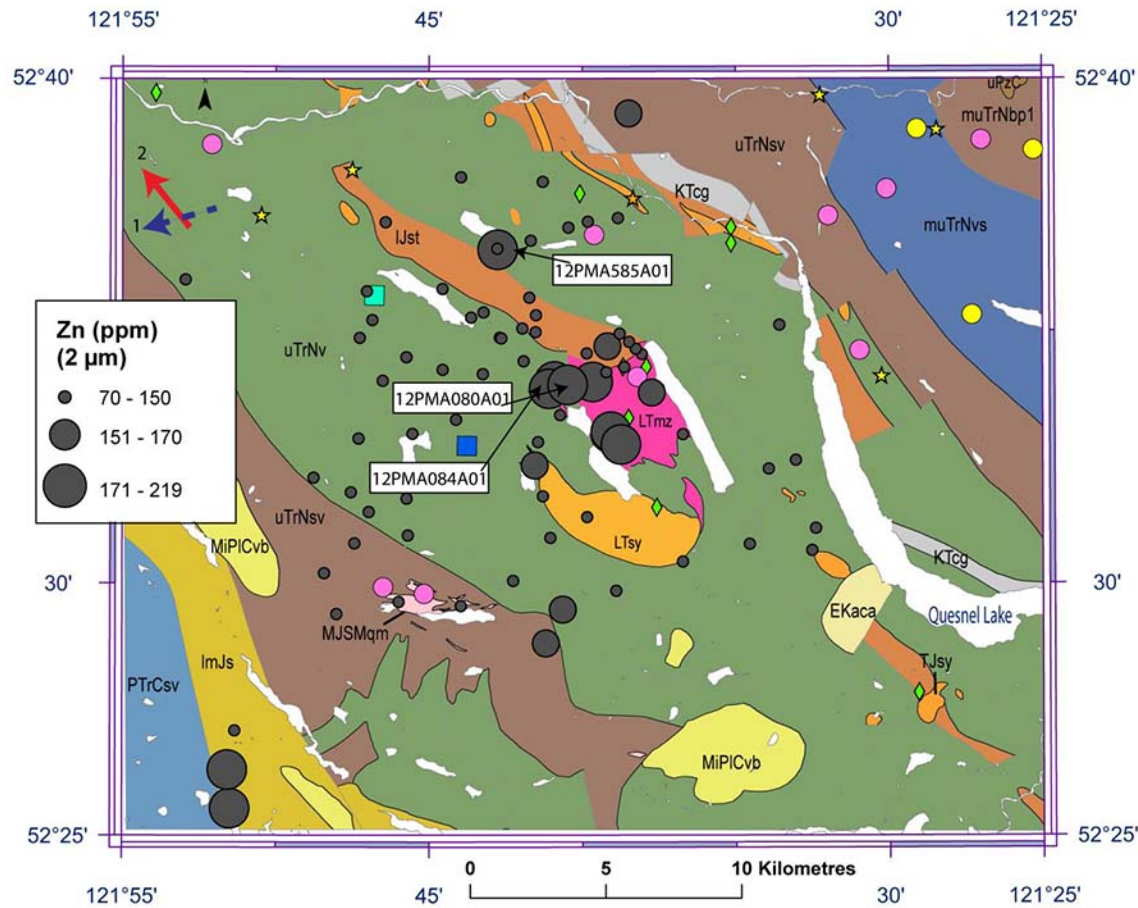

Figure 4.12: Proportional dot for Zn. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.

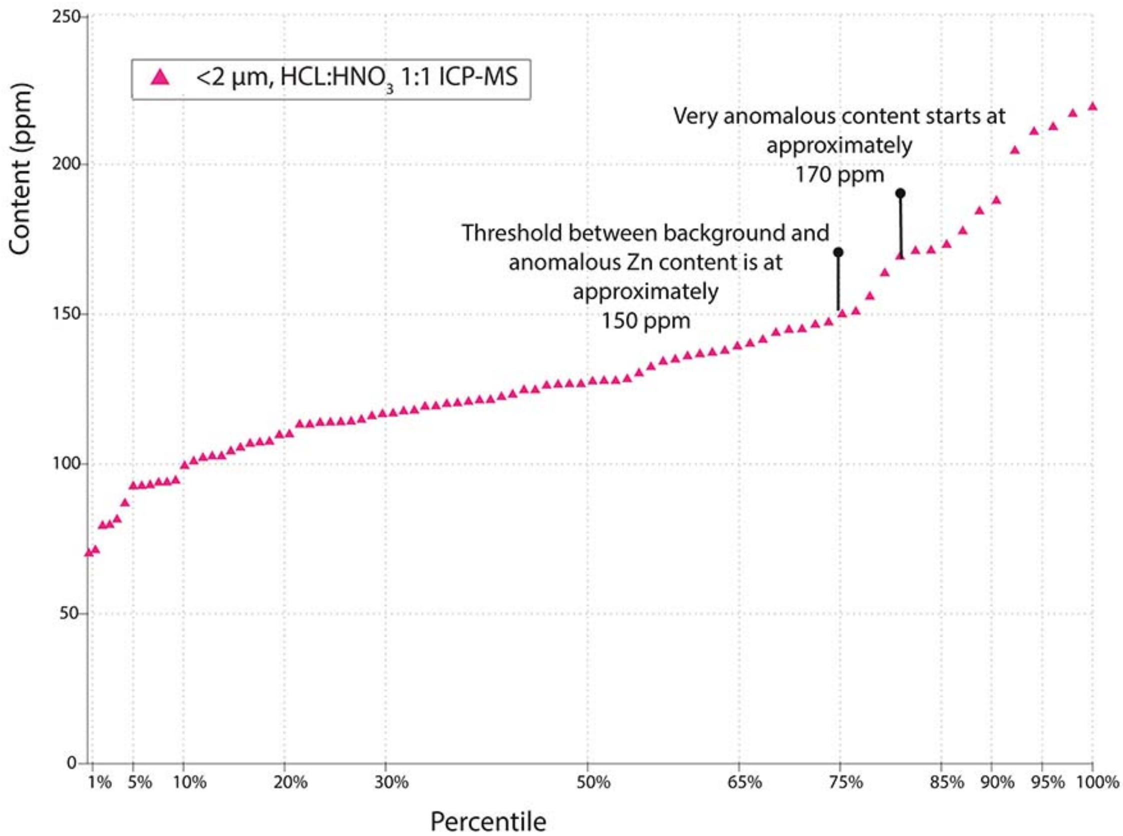

Figure 4.13: Cumulative probability plot for Zn in the clay-sized fraction (<2 µm).

4.4.4. Till mineralogy

Porphyry indicator minerals (PIMs) recovered from till samples in this study are: 1) mid density (2.8-3.2 s.g.) to high density (> 3.2 s.g.) minerals; 2) strongly to somewhat resistant to physical and chemical weathering; and 3) associated with, and characteristic of porphyry deposits (Averill 2011). These minerals have physical characteristics (colour, shape, size), which make them visually distinguishable from other constituent minerals in a medium to heavy mineral concentrate of a sediment sample. We have identified several potential Cu-Au PIMs associated with mineralization (chalcopyrite and gold grains) and alteration minerals (andradite garnet, apatite, epidote and jarosite), that can be used to detect regional scale alteration associated to Cu-Au porphyry deposits in drift covered area.

4.4.5. Ore minerals: Chalcopyrite (0.25-0.5 mm; > 3.2 s.g.) and gold grains (0.015-0.425 mm)

Chalcopyrite is the dominant ore mineral at Mount Polley, hosting Cu and native Au inclusions (Rees 2013). Chalcopyrite is observed in 21 till samples, ranging between 1 to 98 grains (normalized grain count) (Table 4.1; 4.2) (Fig. 4.14). Based on the spatial distribution of chalcopyrite grain counts in the till samples, the background is estimated to be 0 to 1 grain per sample. Of the 10 anomalous samples, four overlie the deposit. The highest grain count (98 grains) was observed approximately 840 m to the northwest (12PMA501A01). Twelve chalcopyrite grains were recovered from sample 12PMA585A01, 6 km northwest of Mount Polley (coinciding with the Zn anomaly). The farthest anomalous sample northwest of the deposit is 12PMA586A01, approximately 10 km northwest of Mount Polley and contains 2 chalcopyrite grains. The minimum and maximum dispersal distances for chalcopyrite grains down-ice (northwest) of Mount Polley are approximately 10 km and 12 km, respectively.

Chalcopyrite distribution in till samples taken west and southwest of the Mount Polley intrusive complex is indicative of glacial transport towards the southwest. For example, samples 12PMA092A01 (3 grains of chalcopyrite normalized to a 10 kg sample), 12PMA092A02 (6 grains), 12PMA093A01 (3 grains of chalcopyrite normalized to a 10 kg sample) and 12PMA101A02 (3 grains of chalcopyrite normalized to a 10 kg sample) are anomalous. Based on their position relative to the Mount Polley Intrusive Complex, they are suggestive of a palimpsest dispersal (initial southwestward dispersal re-entrained into the later northwestward dispersal).

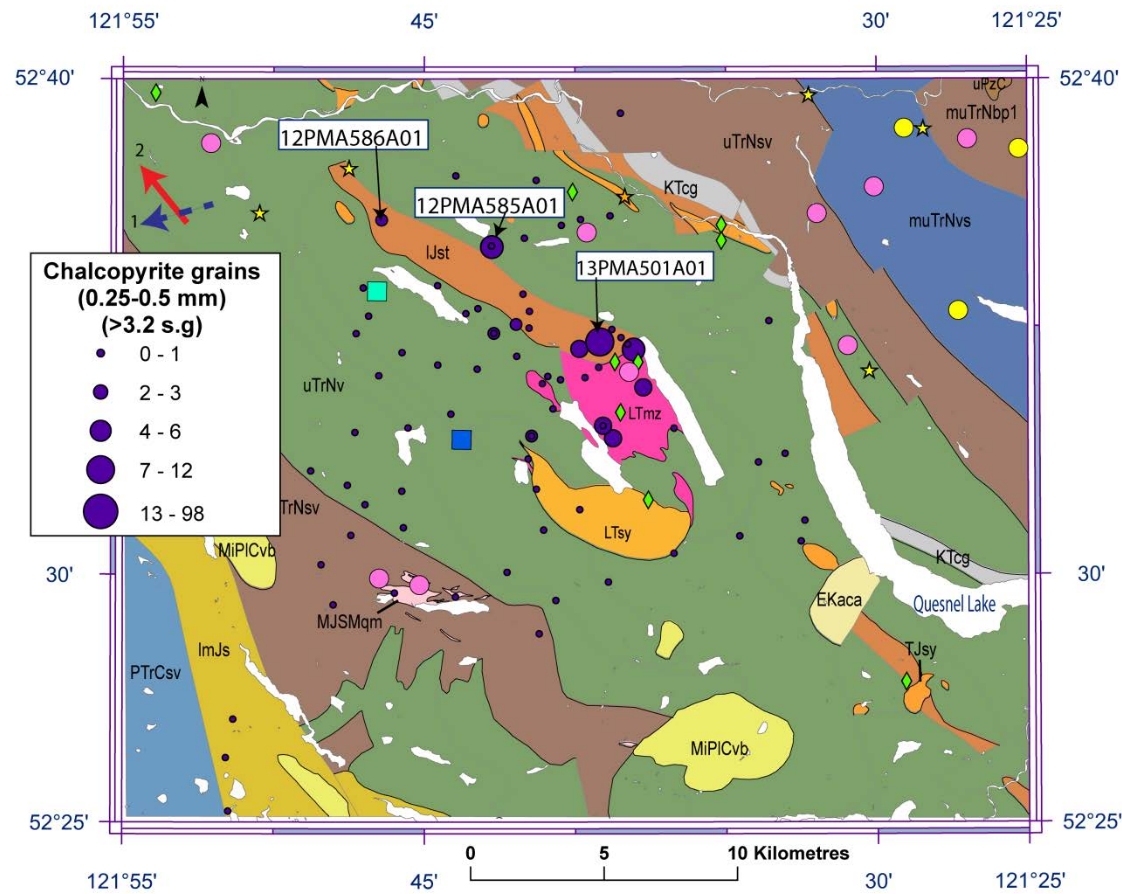

Figure 4.14: Proportional dot plot for chalcopyrite grain. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.

Normalized gold grain counts range between 0 to 105 grains. With two exceptions, all till samples containing > 15 gold grains were taken overlying the Mount Polley deposit, as well as to the southwest and northwest of the intrusion, i.e. down-ice of the deposit based on the two phases of ice flow (Fig. 4.15). Therefore, the regional threshold for gold grain content in till is determined to be 15 grains. The minimum and maximum dispersal distances for gold grains down-ice (northwest) of Mount Polley are 5.2 km and 7 km, respectively.

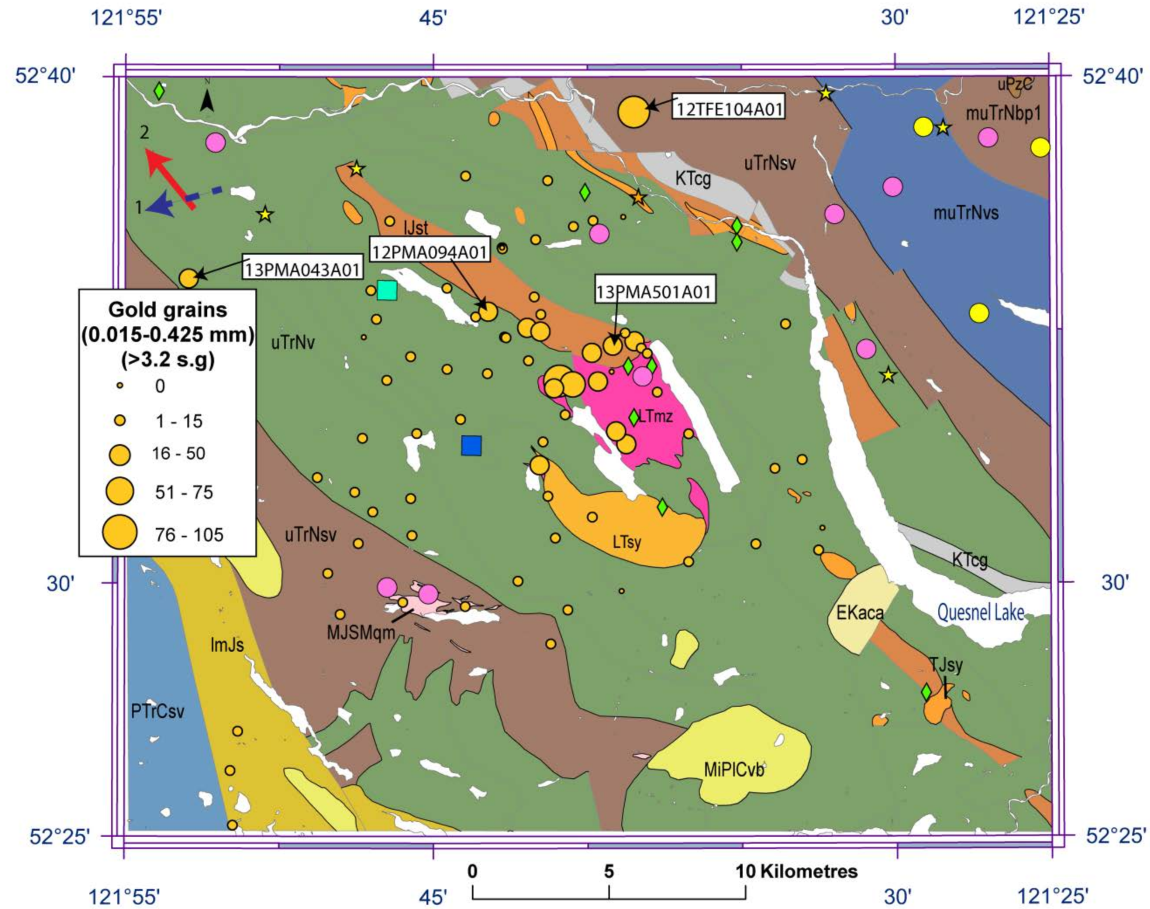

Figure 4.15: ***Proportional dot plot for gold grains. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.***

The small size of gold grains recovered from till (0.015 to 0.425 mm) correspond to the micron-scale gold inclusions reported in the porphyry mineralization (in the northeast zone) at Mount Polley (Rees 2013). Till samples collected close to the Mount Polley mineralization generally contain a larger relative amount of pristine gold grains (as defined by DiLabio 1990*b*) compared to distal samples. For example, sample 13PMA501A01, located less than one kilometer from the Mount Polley mineralization, contains 33 gold grains (normalized gold grain counts is 41 grains per 10 kg) of which 15 are pristine in shape. On the other hand, sample 12PMA094A01, located approximately 5.2 km northwest (down-ice) of the mineralization, contains 38 gold grains (normalized gold grain counts is 40 grains per 10 kg) of which 5 are pristine.

4.4.6. *Alteration minerals: andradite garnet (0.25-0.50 mm, > 3.2 s.g.), apatite (0.25-0.50 mm, > 3.2 s.g.), epidote (0.25-0.50 mm, > 3.2 s.g.) and jarosite (0.25-0.50 mm, 2.8-3.2 s.g.)*

Andradite garnet is known to occur in alteration zones associated with porphyry deposits (Averill 2011; Kelley *et al.* 2011; Celis *et al.* 2014). It was identified by its yellow, brown and orange colour and crystal form in 63 of the 87 till samples. Grain counts ranged from 1 to approximately 78,000 (Fig. 4.16; Table 4.1, 4.2). The four samples with the greatest amount of andradite (> 290 grains) are located overlying and along the west margin of the Mount Polley Intrusive Complex as well as in one sample at 2.6 km northwest of the intrusion (13PMA521A01; 1980 grains). The minimum and maximum dispersal distances for andradite garnet down-ice (northwest) of Mount Polley are 2.6 km and 5.5 km, respectively.

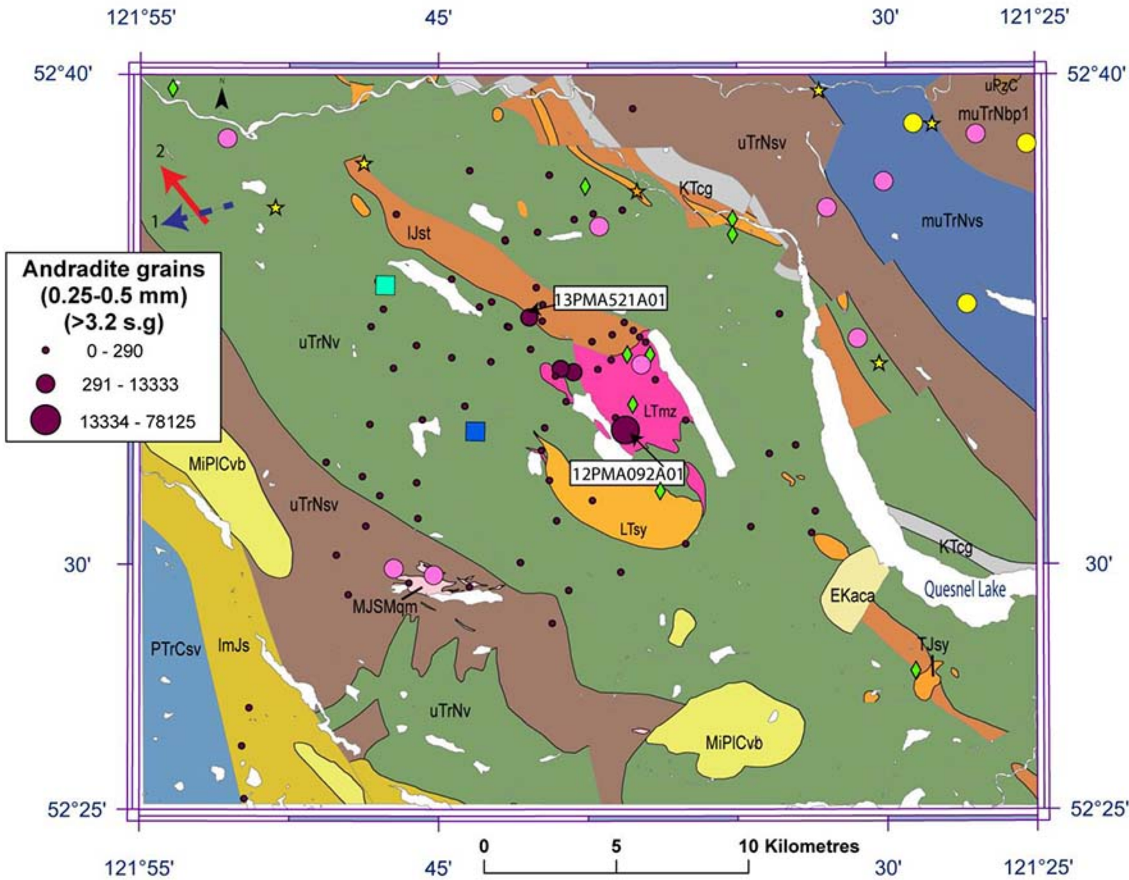

Figure 4.16: ***Proportional dot plot for andradite garnet grains. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.***

Apatite is a resistate mineral known to occur in calc-alkaline and alkaline Cu-porphyry deposits (Bouzari *et al.* 2011; Celis *et al.* 2013, 2014). Apatite recovered from till at Mount Polley is colourless and occurs in only 22 samples (Fig. 4.17). Eighteen samples distributed throughout the study area contain only traces of apatite (i.e. 0.1%). In contrast, samples containing 0.5-3% apatite are located over the deposit and up to 2.6 km down-ice (northwest) of the deposit. The highest apatite content (3%) was reported for sample 13PMA520A01, which is located approximately 2.2 km to the northwest of the deposit. The minimum and maximum dispersal distances for apatite down-ice (northwest) of Mount Polley are 2.6 km and 3.2 km, respectively.

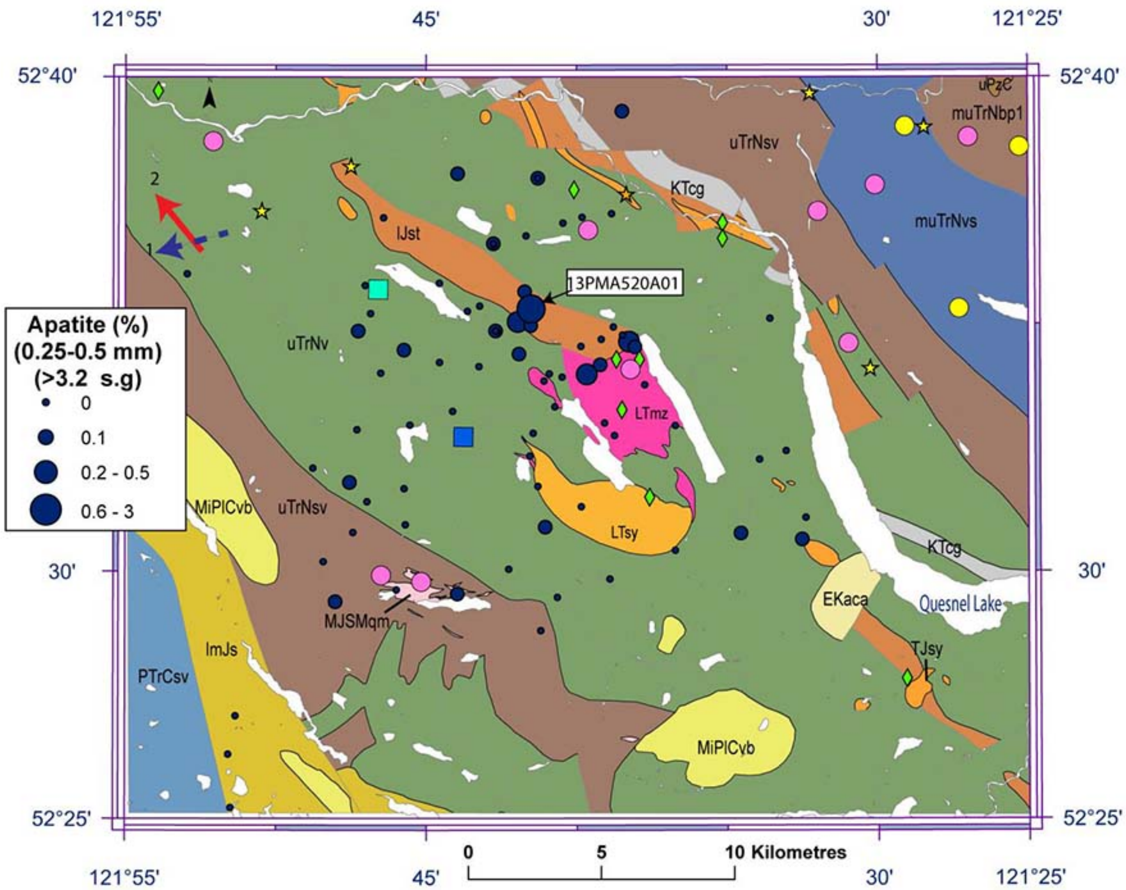

Figure 4.17: ***Proportional dot plot for apatite. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.***

Epidote is a resistate mineral known to occur in Cu, Cu-Au and Cu-Au-Mo porphyry deposits (Averill 2011; Kelley *et al.* 2011; Rees *et al.* 2014). The epidote reported here is of pistachio green color and therefore different than the Mn-epidote reported by Kelley *et al.* (2011) for the Pebble porphyry deposit in Alaska. Samples with more than 15% epidote were taken overlying, southwest and northwest of the Mount Polley Intrusive Complex, (i.e. down-ice, if considering both phases of ice flow; Fig. 4.18). In fact the highest epidote value (90%) was reported for sample 12PMA101A01, taken approximately 2 km down-ice (southwest) of the Mount Polley deposit. The approximate minimum and maximum northwestward dispersal distances for epidote are 2.6 km (13PMA521A01) and 3.4 km, respectively. Further, the approximate minimum and maximum southwestward dispersal distances for epidote are 2.6 km (12PMA100A01) and 5.5 km, respectively.

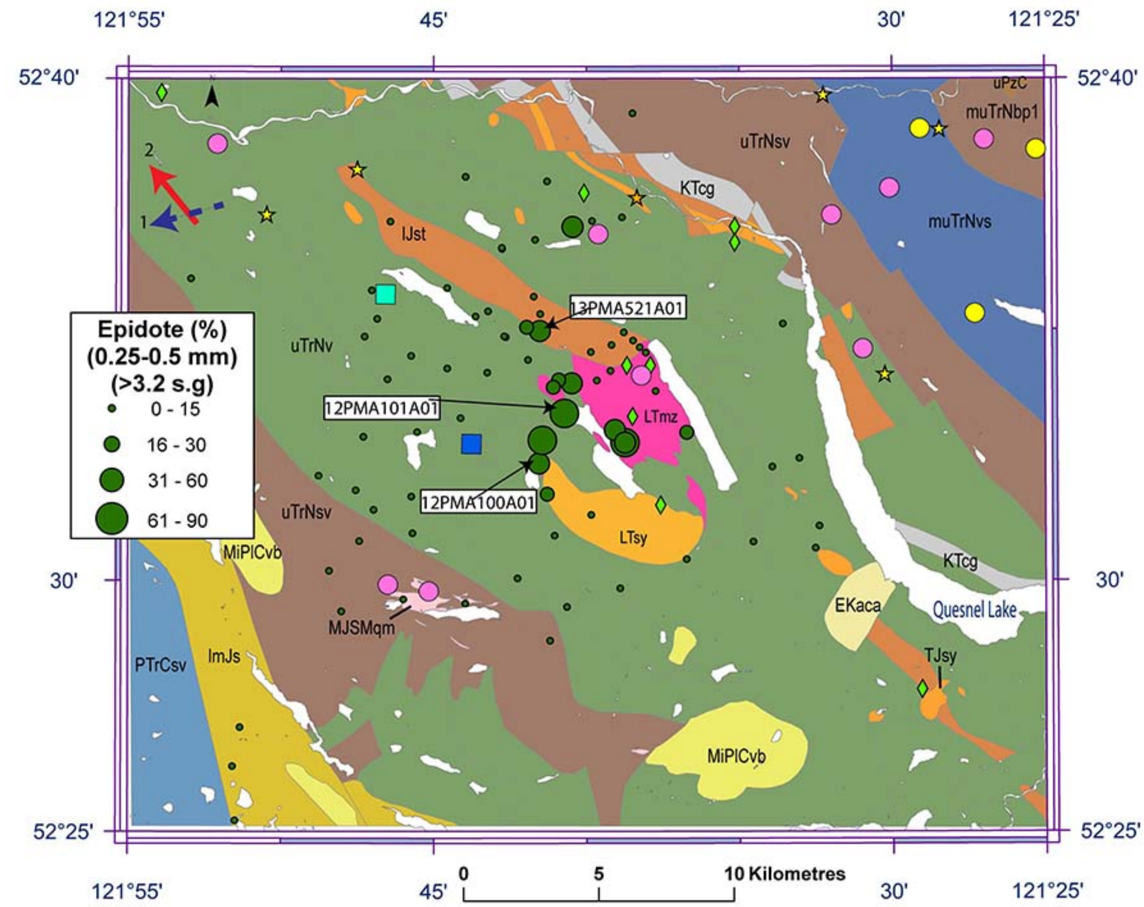

Figure 4.18: ***Proportional dot plot for epidote. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.***

Jarosite is known to occur in supergene alteration associated to Cu porphyry deposits (Averill 2011; Kelley *et al.* 2011). Jarosite grains recovered from till samples occurred in only 8 samples, ranging from 1 to 74 grains typically sub-angular with a pinkish color. Of these, only 4 samples contain more than one jarosite grain. The highest jarosite grain count (74 grains) is recovered from sample 12PMA092A02, taken over the Mount Polley deposit (Fig. 4.19). The farthest anomalous jarosite grain count was recovered from sample 13PMA503A01, approximately 4.4 km down-ice (northwest) of Mount Polley and contains 19 jarosite grains. Therefore, the minimum and maximum dispersal distances for jarosite are approximately 4.4 km and 5.9 km, respectively.

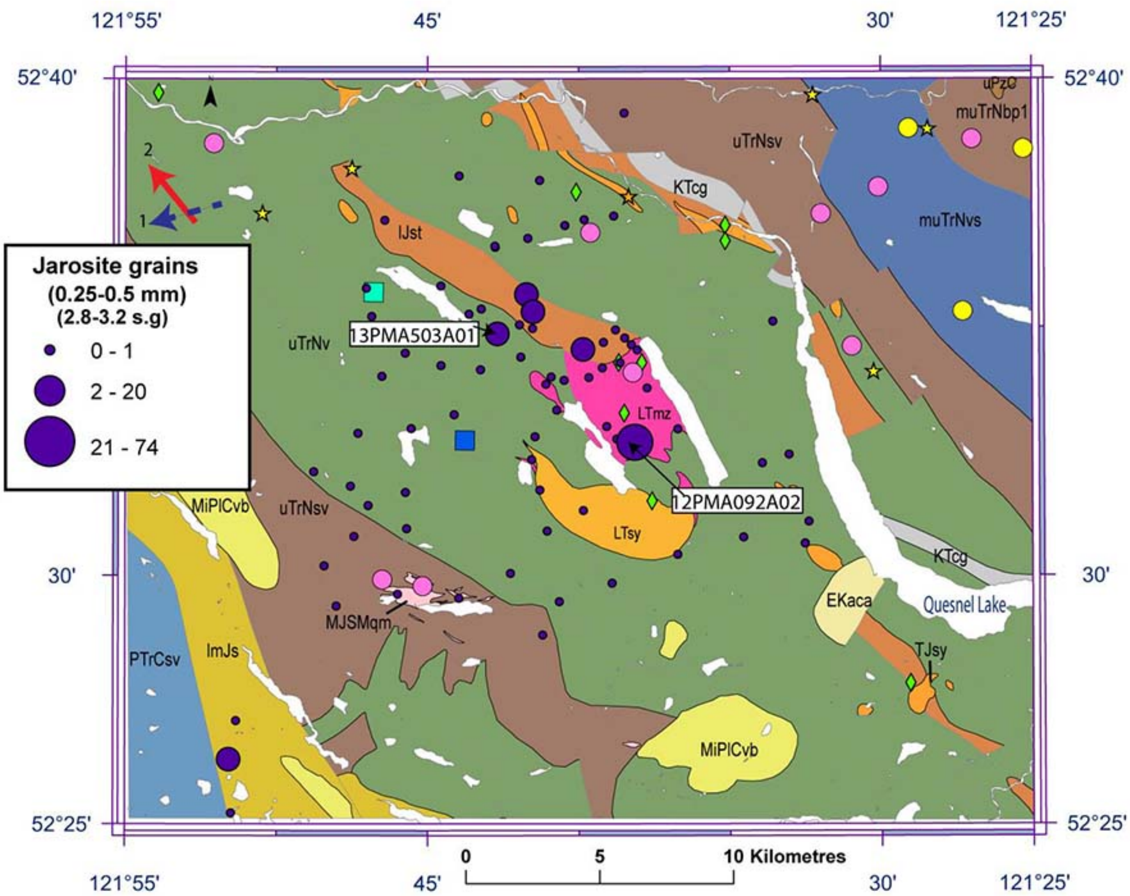

Figure 4.19: ***Proportional dot plot for jarosite. The sample sites labeled are discussed in the text. Generalized regional ice-flow movements are shown with the blue and red arrows.***

Table 4.1: Summary of PIMs data in till for the region of the Mount Polley deposit. Grain contents are normalized to 10 kg bulk sediment (<2 mm) except for apatite and epidote which are reported as percentages.

Mineral (0.25-0.5 mm) Gold grains (0.15-0.425 mm)	Content range	Highest content (Sample no.)	No. of till samples containing the mineral	Background range
Apatite %	0-3	3% (13PMA520A01)	22	0-0.1
Andradite grains	0-78125	78125 (12PMA092A01)	63	0-290
Chalcopyrite grains	0-98	98 ((13PMA501A01)	21	0-1
Epidote %	0-90	90% (12PMA101A01)	55	0-15
Gold grains	0-105	105 (12TFE104A01)	83	0-15
Jarosite grains	0-74	74 (12PMA092A01)	8	0-1

4.5. Pebble lithology

The lithological composition of the pebble sized fraction of the till samples was identified with the aim of determining the spatial extent of glacial dispersal of intrusive clasts in till, assumed to have been eroded off the Mount Polley Intrusive Complex and dispersed northwest by glaciers. A few samples were also chosen randomly (Fig. 4.20) in the study area to determine the regional intrusive count and their potential source. The spatial distribution of the pebble lithologies are plotted (in ArcGIS) as pie charts.

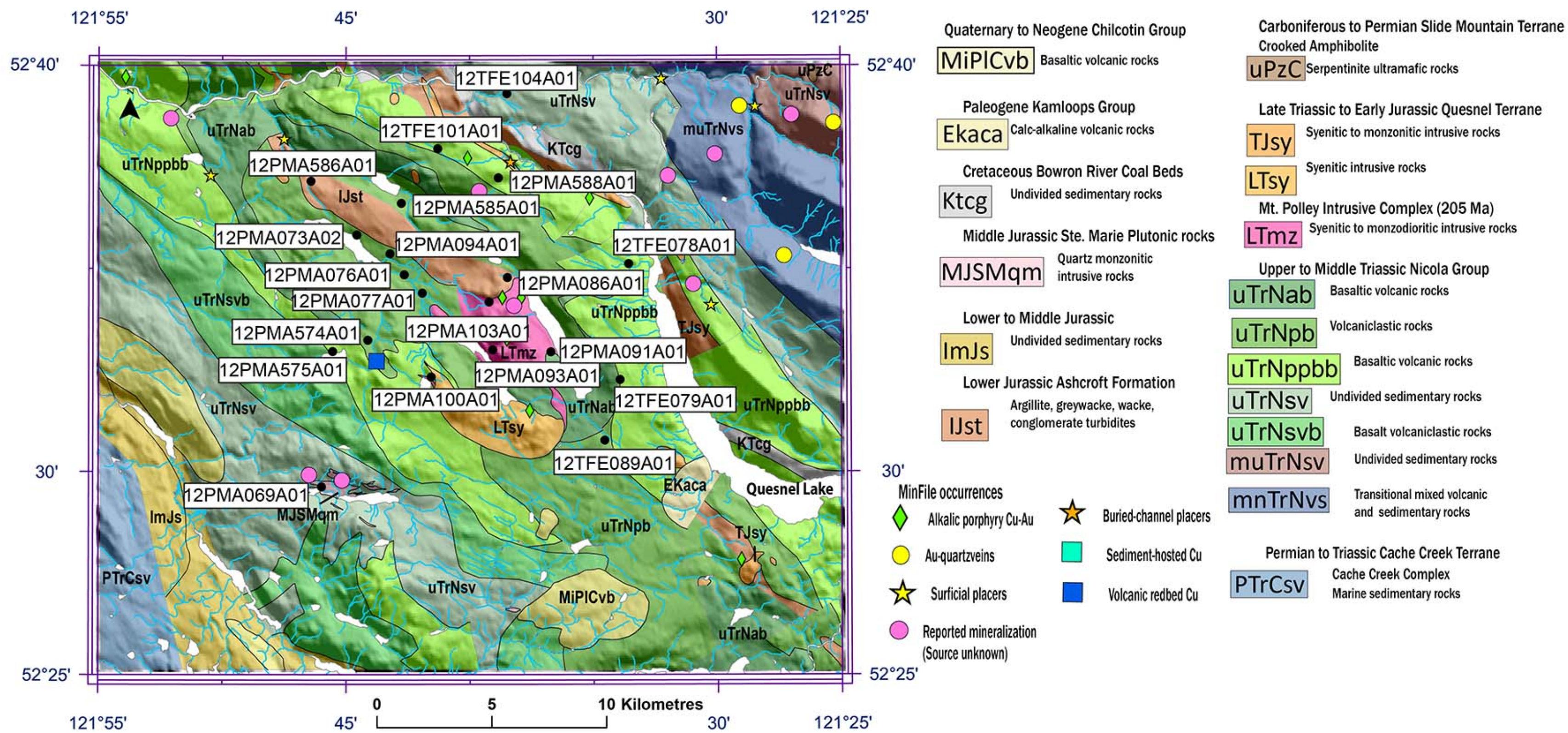

Figure 4.20: Pebble lithology sample sites.

4.5.1. Intrusives

Generally, the intrusive clasts examined were angular to sub-rounded and compared to the volcanic and sedimentary pebbles, larger in size (Fig. 4.21; 4.22). Overall, the intrusive rocks identified in the samples include monzonites, diorites, monzodiorites and peridotites, all associated with the Mount Polley Intrusive Complex and the late Triassic syenitic intrusive body, southwest of Mount Polley. No mineralized clasts were identified in the pebble size fraction. Lithologies within each sample are not individually identified due to the large sample size and time constraints.

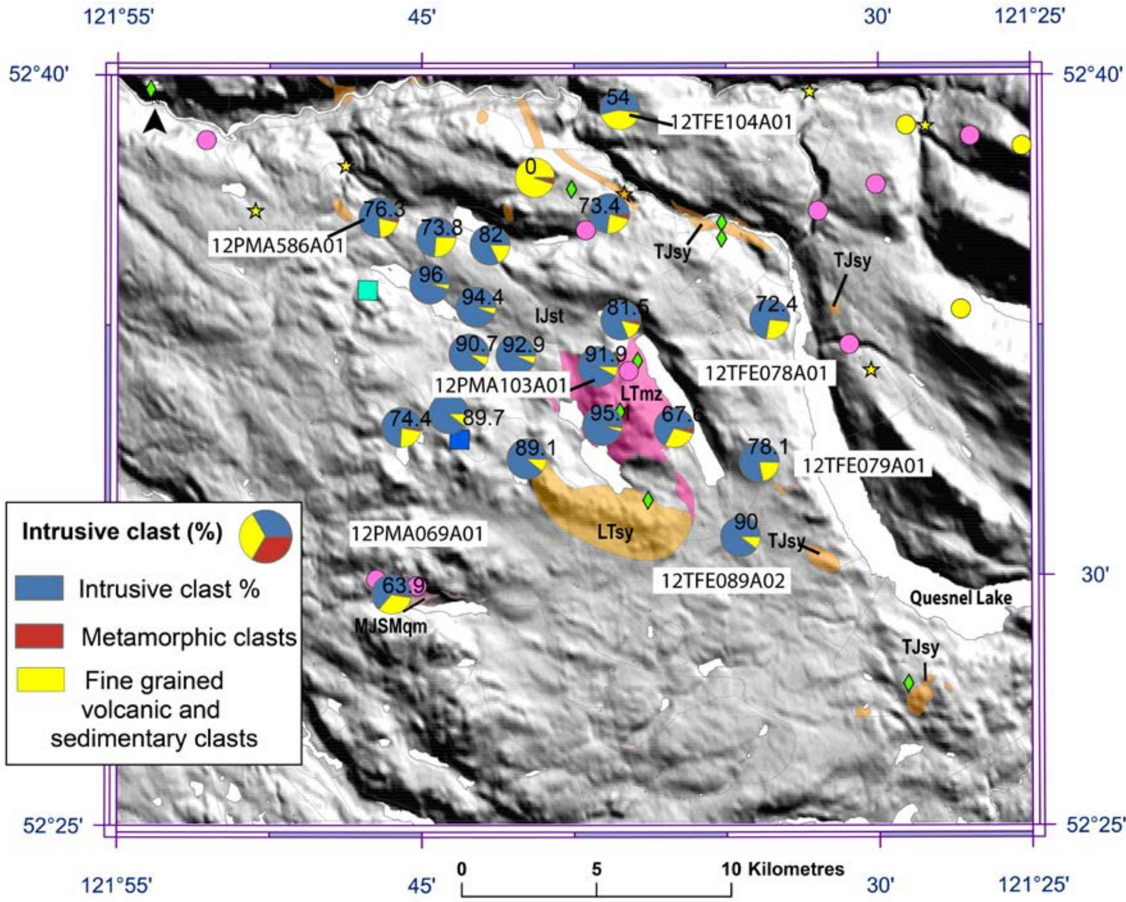

Figure 4.21: ***Pie chart representing intrusive, fine-grained volcanic and sedimentary and metamorphic clast percentage identified in the Mount Polley region. The number over the pie charts is the % intrusive clasts identified from the sample. Bedrock geology (only intrusive units are colored) is modified after Logan et al. (2007).***

Overall, intrusive clasts collected within and immediately down-ice from Mount Polley are angular, whereas the intrusives identified in samples some distance down-ice from Mount Polley vary from angular to sub-angular. The highest number of intrusive clasts (comprising 92% of the sample) was recovered from sample 12PMA103A01, collected over the Mount Polley Intrusive Complex. Intrusive content ranging 96% to 74% is observed in samples at least as far as 10 km to the northwest of the Mount Polley Intrusive Complex (12PMA586A01; comprising 76%). The source of these intrusives may be the main body of the Mount Polley Intrusive Complex or a smaller intrusive body immediately west of it. Isolated high counts are recorded elsewhere in the study area including samples 12TFE104A01, 12TFE078A01, TFE079A01, 12TFE089A02 and 12PMA069A01. Of these, samples 12TFE104A01, 12TFE078A01 and 12TFE079A01 also contain elevated Ag, Au, Cu and/or gold grain content. The most likely source of the intrusives (intrusive count 78%; 442 ppm Cu) (Fig. 4.21, 5.1) present in 12PMA079A01 is the syenitic to monzonitic intrusive rocks (Late Triassic to Early Jurassic) approximately 900 m southeast of the sample site. Similarly, the high intrusive count in sample 12TFE078A01 (72%) is the syenitic to monzonitic intrusive rocks unit 2.2 km east northeast of the sample.

The likely source of the high intrusive count in sample 12TFE104A01 (54%; normalized gold grain count: 105; 31 ppb Au; 192 ppb Ag) is the Late Triassic to Early Jurassic, syenitic to monzonitic intrusive rock unit (TJsy). This unit is located approximately 3.8 km to the southeast of the sample site and also has two MinFile occurrences for alkaline Cu-Au porphyry. An elevated count of intrusive clasts is also observed in sample 12PMA069A01 (making up 64% of the sample), which is most likely associated with the intrusives occurring in the Ste. Marie Plutonic group (MJSMqm). Further, the most probable source of intrusives present in samples 12PMA574A01 (90%) and 12PMA100A01 (89%) is the Late Triassic syenitic intrusive unit (LTsy).

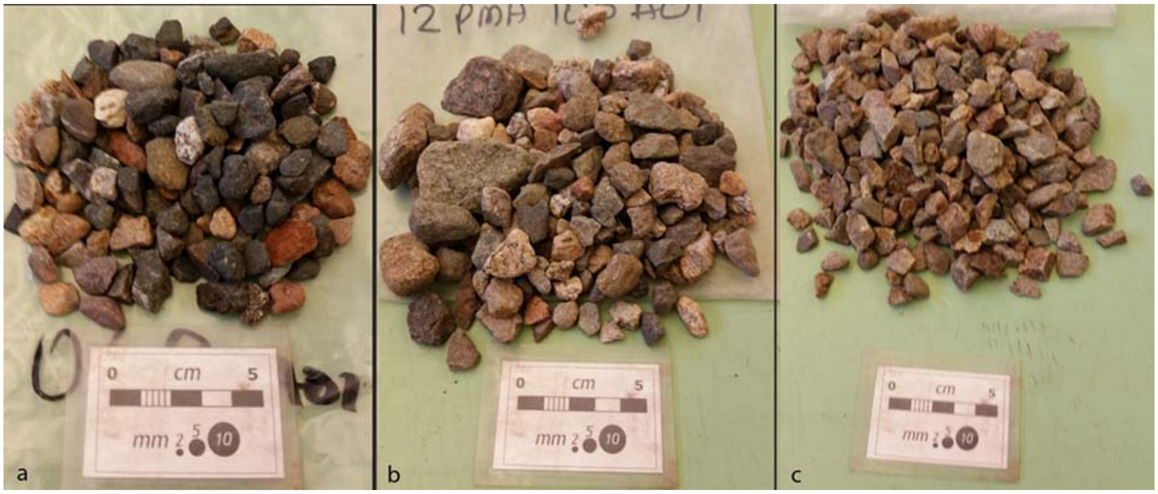

Figure 4.22: ***Separated intrusives from >8 mm pebble fraction of the till sample; (a) Sample 12PMA069A01; (b) Sample 12PMA100A01; (c) Sample 12PMA093A01.***

4.5.2. Fine grained sedimentary and volcanic rocks

Fine-grained sedimentary and volcanic rocks are the most prevalent rock units mapped in the region (Fig. 4.23; 4.24). Generally they are slightly smaller than the clasts of intrusive rocks, sub-angular to rounded, pitted and contain micro-striations because they are easier to erode and imprint. Although the category includes both volcanic and sedimentary rocks; the dominant clast type is volcanic, primarily Nicola volcanics. The percentage of sedimentary and volcanic pebbles in the samples varies from 4% to 95%. Samples taken immediately down-ice from Mount Polley contain as little as 4% to 20% and this amount increases as the distance down-ice from Mount Polley increases. The sample with the highest sedimentary and volcanic pebble count of 95% is 12TFE101A01.

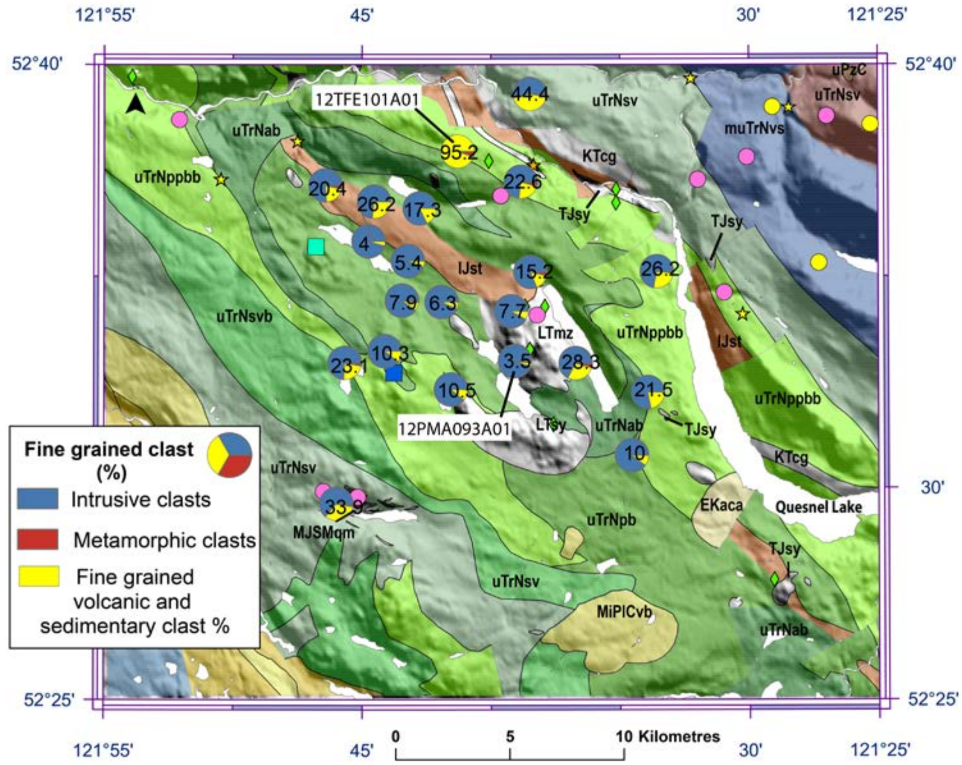

Figure 4.23: ***Pie chart representing intrusive, fine-grained volcanic and sedimentary and metamorphic clast percentage identified in the Mount Polley region. The number over the pie charts is the % fine-grained sedimentary and volcanic clasts identified from the sample. Bedrock geology (only volcanic and sedimentary units are colored) is modified after Logan et al. (2007).***

The most probable source of volcanics in this sample is the basaltic and volcanic rocks of the Nicola group (uTrNppbb) underlying and southeast of the sample site. The lowest fine-grained, volcanic and sedimentary pebble count is in samples overlying and immediately down-ice of the Mount Polley Intrusive Complex. For example, sedimentary and volcanic pebbles make up approximately 4% of sample 12PMA093A01. The most likely source of the volcanics (fine-grained mafic) is the Nicola group (uTrNab) immediately south, south east of the Mount Polley Intrusive Complex.

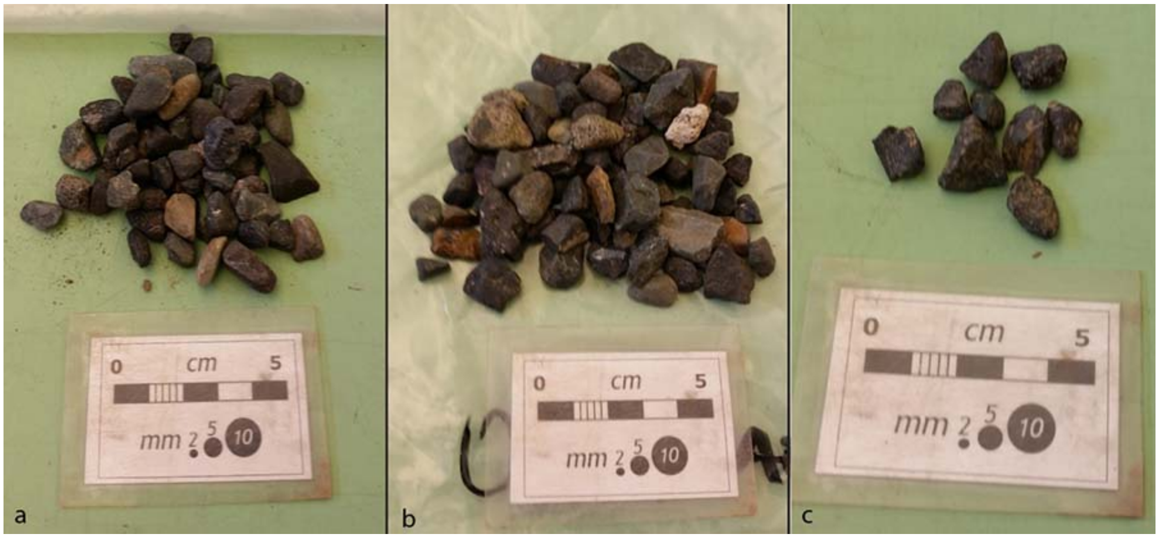

Figure 4.24: Fine-grained sedimentary and volcanic rocks recovered from > 8 mm fraction of the till samples; (a) sample 12PMA073A01, (b) sample 12PMA069A01, (c) sample 12PMA093A01.

4.5.3. Metamorphic rocks

Metamorphic rocks, dominantly schist, make up a minute proportion, (3 to 4.8%) of samples because of the rarity of metamorphic rock units in the area. All metamorphic rocks range sub-rounded to rounded, suggesting long transport distance (Fig. 4.25; 4.26).

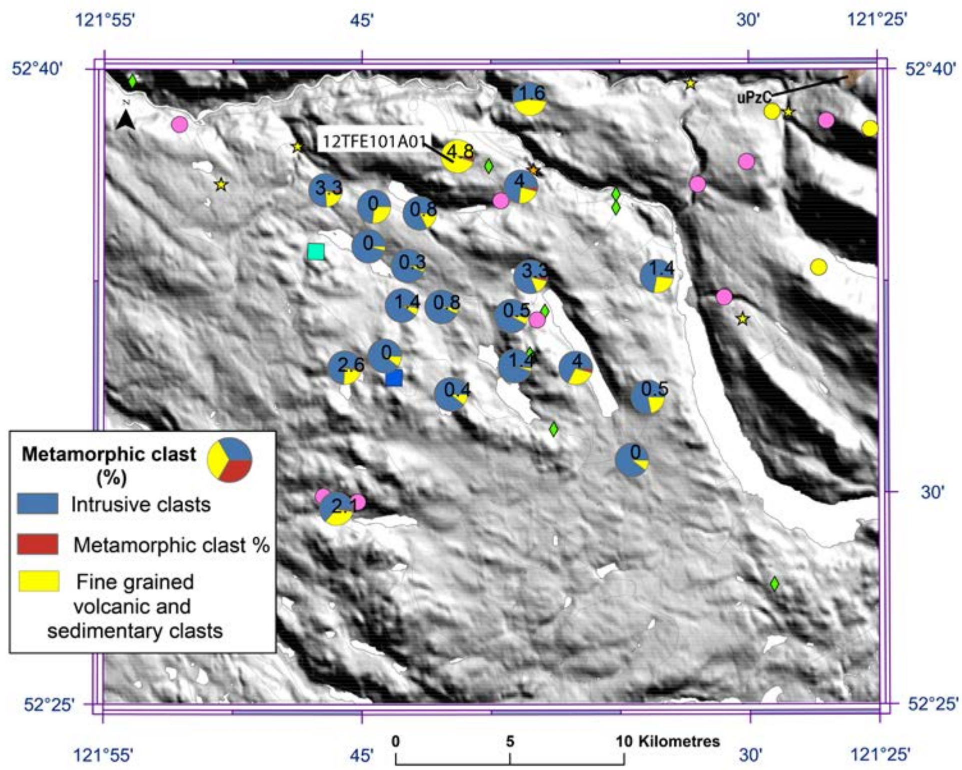

Figure 4.25: ***Pie chart representing intrusive, fine-grained volcanic and sedimentary and metamorphic clast percentage identified in the Mount Polley region. The number over the pie charts is the % metamorphic clasts identified from the sample. Bedrock geology (only 1 metamorphic unit in the northwest corner "uPzC Crooked amphibolite" is colored) is modified after Logan et al. (2007).***

The highest count comprising 4.8% is in sample 12TFE101A01, which may have been eroded and transported from outside the study area. In fact, the only metamorphic unit mapped in the study area is the "Crooked Amphibolite" group, in the northeast corner of the study area and includes serpentinite, amphibolite, talc and schist. Therefore, the most likely source of all the metamorphic pebbles in samples is from outside the study area. For example, a white quartzite pebble recovered from sample 12PMA069A01 (Fig. 4.26) could have been derived from the Cariboo Mountains and suggestive of long distance glacial transport.

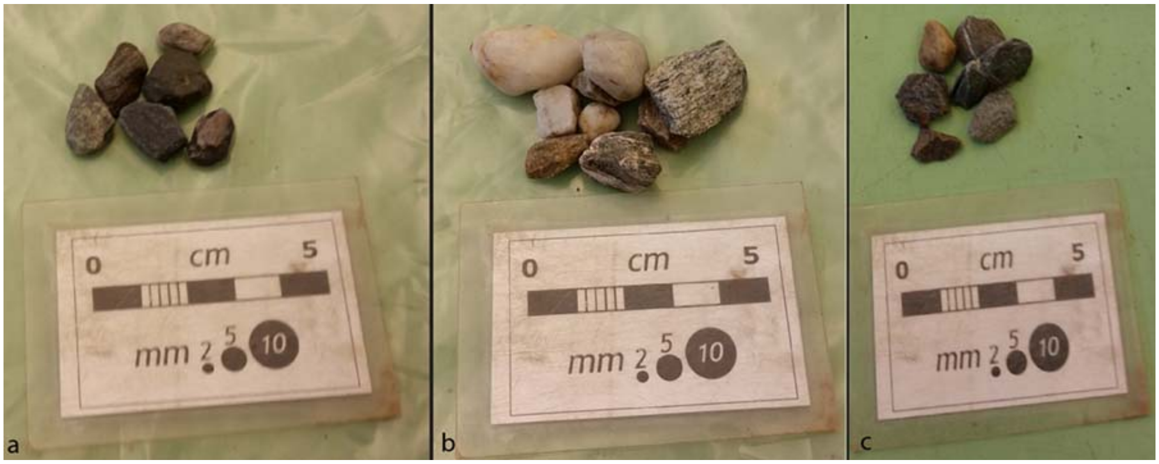

Figure 4.26: ***Metamorphic pebbles recovered from the > 8 mm fraction of the till samples; (a) Sample 12PMA076A01, (b) Sample 12PMA069A01, (c) Sample 12PMA073A01.***

4.6. Discussion

4.6.1. Extent and characteristics of glacial dispersal at Mount Polley

The Mount Polley deposit lies within an intrusive complex, which forms a topographic high (Mount Polley at 1266 m a.s.l) between Bootjack and Polley lakes (Rees 2013). This topographic feature was an obstruction to glacier flow, but was completely overridden by the Cordilleran Ice Sheet. It may have an area where increased glacial erosion occurred (cf. Iverson *et al.* 2012), especially on the up-ice (southeast) end of the intrusive body. Mineralized debris derived from the Mount Polley deposit and alteration zones was eroded, transported, and deposited down-ice (southwest and northwest) resulting in dispersal trains defined by ore elements Ag, Au and Cu, and pathfinder elements Hg and Zn content of till. These ore and pathfinder elements are likely derived from the sulphide minerals (i.e. chalcopyrite, pyrite for Au, Cu and galena for Ag). Pathfinder elements Hg and Zn are likely associated with minerals occurring within the small patch of skarn mineralization (hosting the Pond pit) (Panteleyev 1995; Sinclair 2007). Overall, there is a decrease in element content in till with increasing distance of transport to the northwest, similar to typical glacial dispersal models described by Miller (1984) and DiLabio (1990*b*). The zone of element (and mineral) enrichment in till samples taken overlying and down-ice of the Mount Polley Intrusive Complex extends up to 12 km to the northwest.

Glacial dispersal of ore and pathfinder elements was studied by Sibbick & Kerr (1995) at the alkaline Mount Milligan Cu-Au porphyry deposit located approximately 335 km northwest of Mount Polley (Fig. 1.1). Geochemical analyses of till samples were completed on the silt plus clay fraction using a combination of instrumental neutron activation (INAA) and aqua regia digestion followed by ICP-ES analysis (Sibbick & Kerr 1995). Glacial dispersal was defined at Mount Milligan using As, Au, Cu, K and Fe and the authors suggested that the geochemical dispersal at Mount Milligan extends up to 15 km down-ice (Sibbick & Kerr 1995). This longer distance of glacial transport detectable at Mount Milligan (compared to Mount Polley) might result from one or a combination of the following factors: 1) larger mineralized zone exposed to glacial erosion at Mount Milligan compared to Mount Polley; 2) higher contrast in elemental enrichment between the mineralization and country rocks at Mount Milligan (compared to Mount Polley); and 3) long lived and consistent direction of ice flow, which would have distributed mineralized debris over a long distance at Mount Milligan.

Plouffe *et al.* (2013*b*) reported that chalcopyrite occurred in pre-mining bedrock outcrops in the Northeast Zone (Wight Pit), implying that chalcopyrite bearing rocks were exposed to glacial erosion. Although a common constituent of the Mount Polley deposit and exposed to glacial erosion, chalcopyrite is not abundant down-ice (northwest and southwest) from mineralization, generally less than 7 grains per 10 kg. The small number of chalcopyrite grains down-ice from mineralization could be the result of post-glacial weathering and oxidation of the chalcopyrite in till. Regardless, these results indicate that the presence of chalcopyrite in till can be significant and represents a useful indicator mineral for Cu-Au porphyry mineralization.

Sample 12TFE104A01, located approximately 9 km to the north of the Mount Polley porphyry deposit, contains an anomalous content of gold grains (normalized gold grain count 105). This anomaly is inconsistent with the Mount Polley deposit being the bedrock source, based on known ice-flow trajectories. Gold grains in 12TFE104A01 are likely derived from a buried Au placer deposit, similar to the Bullion Pit placer deposit, or from mineralized bedrock source in that region. The dominance of modified and reshaped gold grains support a placer source; however, the presence of 17 pristine grains in the same sample implies that these gold grains have not been transported very far and might be derived from a local bedrock source (Logan & Mihalynuk 2005). Similarly, the source of gold grain content (30 grains; 19 reshaped, 10 modified, 1 pristine) in a till sample (13PMA043A01) taken approximately 15 km to the west northwest of the Mount Polley deposit is unknown.

Our results support the observation that the shape of gold grains (pristine, modified and reshaped) can provide an estimation of the distance of glacial transport with pristine gold grains having generally sustained shorter transport compared to modified and reshaped gold grains (DiLabio 1990*a*). However, we cannot rule out that pristine gold grains identified in till at various distances from the Mount Polley mineralization might have been liberated from weathered sulphide rich clasts in till (as suggested by DiLabio, 1990*a*) or might be derived from unknown mineralization close to the sample location.

The distribution of andradite garnet is heterogeneous in the till samples but enrichment near the deposit is observed compared to the regional data. Andradite garnet present in till sampled down-ice of the Mount Polley deposit may originate from multiple alteration zones within the Mount Polley Intrusive Complex, including the sodic-potassic, potassic, and skarn-like alteration zones Celis *et al.* (2014) report that the garnets recovered from the sodic-potassic alteration zone are characterized by their brown to honey-brown colour, similar to the brown andradite grains identified in till samples in this study. Consequently, andradite garnet may be a useful indicator mineral for the Cu-Au Mount Polley deposit. Andradite garnet is also an indicator mineral at the giant Pebble porphyry deposit in Alaska (Kelley *et al.* 2011; Eppinger *et al.* 2013).

At Mount Polley, several alteration zones contain epidote (Rees *et al.* 2014). Mapping of the alteration zones has been completed to only within 1-2 km of the mine (Fraser 1994; Logan & Mihalynuk 2005). The propylitic alteration, with abundant epidote, has been principally defined along the southern margin of the intrusion. The distribution of epidote in till southwest and northwest of the mine is interpreted to reflect a combination of the location of propylitic alteration at the southern margin of the intrusion and glacial transport to the southwest and northwest.

We have observed large numbers of accessory minerals (andradite garnet, apatite, epidote and jarosite) in till, which we interpret to have been derived from the alteration zones associated with the Mount Polley deposit. However, these minerals could also be derived from other bedrock sources. Therefore, their physical (optical) properties and chemical composition need to be better characterized to determine their bedrock source, similar to the studies conducted on the compositional characteristics of PIMs such as apatite, magnetite and garnet (Bouzari *et al.* 2011; Celis *et al.* 2013, 2014; Grondahl 2014; Piziak *et al.* 2015).

4.6.2. Comparison between till geochemistry and mineralogy

Comparisons between the ore elements and ore minerals highlight several similarities and differences. The chalcopyrite (and Ag) anomaly associated with Mount Polley extend as far as 10 km down-ice (northwest) (12PMA586A01), whereas the Au anomaly in till extends to 8.5 km and gold grain count to 5.2 km (Table 4.1, 4.2). Further, even though Au anomaly extends further down-ice (northwest) than the gold grain count anomaly, anomalous gold grain content (normalized to 40 gold grains) was recovered from samples containing background Au values (4.8 ppb) (e.g. sample 13PMA043A01). These results attest to the heterogeneous distribution of gold in sediments (nugget effect) and reveal that combining till geochemistry and mineralogy increases the probability of intercepting gold dispersal in till. Several samples collected immediately down-ice from Mount Polley (<1 km) with background values for Cu also contained background values for chalcopyrite (e.g. 13PMA500A01, 12PMA086A01, 12PMA087A01).

Processing for PIMs has several advantages and complements the till geochemistry at Mount Polley. For example, sample 13PMA520A01 taken 2.2 km to the northwest of Mount Polley contained anomalous Cu (597 ppm), Au (18.7 ppb) and Hg (698 ppb) values as well as abundant apatite (3%) (Table 4.1). Similarly, sample 13PMA521A01 taken 2.6 km down-ice (northwest) of Mount Polley contained anomalous Cu (525 ppm) and Au (17.6 ppb) content as well as anomalous gold grain (40 grains), chalcopyrite (2 grains), andradite garnet (1980 grains), apatite (0.5%) and epidote (20%) content. Further, samples 13PMA519A01 taken 3.4 km down-ice (northwest) of Mount Polley contained background values for Cu (333 ppm), Au (12.2 ppb) and Ag (158 ppb) but contained anomalous Hg (329 ppb) and jarosite (19 grains) values. The presence of PIMS where elemental content is low adds to the picture of glacial dispersal, and also help to confirm the nature of the source of the Cu anomaly.

Processing for PIMs can also greatly improve the probability of finding a porphyry deposit. This is because the element data for both the ore elements reflected background values in many samples taken various distances down-ice (northwest and southwest) of Mount Polley; whereas, the ore and alteration minerals were anomalous in those samples. For example, sample 12PMA585A01 taken 6 km to the northwest of Mount Polley contained background content for Cu (296 ppm), Au (4.9 ppb) and Ag (92 ppb) but contained 12 grains of chalcopyrite. Also, sample 12PMA100A01 taken 2.6 km to the southwest of Mount Polley contains background Cu (304 ppm), Au (11) and Ag (82 ppb) content but contains 23 gold grains and 60% epidote.

Using alteration minerals may also prove useful in detecting buried porphyry deposits because in a scenario where only the alteration zones and not the Cu-Au mineralization was exposed to glacial erosion, only enrichment of elements and minerals present in the alteration zones could potentially be detected in till. Therefore, further research on the physical characteristics and chemical composition of PIMs may help infer a) the presence of porphyry mineralization; and b) the mineralization potential of the deposit itself (Kelley *et al.* 2011).

Finally, at Mount Polley, evidence of southwestward glacial dispersal associated with the first phase of ice movement was only detected with indicator minerals (chalcopyrite, gold grains and epidote) and not till geochemistry. These results reveal that the distribution of indicator minerals in till reflect two phases of ice-flow (see also Stea *et al.*, 2009; Plouffe *et al.*, 2011*c*; Paulen *et al.*, 2013); this reinforces the point that a complete understanding of the ice-flow history, and distribution of both elemental and mineralogical contents are necessary to interpret glacial dispersal and track a potential bedrock source.

Table 4.2. Selected till geochemical/mineralogical results listed by location (up-ice, overlying, down-ice (NW and SW) relative to the Mount Polley deposit. Samples with a "02" suffix are duplicate samples, e.g. 12PMA092A02.

Distance relative to the deposit		Sample no.	Distance (km)	Element and mineral content										
				Cu (2µm) (ppm)	Au (63µm) (ppb)	Ag (2µm) (ppb)	Hg (2µm)(ppb)	Zn (2µm) (ppm)	Normalized Gold grains (0.15-0.425 mm)	Chalcopyrite (0.25-0.5 mm) (Grains)	Andradite (0.25-0.5 mm) (Grains)	Apatite (0.25-0.5 mm) %	Epidote (0.25-0.5 mm) %	Jarosite (0.25-0.5 mm) (Grains)
Up-ice / overlying samples		12PMA068A01	12 (SW)	205.1	2.8	148.0	228.0	126.6	7	0	8	0.1	0.1	0
		12PMA564A01	19 (SW)	108.4	0.4	94.0	195.0	173.1	2	0	14	0.0	5.0	0
		12PMA092A01 12PMA092A02	overlying	877.3	50.4	335.0	278.0	204.5 (A02)	38	6 (A02)	78125	0.0	80.0 (A02)	74(A02)
		12PMA093B01 12PMA093B02	overlying	1195.4	90.2	476.0	399.0	216.8 (B02)	38	3	147 (B02)	0.0	60 (B02)	0
Samples down-ice of the Mount Polley Intrusive Complex	NW dispersal	12PMA080A01	.330	1487.9	87.2	168.0	476.0	219.0	55	0	13333	0.0	40.0	0
		13PMA502A01	.650	210.3	5.3	154.0	475.0	106.7	35	3	0	0.0	10.0	1
		13PMA501A01	.840	1547.6	36.7	251.0	385.0	163.6	41	98	0	0.0	0.5	0
		12PMA095A01	1.7	325.1	14.0	389.0	1954.0	92.6	21	0	38	0.1	60.0	0
		13PMA520A01	2.2	596.6	18.7	216.0	698.0	132.3	9	0	1	3.0	10.0	1
		13PMA521A01	2.6	525.0	17.6	111.0	724.0	130.2	40	2	1980	0.5	20.0	0
		13PMA519A01	3.4	333.2	12.2	158.0	329.0	100.8	8	0	7	0.1	0.1	19
		13PMA503A01/ A02	4.5	222.2	10.7	95.0 (A02)	205.0	137.7	9 (A02)	3	65	0.1	0.5 (A02)	19
		12PMA094A01	5	192.2	17.5	330.0	170.0	143.7	40	0	85	0.0	5.0	0
		12PMA585A01	6	296.0	4.9	92.0	260.0	171.0	1	12	8	0.0	0.1	0
		12PMA586A01	10	222.3	8.9	285.0	221.0	114.7	8	2	0	0.0	5.0	0
		12PMA084A01	1.9	847.2	25.9	219.0	550.0	184.3	47	0	0	0.0	30.0	0
	SW	12PMA101A01	2	245.2	13.8	57.0	321.0	144.9	9	0	247	0.0	80.0	0
		12PMA100A01	2.6	303.6	11.0	82.0	454.0	147.2	23	0	8	0.0	60.0	0

4.6.3. *Implications for mineral exploration*

As indicated above, the first phase of glacial advance transported metal-rich debris (e.g. chalcopyrite, gold grains and epidote) towards the southwest of the Mount Polley Intrusive Complex. Part of the mineralized debris transported during the first phase of ice movement, was in part reworked by the second phase of ice movement to the northwest during the second phase. Therefore, we suggest that the glacial dispersal pattern documented at Mount Polley is a palimpsest dispersal train (e.g., Parent *et al.* 1996; Stea *et al.*, 2009; Plouffe *et al.*, 2011c; Paulen *et al.* 2013) formed by two phases of ice movements: first to the southwest and then the northwest. Based on the anomalous element and mineral content, the maximum northwestward dispersal of the geochemical and mineralogical signal from Mount Polley varies from <1 km to 12 km. This provides a much bigger target for exploration than the mineralized intrusion itself.

This study contributes to the development of the use of porphyry Cu-Au indicator minerals in glacial sediments to mineral exploration. Our study builds on previous investigations of PIMs characterizing porphyry deposits in the Canadian Cordillera (Bouzari *et al.* 2011; Celis *et al.* 2013, 2014; Grondahl, 2014; Piziak *et al.* 2015), and in Alaska (Kelley *et al.* 2011; Eppinger *et al.* 2013). One potential limiting factor of the application of indicator mineral in an exploration program is the extra cost of processing sediment samples to recover for indicator minerals. Indicator mineral samples are more expensive to process and pick compared to conventional geochemical analysis of the < 2 µm or the < 63 µm fractions. Costs could be reduced by processing all samples for geochemical analysis and process selected samples for indicator minerals based on the geochemical results. On the other hand, identifying indicator minerals in the sediment can provide an indication of the type of mineralization, which creates the geochemical enrichment in till.

4.6.4. *Overall trends in clast dispersal*

The intrusive clast content of till was eroded and transported down-ice (both to the southwest and the northwest) from the Mount Polley Intrusive Complex but also from other unknown intrusive rocks present within the study area. The sample composition and provenance of the intrusives suggests a few general trends. The intrusive clast content of till can be explained with a northwestward ice movement. The highest intrusive count is in samples overlying the Mount Polley Intrusive Complex, which decreases as the distance of transport increases to the northwest. The angularity is a good indicator of the distance transported from the source unit. The pebbles (intrusive) become increasingly more rounded as the distance of glacial transport increases from the source rock. With the exception of sample 12TFE101A01 (discussed previously), all samples contain less than 50% sedimentary and volcanic pebbles regardless of their proximity to the Mount Polley Intrusive Complex due to ease of erosion. However, no mineralized clasts were recovered from the pebble size fraction; therefore, analyzing the pebble size fraction with the objective of determining the presence of mineralized clasts is not recommended.

The metamorphic pebbles (schist, quartzite) form isolated highs and their bedrock source appears to be outside the study area as the only metamorphic unit identified in the study area is mapped in the northeast corner, not close to any of the samples examined for pebble lithology.

4.7. References

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5. Conclusions and recommendations for future work

The three main objectives of this thesis were to: 1) map the surficial sediments at a 1:50,000 scale; 2) reconstruct the glacial history; and 3) define and characterize the till geochemical, mineralogical and lithological dispersal from the Mount Polley Cu-Au porphyry deposit. These objectives were accomplished by 1) aerial photograph interpretation and field checking; 2) documenting the stratigraphy and incorporating geomorphology to understand past glacial environment; and 3) till sampling and spatial analysis of the geochemical, mineralogical and lithological results using GIS software. This chapter summarizes the results of each of the three components and recommendations for future work.

5.1. Surficial mapping

5.1.1. Summary

A 1:50,000 surficial geology map was created using the GSC's mapping protocol and included portions of map sheets NTS 093A/05, 06, 11, 12. The main benefits of this exercise were: 1) an updated and improved surficial geology map; 2) assessment of resourceful surficial material for infrastructure development; 3) till distribution for future exploration surveys; and 4) aid reconstruction of past glacial environments.

The mapping exercise concludes that (basal) till is the most abundant surficial sediment present in this region. Till is characterized as a moderately to highly compact diamicton, composed of a silty sand matrix and with clasts ranging pebble to boulder sized and varying lithologies derived from local bedrock. It is mapped as blanket, veneer and as streamlined till. In many places it is overlain by glacial retreat sediments, i.e., (glaciolacustrine, glaciofluvial), and post-glacial sediments (alluvial and colluvial). Bedrock exposures are minimal and mapped at high elevation and steep slopes. In the uplands, bedrock is covered by a thin veneer of colluvium or till and in the lowlands it is covered by thick accumulations of glacial advance sediments, till, glacial retreat sediments and Holocene sediments. Retreat phase units include glaciofluvial sediments, mapped as blankets, outwash terraces and as ice-contact deposits such as kame terraces, kettle and kame topography, hummocks and eskers. Ablation till is also included under ice-contact topography as it forms irregular features and is dominantly poorly sorted sand and gravel with minor diamicton and silty-sand lenses. Retreat phase glaciolacustrine sediment exposures at surface are rare and mainly mapped along Beaver Valley. Glaciolacustrine sediments exposed at the surface are mapped as hummocky, veneer, blankets and consist of massive to finely laminated, medium-fine sand, silt and clay.

Meltwater channels are abundant throughout the study area and have some glaciofluvial sand and gravel associated with them. Lateral meltwater channels are mapped in valleys to the northeast. Sub-glacial (Nye) channels are mapped in the uplands, where they incise till and bedrock. Pro-glacial channels form modern lakes and small river valleys in this region. Poquette Lake and Spanish and Blackbear creek mapped in the northeast portion are typical examples.

Alluvial and colluvial sediments accumulated in postglacial time, probably during the Holocene since deglaciation of the area occurred around 10 ^{14}C ka BP (Dyke 2004). Alluvial sediments are mapped as terraces, fans and active flood plains. These are present in Cariboo and Quesnel river valleys, Beaver valley, and Spanish and Blackbear creeks in the northeastern portion of the study area. Colluvium is also abundant along the Quesnel and Cariboo River valleys, as well as Beaver valley and at steep slopes and high elevations. Colluvium is mapped as veneer, blanket, aprons and as landslide deposits. Lastly, organics make up a small portion of the mapped area and include bogs, fens and marshes within the same polygon. Organics are present near modern and over dried lakes as well as poorly drained till.

Infrastructure resource development potential

The Mount Polley study area has abundant deposits of sediments which are resourceful for infrastructure development. For example, glaciofluvial deposits are excellent aggregate material. The Cariboo and Quesnel river valleys and the meltwater channels to the northeast contain an abundance of glaciofluvial terraces. A few of these are also past placer operations. These glaciofluvial deposits can be utilized to build the forestry road network in this region.

5.1.2. Future work

The majority of the study area is covered in a dense tree cover, concealing geomorphic features and the sediments present and therefore limiting the interpretation from aerial photograph interpretation. LiDAR is an expensive but extremely useful tool in detecting subtle changes in topography, which may be masked by a thick canopy of vegetation. As a result, geomorphic features may not be readily observed during air photo interpretation. This region will benefit from remapping at a smaller scale (1:20,000) incorporating LiDAR technology, especially near the Quesnel and Cariboo River valleys. Further, landslide risk assessment within the Quesnel and Cariboo River valleys must be conducted to ensure that future roads and infrastructure development is not at risk due to the failing underlying glaciolacustrine sediments.

5.2. Glacial history

5.2.1. Summary

Reconstruction of the events of Fraser Glaciation in the study area was based on a combination of the results of surficial mapping, ice-flow measurements and documentation of stratigraphy. The Fraser Glaciation began at about 29 ^{14}C ka BP (radiocarbon years before present) (Ryder *et al.* 1991). At the onset of the Fraser Glaciation, the Coast and Cariboo mountains served as ice accumulation centres for glaciers, which subsequently advanced onto the Interior Plateau. Valley glaciers from the Cariboo Mountains developed into piedmont glaciers. Glacial advance in the study area is marked by the presence of advance phase glaciolacustrine sediments, suggesting the presence of glacial lake conditions. Glaciers initially advanced into the study area in a general westward to southwestward direction (250°-275°). At the maximum extent of glaciation between 14.5 to 14 ^{14}C ka BP, glaciers flowing from the Coast and Cariboo Mountains coalesced over south-central British Columbia forcing ice flow to the north and south from an ice divide located at approximately the 52° latitude (Tipper 1971; Fulton 1991). This resulted in a northwestward ice-flow movement (290°-330°) over the Mount Polley area.

Deglaciation in the study area is reconstructed following a modified version of Fulton's (1967, 1991) four stage deglaciation model. The first stage is the active ice phase. Ice-flow continued in the valleys while the highest peak became ice free. The next phase is the upland ice phase. During this time the highest peaks and portions of the uplands became ice-free and the meltwater flowing through sub-glacial channels discharged into the Quesnel and Cariboo river valleys as well as the Beaver Lake valley. Melting of ice within valleys to the east, e.g. Spanish Lake valley and Blackbear creek, is marked by the formation of lateral meltwater channels. The third phase is the stagnant ice phase, where either ice mass or sediment aggradation further west, likely within the Fraser River, cause an obstruction to drainage resulting in the formation of pro-glacial lakes within the Quesnel River valley and the Beaver Lake valley. The formation glacial lakes in the Quesnel River and Beaver Lake valleys is time transgressive and it is possible that glacial lake conditions may have persisted in this region as early as the upland ice phase. Due to a large difference in the elevation (125 m) of glaciolacustrine sediments within Quesnel River and Beaver Lake valleys, it is unlikely that the glacial lakes connected within the Mount Polley study area. However, these glacial lakes were likely to have been part of a system of glacial lakes connected to Glacial Lake Fraser. Once the blockage obstructing meltwater flow and responsible for the formation of the glacial lakes within the study area got removed, drainage became re-established in this region. Sediment aggradation and erosion resulted in the formation of glaciofluvial terraces within the Quesnel and Cariboo River valleys as well as Black bear and Spanish Lake creeks. The fourth and final phase is the dead ice phase. During this stage, the remaining isolated melting ice masses scattered within the low relief regions formed ice-stagnation topography characterized by glaciofluvial sand and gravel deposits forming hummocky topography as well as kettle and kame features. The study area was completely deglaciated by 10 ^{14}C ka BP (Dyke 2004). Soon thereafter, post-glacial alluvial and colluvial activity followed as a result of abundance of water saturated sediment present in unstable areas, e.g steep terrain. Colluvial activity lessened approximately around 7 ka BP once forests and grasslands established in this region.

5.2.2. Future work

Within Mount Polley lie well exposed stratigraphic sections (uncovered during the construction of the mine) that have remained intact, including glacial and non-glacial units. These sections have not been studied previously and may add significantly towards better understanding of the past glacial and non-glacial environments. Further, stratigraphic studies on the exposed sections, just south of the area (within Beaver valley) will also be extremely useful to gain a better understanding of the events of deglaciation, extent of the ice cover and the formation of the retreat phase glacial lake Beaver.

Finally, even though our study concludes that two distinct ice movements (SW and NW) and one transitional phase (W) occurred in the study area, the exact events are still poorly understood. A better understanding of the flow dynamics could be established by conducting till fabric analysis at different levels within thick till profiles. Additional ice-flow measurements in the southeast portion of the study area where macroforms indicating southwest and westward ice-flow are documented could also be completed.

5.3. Drift prospecting

5.3.1. Summary

This study demonstrates that till composition (mineralogy and geochemistry) can be used to detect buried Cu-Au porphyry mineralization in glaciated terrain. Ore elements for the Mount Polley deposit include Ag, Au and Cu that were detectable in till samples overlying the deposit and up to 10 km, 8.5 km and 2.6 km down-ice (northwest) of the mineralization, respectively. Additional pathfinder elements Hg and Zn are dispersed in till samples overlying and up to 2.6 km and 1.9 km, respectively, down-ice (northwest) from the Mount Polley deposit. Both ore and pathfinder elements define geochemical glacial dispersal of mineralization down-ice from the porphyry mineralized zones at Mount Polley deposit.

Chalcopyrite and gold grains associated with the mineralization at the Mount as well as andradite garnet, apatite, epidote and jarosite associated with alteration zones peripheral to mineralization are abundant (compared to background values) in till down-ice from the mineralization (both to the southwest and northwest). Results from this study therefore establish andradite garnet, apatite, chalcopyrite, gold, epidote and jarosite as Cu-Au porphyry deposit indicator minerals. Gaining a complete understanding of the glacial history is necessary for interpreting the distribution of indicator minerals in till because these minerals might have been transported by more than one phase of ice movement.

Examining for mineralized clasts is not well suited to the pebble sized fraction, based on the findings of the pebble lithology exercise. Therefore, it is not recommended for future studies on characterizing the mineralization characteristics and its extent.

5.3.2. Future work

The Mount Polley study area has benefited from abundant soil/till geochemical surveys conducted as part of this and earlier studies. Anomalous economic element and mineral abundance not directly down-ice from Mount Polley can be related to known mineral occurrences (see MinFile report). However, further investigation (and profile sampling) may be required for samples containing anomalous element and mineral content. For example, normalized gold grain content in samples 13PMA036A01 (66 gold grains), 13PMA043A01 (30 gold grains) and 12PMA100A01 (23 gold grains) should be further investigated (Fig. 5.1). Anomalous Ag, Au and Cu content in samples 12TFE080A01 (443 ppm Cu), 12PMA578A01 (27 ppb Au), 12PMA566A01 (321 ppb Ag), 12TFE078A01 (270 ppb Ag), 12PMA570A01 (283 ppb Ag) and 12PMA580A01 (29 ppb Ag) should also be examined for future till geochemical/mineralogical surveys (Fig. 5.1). Future drift prospecting work may be conducted in tracing the source of these anomalous samples, likely some distance down-ice (southwest and/or northwest) from the source of mineralization.

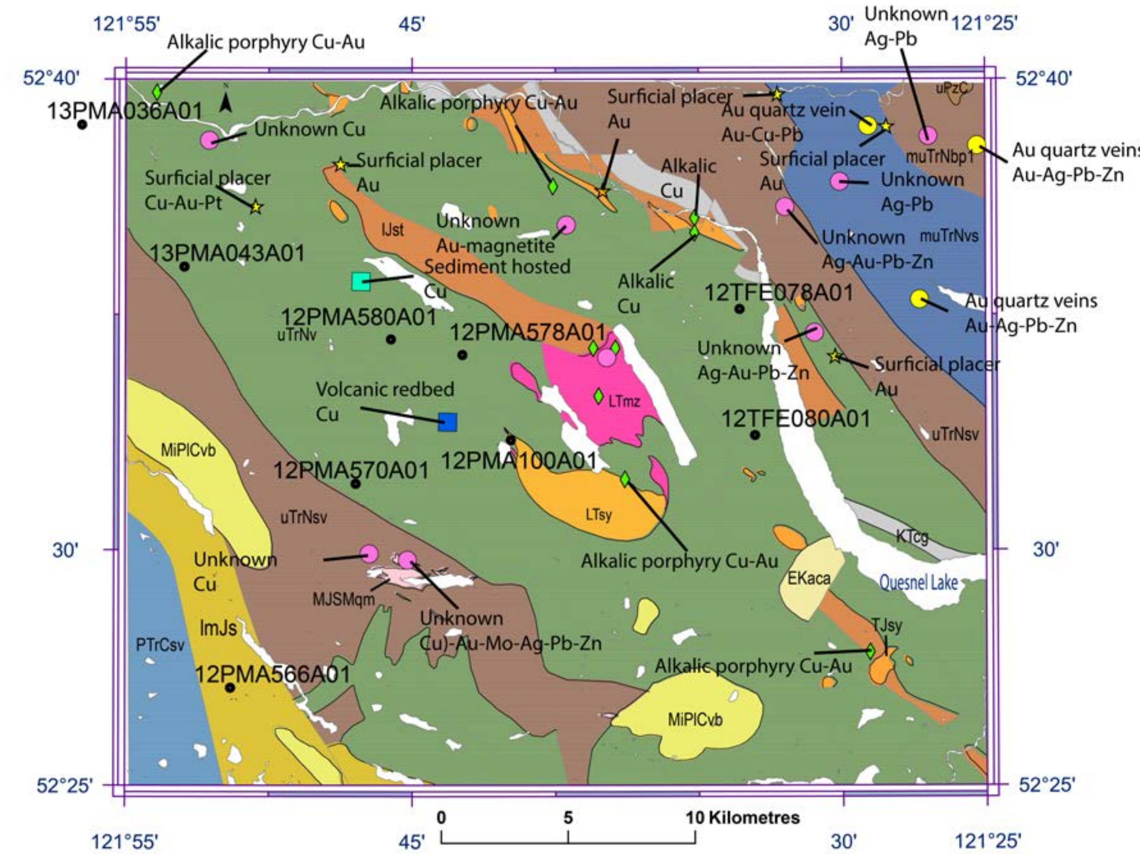


Figure 5.1: ***Spatial distribution of samples with anomalous gold grain, Ag, Au and Cu content as well as labelled MinFile occurrence reports for the region.***

Appendix A.

Surficial geology of the Mount Polley mine area

Map sheet (PDF file): Surficial geology of the Mount Polley mine area.

File name: Surficial Geology_BootjackMountain.pdf

Description: Pdf file of the surficial geology map of the study area.

Appendix B.

Field data

Supplementary data file: Ice-flow indicator data

File name: B1_Striation_data_Mount_Polley_2012-2013.xls

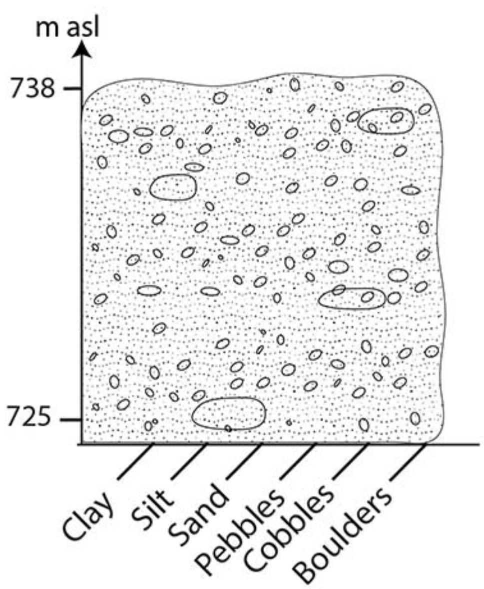
Description: The excel spread sheet includes the complete set of ice-flow measurement data in the Mount Polley region, collected (in the Ganfeld) during the field seasons of 2012 and 2013.

Stratigraphic cross-sections and landforms

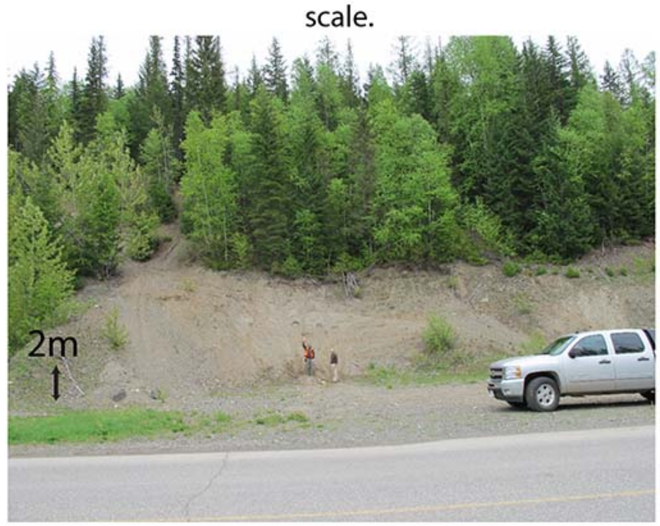
Description: Select stratigraphic sections and landforms documented in the study area.

Site: 13PMA002 Elevation: 725 m asl
Landform: Alluvial fan
Location: Easting: 599233.17 Northing: 5826657.83
Latitude: 52.58089733 Longitude: -121.53544390

Description: Moderately sorted, sandy gravel with a medium, coarse sand matrix and pebbly to cobbly, sub-rounded, faceted gravel. Boulders are present as well. This sandy gravel deposit is crudely stratified with alternating gravel and sand rich layers.



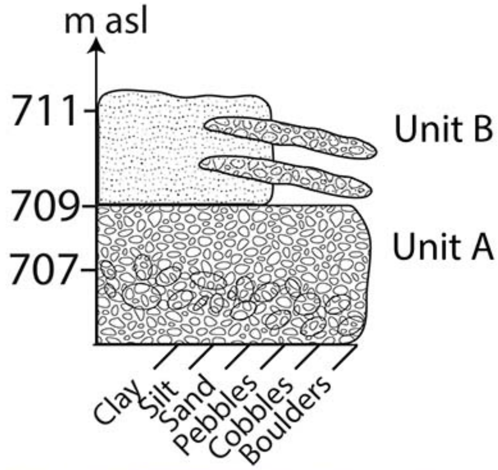
Exposed gravel section along road. Alain (2 m) for scale.



Exposed alluvial sandy gravel (13 m high), looking east.

Site: 13PMA056 Elevation: 707 m asl
Landform: Ice-contact kame hill deposit
Location: Easting: 579945.09 Northing: 5811500.52
Latitude: 52.44783737 Longitude: -121.82368222

Description: This section was exposed road cut in an undulating to rolling topography. This 4-6 m high section is in close vicinity to other ice-contact topography features such as kame terraces, glaciofluvial blankets and crevesse fill deposits.



Unit B is the overlying silt-fine sand unit. It is matrix-supported, crudely laminated with pebble sized dropstones and contains lenses ranging 20 to 30 cm of sandy gravel, similar to unit A.

Unit A is an easterly dipping, sandy gravel unit, approximately 1 m thick. The gravel is crudely stratified, clast-supported, moderately sorted, faceted, sub-angular to sub-rounded, ranging granule to boulder sized.

Section exposure. Sarah (1.8 m) for scale.

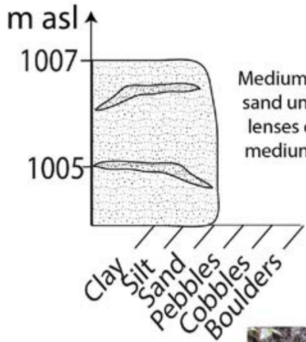
View of rolling to undulating topography, facing north.

Silt and fine sand unit

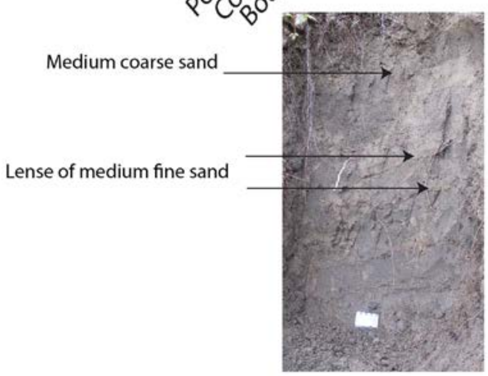
East dipping sandy gravel beds

Site: 13PMA090 Elevation: 1005m asl
Landform: Crevesse fill
Location: Easting: 602545.38 Northing: 5826859.74
Latitude: 52.58209732 Longitude: -121.48651557

Description: Dug into a road side exposure of a short crevesse fill. This massive, matrix-supported, pebbly sand is dark brown in colour, well-sorted and ranges 2-3 m in thickness. Within the medium coarse sand are thin lenses of medium fine sand. The clasts present within this unit are dominantly volcanics. Pebbly to bouldery, faceted, sub-angular to sub-rounded boulders caps this exposure.



Crevasse fill along road cut. Steph (1.5 m) for scale.

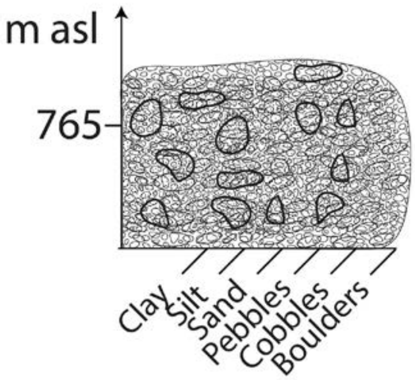


View of the section. Scale card is 5 cm

Closer view of the section. Gravel cap on top.

Site: 13PMA083 Elevation: 765 m asl
Landform: Glaciofluvial outwash terrace
Location: Easting: 600903.06 Northing: 5835495.70
Latitude: 52.66001565 Longitude: -121.50810887

Description: Exposed sandy gravel exposure in a gravel pit adjacent to the Quesnel River valley. This crudely bedded, clast-supported glaciofluvial gravel pit consists of medium sand matrix and a pebbly to bouldery gravel. The clasts are sub-rounded to sub-angualar, platy and faceted. This section has been mapped as a glaciofluvial outwash terrace.



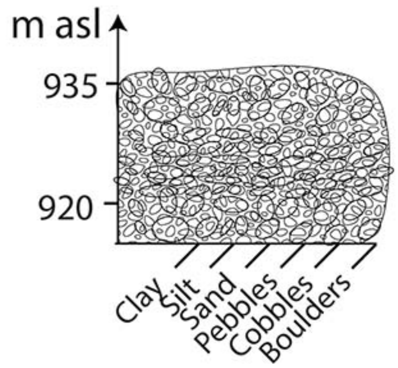
View of the Quesnel River from the glaciofluvial outwash terrace

Crudely bedded gravel ranging pebbles to boulder (on the right). Sarah (1.8 m in height) for scale.

Gravel is composedof intrusives and volcanics, are sub-angular to sub-rounded in angularity and platy to faceted shaped. Trowel is 17.5 cm.

Site: 13PMA079 Elevation: 920 m asl
Landform: Glaciofluvial outwash terrace
Location: Easting: 602927.18 Northing: 5831377.12
Latitude: 52.62262232 Longitude: -121.47947723

Description: Exposed section of a glaciofluvial outwash terrace adjacent to Sapnish creek. Exposure consists of crudely bedded medium-coarse sand and gravel. Gravel is dominantly cobbly (on average 3 cm), although large boulders (over 1 m) are present. The terrace is 15 m in thickness. Clasts are dominantly volcanics, ranging angular to sub-rounded, and are faceted. The gravel is also imbricated, indicating paleocurrent direction approximately as 30 ° (to the northeast), i.e. paleocurrent towards the Cariboo River valley.



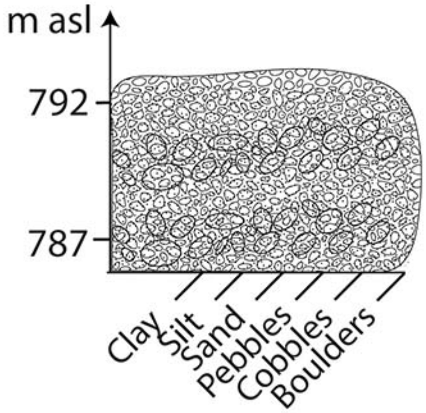
Close up view of the gravels. Clasts are sub-rounded to angular, faceted and bullet shaped.

View looking at the upper part of the terrace section.

Bigger view of the exposed section. Pick for scale is 1 m long.

Site: 13PMA075 Elevation: 787 m asl
Landform: Glaciofluvial outwash terrace
Location: Easting: 597351.45 Northing: 5830653.13
Latitude: 52.61714400 Longitude: -121.56203055

Description: Large glaciofluvial outwash terrace (3 to 5 m high) along Quesnel Lake/ Quesnel River. Road cut exposure shows crudely bedded gravel of variable sizes (gently dipping to the north), ranging pebbles to large boulders (up to 1 m) with a coarse sand matrix. Clasts are (on average) 5 cm long, sub-rounded, faceted and striated, dominantly composed of Nicola volcanics.



Larger view of the exposure along the road cut.

Crudely stratified, north dipping, angular cobble to boulder sized clasts.

Coarse sand and pebble rich bed

Road cut exposure of crudely stratified to massive structured glaciofluvial outwash terrace. Pick for scale is 65 cm.

Appendix C

Till sample data

Raw sample data

File name: C1_till_sample_data_Mount Polley_2012-2013.xls

Description: The excel spread sheet includes the complete till sample data collected (in Ganfeld) over the 2012 and 2013 field seasons in the study area.

Till geochemistry data (clay and silt plus clay sized fraction)

File name: C2_till geochemistry_2µm_63µm.xls

Description: Complete till geochemistry data for the clay-sized fraction and for the silt plus clay –sized fraction (of the 2 kg sample) using methods 1F, i.e. modified Aqua Regia digestion (near total leach) followed by analysis by ICP-MS.

Till mineralogy data

File name: C3_till mineralogy.xls

Description: Complete till mineralogy data for the indicator mineral separation at Overburden Drilling Management. All minerals are reported in the 0.25-0.50 mm size-fraction. The exception is gold grains, whose reported grain count is in the 0.015-0.425 mm size fraction. Minerals reported as percent observed are denoted (%) and minerals reported as grain counts are denoted (number/10 kg).

Pebble lithology data

File name: C4_pebble_lithology.xls

Description: Pebble lithology identification on select till samples in the 8-16 mm and +8 mm size fraction.