The Impact of the Mount Polley Tailings Pond Failure on the Sedimentary Record of Quesnel Lake, British Columbia

By

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A thesis submitted in conformity with the requirements for the degree of Master of Science
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Abstract

The Mount Polley tailings pond failure that occurred on August 4, 2014 provided an opportunity to understand the effects of point-source sedimentation events in the sedimentary record. Six sediment cores that were taken at both distal and proximal locations in Quesnel Lake (B.C.) were used to identify if turbidity currents or subaqueous debris flows were generated. Geotechnical (grain size and LOI), mineralogical and copper metal concentrations confirmed the presence of turbidite deposits in four cores. All of these turbidites contained a coarser-grained base and an uppermost fine-grained cap. Two out of the four turbidite deposits that were most proximal to the spill mouth contained mixed basal layers that may signify the energy of the current at that depth. Sediment is focused in the deepest part of the basin. The spill sediments will compress over time but will represent sedimentation rates at 4-5 orders of magnitude larger than Holocene natural rates.
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Chapter 1
Introduction to the Project

1.1 Introduction

Lake bottom sediments are invaluable archives of environmental change. Depositional facies can reflect changes in lake properties and characteristics as well as characteristics of the contributing watershed over the long term (Basilici, 1997; Carroll and Bohacs, 1999; Hodder et al., 2006).

Lacustrine sediments have been used to reconstruct paleo-environments and changes in regional hydrology and climate (Kaplan and Wolfe, 2002; Hodder et al., 2006). For example, lake sediment records can show both changes in annual and extreme hydrologic regimes such as the timing and duration of the spring snowmelt (Cockburn and Lamoureux, 2008) and the occurrence of large-scaled floods (Brown et al., 2000).

Extreme depositional episodes may also be reflected in the lacustrine (or marine) environment. For example, volcanic activity may be reflected as ash layers within a sediment core (Gilbert and Desloges, 2012), and intense glacial runoff may leave behind thick cross-bedded stratigraphic features (Couch and Eyles, 2008). Heavy rainfall or storm activity may re-suspend lake bottom sediment and transport materials to the deeper basins, thereby “focusing” sediment accumulation (Eadie et al., 2008). Furthermore, sediment records may depict any anthropogenic disturbances in the catchment area. Examples include agriculture, forestry and mining activities that yield sediment. These disturbances are often indicated by unique mineralogical, chemical or sedimentological signatures in the sediments (Nriagu, et al., 1979; Audry et al., 2004; Wu et al., 2007).

Lakes act as repositories for incoming clastic material from within the catchment which is introduced via the fluvial system. Lake sediments also include autochthonous materials (materials that are sourced within the lake itself) such as organic matter content. The material discharged into a lake environment depends on the relationship between the energy of the river inflow and the entrainment of the sediments (Schillereff et al., 2014). This relationship should be reflected in the lake bottom sedimentary record, most likely as coarser intermittent
laminations or beds (Schiefer, 2006). The recurrences of specific sedimentary features are used to infer frequencies and magnitudes of specific sedimentation events.

Flow dynamics also play a part in determining the spatial distribution of incoming river inflow and the material it carries. For example, density currents are generated when two fluids with differing densities mix (Mulder and Alexander, 2001). This difference in density results in a pressure gradient that causes the denser fluid to intrude below the less dense fluid. Debris flows and turbidity currents are typical examples. Turbidity currents are especially of interest in the lake and marine environments as they can carry large amounts of sediment into distal and deeper regions and even beyond continental shelves (Stow and Bowen, 1980; Ogston et al., 2000; Piper and Normark, 2009). Turbidity currents can be responsible for the destruction of reservoir and sea-floor infrastructure (Heezen and Ewing, 1952; Meiberg and Kneller, 2010).

The objective of this thesis is to use the British Columbia Mount Polley tailings mine spill from 2014 to understand the impacts of a large catastrophic sedimentation event on the Quesnel Lake sedimentary record, and to further an understanding of the record of extreme turbidity currents in lake sedimentation.

1.2 The problem: Mount Polley tailings pond failure

The environmental impact of mining is mainly due to the movement of large volumes of earth. Examples of such include slag mounds, piles of waste rock and the creation of tailings ponds. In general, the mining process (mineral and metal processing) separates the ore from the mined rock. In an average Canadian mining facility, 42% of the excavated material is disposed of as waste rock in rock piles, 52% is removed from the site as tailings (mixture of water and finely ground rock) and 4% is categorized as slag. Only a small percentage (approximately 2%) contains the economic ore (Henry, 2009).

On August 4th 2014, the failure of a tailings pond belonging to Imperial Metals’ Mount Polley Mine resulted in the sudden influx of tailings sediment and other materials into Hazeltine Creek and subsequently into the west basin of Quesnel Lake, British Columbia.
Mount Polley Mine is an open pit copper and gold mine located in the southern interior forest of British Columbia. It is situated 27 km southwest of Likely, BC and 56 km northeast of Williams Lake, and is in the western sub-watershed of Quesnel Lake (Latitude 52° 33’ N, Longitude 121° 39’ W) (Brown et al., 2016). The mine and operational area cover approximately 10.5 km$^2$ of the Quesnel watershed (Brown et al., 2016).

The mine primarily targets porphyry copper-gold and small silver deposits. Gold ore exists as inclusions in copper sulfide minerals (Henry, 2009).

Kennedy et al. (2016) and Henry (2009) describe the ore processing method at Mount Polley. Copper metal is produced via smelting, a pyrometallurgical process involving heat (Henry, 2009). The ore is blasted from the pit and is taken to a processing plant where it is crushed and ground to reduce particle size. This is followed by a series of flotation rounds of the finer fractions. As metal concentrations are increased with decreasing grain size (Horowitz and Elrick, 1897), the material is exposed to several rounds of crushing. Mean particle size at the end of the process is 50 µm (Petticrew et al., 2015). A copper sulphide concentrate is derived from ore processing at Mount Polley. The remainder is discarded as tailings. In theory, the tailings should have a negligible amount of ore minerals (i.e.: copper sulphides). However, tailings can contain up to 20% of the economic minerals that could not be removed from the ore (Northern Dynasty Mines, 2005). In fact, average metal concentrations in 2013 reported that the tailings had elevated concentrations of copper, arsenic, iron and manganese above the British Columbia sediment quality regulations (Petticrew et al., 2015).
Chapter 2

Literature Review

2.1 Introduction

To fully understand how large inputs of sediments are distributed in a large lake, physical processes in lacustrine environments must be initially explored. The following literature review outlines these regimes by considering lake classifications, lake regimes and sediment circulation and deposition.

2.2 Lake classifications

Large lakes can be classified depending on their processes and morphogenic origins. This is important in understanding the nature of lake sedimentation, as these characteristics may govern how and where the sediment is deposited.

Large lakes in mountainous areas such as British Columbia (B.C.) can be classified in terms of their genesis. Most lakes in B.C. have glacial origins: they were either created due to direct contact with ice, formed due to terminal/lateral moraines or in glacial rock basins such as fjord lakes. Many lakes in Europe and North America have been created or influenced by the last glaciation (Dreimanis, 1977; Clayton and Moran, 1982; Allen and Anderson, 1993; McCulloch et al., 2000, Osborn et al., 2007).

Lakes can also be classified as per their trophic level. Oligotrophic lakes typically have low primary productivity, low algae population, and low concentrations of nutrients (namely nitrogen and phosphorus). In contrast, eutrophic lakes have high primary productivity, have high nutrient concentrations and high volumes of algae. Lakes in between these are known as mesotrophic lakes. Lakes are not confined to one trophic level. For example, Karabonov et al. (2000) found that the presence of thermophilic diatom flora, dating back to the Sub-boreal period, suggests that the lake underwent a trophic level change from oligotrophic to eutrophic during the Holocene. In a glacier-fed, oligotrophic lake such as Quesnel Lake, low organic matter is expected to generally characterize the native lake bottom sediment. Any increase in
organic matter may indicate past changes in terrestrial properties in the catchment. For example, Spooner et al. (1997) and Gilbert and Desloges (2012) correlated increases in organics down a sediment core in their study to the maturing of forests and vegetation during the warm Holocene. However, relative differences in organic matter in the sedimentary record may also reflect a difference in clastic material inputs alone.

2.2.1 Thermal stratification and sediment distribution

From a sedimentological perspective, the relationship between the concentration of suspended sediment within the river inflow and the temperature gradient of the lake are important factors (Figure 2.1). Lake water circulation and the fate of sediments are strongly influenced by lake thermal properties. Thermal stratification occurs when temperature varies with water depth, resulting in water masses vertically “stacked” atop each other. The summer temperature profile of a lake typically contains an uppermost warm layer and a lower, undisturbed water mass. These layers are referred to as the epilimnion and the hypolimnion, respectively. The thermocline separates these two layers as indicated by a rapid temperature change. Thermal stratification not only determines sediment distribution, but impacts variations in dissolved gas concentrations (Aberg et al., 2009), photosynthetic efficiency and productivity of marine life (Kaiblinger et al., 2007), and fish species mortality rates (Lee and Bergensen, 1996).

**Figure 2.1**: Processes of sediment dispersal within a lake basin. Taken from Schillereff et al., 2014.
It is in mid-summer where thermal stratification is most stable. In late summer and early fall, cooling begins at the surface and overtime the entire epilimnion cools, deepening the thermocline. Later in the fall the epilimnion temperature cools to a comparable temperature to the hypolimnion, causing the layers to mix to form a freely circulating, isothermal mass (Vanderploeg et al., 2010). This is referred to as overturning. Lakes that overturn in both fall and spring are dimictic lakes. Lakes that turn over once are monomictic, and those overturning at varying times annually are polymictic lakes.

The thermal properties of lakes have been understood as having a large impact on sediment distribution. The input of sediment (as well as water) into a lake is often dominated by river inflow, and the sedimentary record of many lakes reflects this (Hilton et al., 1986; Schwalb et al., 1998; Lockhart et al., 2000; Girardclos et al., 2007; Crookshanks and Gilbert, 2008). River inputs are controlled by characteristics such as density differences, velocity of the incoming water, and suspended sediment load (Lewis et al., 2002, Crookshanks and Gilbert, 2008; Marti et al., 2011). Controls on river inflow will determine how sediment is deposited. River plumes can enter as either a hypopycnal (overflow) or hyperpycnal (underflow) flow (Figure 2.1).

Underflows may generate energetic, sediment-laden flows that spread across the basin floor. These flows either erode the bottom sediment if the energy state is above a density or velocity threshold (Meiberg and Kneller, 2010), or deposit their sediment load if the current loses velocity. First noted by Forel (1885), turbidity currents have been identified as important sediment delivery processes. Suspended sediment concentration within these currents makes the density of the mixture significantly greater than the density of the ambient water. This is what drives the current. Sustained turbidity currents are observed when the mean velocity of the current is significant and unchanged over hours to days. These are referred to as steady or quasi-steady flows (Schillereff et al., 2014) and can last for hours as the flow is continuously fed by river discharge. Surge-like currents generally do not have a sustained time period (Schillereff et al., 2014). Crookshanks and Gilbert (2009) studied the spatial and temporal distribution of sediment in Kluane Lake, a large glacier-fed lake on the Yukon Plateau. Sediment-laden river inflows during peak snowmelt were found
to initiate continuous turbid underflows with maximum velocities of 0.6 m/s when thermal stratification was weak. These underflows deposited very little (<2%) of the sediment load at the delta front. However, at least 1 km away from the delta, significant sediment deposition was occurring which correlated with changes in the turbidity current structure.

The gradient between lake water and the input water results in either an overflow, where the incoming water has a lower density than the lake epilimnion, or an underflow, where the incoming lake water has a higher density. If the densities are similar, an interflow can occur and the incoming plume will flow at an intermediate depth, referred to as a homopycnal flow. Inferring the persistence of over- and interflows from sedimentary structures can be quite difficult, as both these flows transport sediment above the lake bottom (Ashley et al., 1985).

Currents caused by the introduction of dense sediment suspension loads are known as gravity flows. Gravity flows have been documented in the literature as important mechanisms of sediment transport and that have impacted the sedimentary record in some way (Middleton, 1967, 1973, 1976; Postma, 1986; Kneller and Branney, 1995; Mulder et al., 2001; Gilbert et al., 2006; Gilbert and Desloges, 2012). They can form from river inflow or can be triggered by floods, earthquakes or from anthropogenic sources. Two common types of gravity flows are commonly seen in lacustrine environments: turbidity currents, which can have structure, and mud debris flows, which generally form structure-less “debrites” (Pratson et al., 2000).

Turbidity currents are sediment-laded underflows that move down a sloping surface due to sediment entrainment. A turbidity current consists of a dense flow of water and sediment that requires an initiation processes and a sufficient enough gradient to continue the flow (Normark and Piper, 2009). The supporting mechanism for flow is turbulence.

Turbidity currents may result from discrete episodic high flow events. For example, in Lillooet Lake, British Columbia, a severe autumn rainstorm triggered turbid underflows (Gilbert et al., 2006). These velocities ranged from 0.3 m/s near the delta to less than 0.1 m/s distally. However, it was found that the largest amounts of sediment were deposited as the velocity declined with increasing distance away from the point of inflow. The sudden
and discrete input of anthropogenic sediment such as mine tailings into Lake Superior is known to have generated turbidity currents (Normark, 1989).

Furthermore, turbidity currents can either be classified as erosive or depositional. To be considered erosive, turbidity currents must be able to generate enough turbulence in the matrix to entrain sediment from the seafloor, and must also hold the sediment in suspension (Normark and Piper, 2009). If it is unable to, the sediment will deposit and the current diminishes. A turbidity current can also self-accelerate, or “ignite”, in cases where the current is continuously entraining sediment, thus allowing the current to continue (Parker, 1982). One example of an erosional feature carved by these currents are submarine canyons, which are V-shaped, winding course profiles with high steep walls and multiple tributaries entering on both sides (Mulder et al., 2001).

In contrast to erosional processes, turbidity currents deposit their sediment loads when the flow is deaccelerating. Turbidity currents can decelerate due to morphological variations in the lake bottom, such as an increase in elevation in which the current loses momentum and quickly decelerates (Pratson et al., 2000). Large depositional features such as sublacustrine fans are constructed when the current has died, typically further away from the erosive features such as submarine canyons (Middleton et al., 1993; Mulder and Alexander, 2001; Lee et al., 2002). The current will stop once the turbulence cannot suspend sediment and has deposited all sediment entrained in its matrix (Pratson et al., 2000; Wells, 2009). These deposits are referred to as turbidities. They are composed of graded beds (i.e. fining upward) that have a coarse-grained base and a thin cap of fine grained silt and clay (Mulder et al., 2001). Turbidites deposited proximal to its introductory point consist of coarser-grained thick beds, with varying structure, over a scoured base. Distal turbidites consist of finer grained sizes such as silt and clays, and may lack the stratigraphical features that would distinguish them. As aforementioned, underflows in Kluane Lake initiated continuous turbidity currents due to high suspended sediment loads during the melt season (Crookshanks and Gilbert, 2009). Maximum sedimentation rates were observed close to the river mouth (approx. 1 km) and declined distally. Overall there was an increase in sediment transport (i.e. erosion) from the delta to the interior of the lake, implying an increase in
turbidity current thickness which further suggests that the turbidity current was entraining more sediment along its path. During peak flow conditions, these turbidity currents were concluded to be very erosive in the delta-proximal zone (Crookshanks and Gilbert, 2009).

An early landmark study of turbidity currents was conducted by Middleton (1966). Turbidity currents were produced by releasing artificial sediment (plastic beads) from a lock into a horizontally placed flume filled with water. Based on these early experiments, Middleton (1993, 1996) divided the profile of a typical turbidity current into a distinctive head, a quasi-uniform flow body and the tail (Figure 2.2). The head of the current, in order to displace the less dense fluid in its path, must have more potential energy than the body of the current. Friction that occurs from the bed results in the ambient flow mixing in with the current forming the lobular 3D structure observed. The average speed of the back of the head must be faster than the speed of the head in order to maintain a constant rate of advance.

![Figure 2.2: Structure of the head and body of a turbidity current. Taken from Middleton (1993).](image)

He concluded that the head of the turbidity current rises and diverges and appeared not to cause any deposition within the bed in this section of the flow. Instead, rapid deposition seemed to occur behind the head, before any decline in velocity was even reached.

As mentioned, as the mass of the suspended sediment increases, the velocity of the current increases. The flow velocity of the head is defined using the following relationship (Kneller and Buckee, 2000):
\[ U_{\text{head}} = \frac{F_r}{\sqrt{P_t/(P - 1)}} g h \]  

Equation 2.1

Where:

\( U_{\text{head}} \) = velocity of the turbid flow (m/s)

\( F_r \) = Froude number, which is the ratio of gravitational forces acting on the flow

\( P \) = density of ambient water (kg/m\(^3\))

\( P_t \) = density of sediment-laden water (kg/m\(^3\))

\( g \) = acceleration due to gravity (m/s\(^2\))

\( h \) = height of the turbidity current (m)

When \( F_r > 1 \), the flow is rapid, and when \( F_r < 1 \), the flow is tranquil. Froude numbers for turbidity currents range from 0.7 to 1.0 in turbulent flows in deep water (Meiburg and Kneller, 2009).

Turbidity current properties can also be further expressed using three additional equations: the Reynolds number, the Richardson number and the Rouse number. All flows can be assigned a Reynolds number (Re), a unitless quantity that indicates whether the flow will be turbulent or laminar. Re is the ratio of turbulent forces that drive the flow versus the frictional forces that try to impede flow. It is described in the following expression (Kneller and Buckee, 2000):

\[ R_e = P_t U_{\text{head}} h / \mu \]  

(Equation 2.2)

\( U_{\text{head}} \) = velocity of the turbid flow (m/s)

\( R_e \) = Reynolds number

\( P_t \) = density of sediment-laden water (kg/m\(^3\))
\( h \) = height of the turbidity current (m)

\( \mu \) = dynamic viscosity of the water (kg/s)

If \( Re < 2000 \), the flow is laminar. If \( Re > 2000 \), the flow is turbulent. The dynamic viscosity is a function of temperature – normally, higher temperatures have lower viscosities (and also lower densities).

The Richardson number determines the stability of the flow. It is defined as buoyancy over shear velocity, and is numerically expressed as follows: (Kneller and Buckee, 2000):

\[
R_i = \frac{(P_t - P)gh}{2u^2} \quad \text{(Equation 2.3)}
\]

Where:

\( R_i \) = Richardson number

\( P_t \) = density of sediment-laden water (kg/m\(^3\))

\( P \) = density of ambient water (kg/m\(^3\))

\( g \) = acceleration due to gravity (m/s\(^2\))

\( C \) = volume concentration of sediment in the flow

\( h \) = height of the turbidity current (m)

\( u^* \) = shear velocity, which is the rate of change of the velocity with depth (m/s)

When \( R_i > 1 \), the flow is said to be subcritical (Fr < 1). In this case the flow is tranquil. When \( R_i < 1 \), the flow is supercritical, and the flow is rapid and swift (Fr > 1). Subaqueous turbidity currents are typically supercritical when there is a steep bottom slope and shallow depth of flow (Alexander, 2008). Bridge and Demicco (2006) report a slope that is a fraction of a degree may cause supercritical flows. When the flow transitions from a supercritical flow to a subcritical one, a hydraulic jump occurs due to the abrupt head loss which occurs when the
bottom slope cannot sustain a supercritical flow (Bridge and Demicco, 2006). Furthermore, when flowing over a conformable boundary, the instability of a supercritical turbidity current allows for ready mixing with the lake floor, which may result in distinguishable, cross-bedded sedimentary features (Bridge and Demicco, 2006). In a sediment core therefore, supercritical flows may be represented by features such as ripples or also the presence of a non-planar contact point between the pre-existing sediment and newly introduced sediment due to sediment mixing.

Shear velocity is the scale of the momentum that is absorbed by the bed (Pokrajac et al., 2006). With an increase in shear, there is an increase in turbulence. Shear velocity is further defined as follows:

\[ u_\ast = \sqrt{\frac{\tau}{P_t}} \]  

(Equation 2.4)

Where:

\( u_\ast \) = shear velocity, m/s
\( \tau \) = bottom boundary shear stress (\( \tau = \mu \frac{du}{dz} \), therefore \( u_\ast = \sqrt{\frac{\mu}{P_t} \frac{du}{dz}} \))
\( P_t \) = density of the turbulent flow (kg/m\(^3\))

Lastly, the Rouse number describes how the sediment is transported by the flow, reflecting the rate of sediment fall out versus the particle sizes being suspended due to turbulence. It relates the settling velocity of a single grain to the shear boundary which acts on it, expressed as (Udo and Mano, 2011):

\[ P = \frac{W_s}{ku_\ast} \]  

(Equation 2.5)

Where:

\( P \) = Rouse number
\( W_s \) = settling velocity of particles (m/s)
\( k \) = von Karman constant, assumed to be 0.41 (Gaudio et al., 2010)
If Rouse numbers are <0.8, the sediment is described as a wash-load transport, typical of fine-grained sediment. Values that range between 0.8-1.2, suspended load transport is observed. Values ranging from 1.2-2.5 indicate that 50% of the sediment is lingering in suspension. Rouse numbers > 2.5 indicate bedload transport (Udo and Mano, 2011).

The settling velocity, \( W_s \), can further as expressed in the following equation, which is a variant of Stokes Law (Udo and Mano, 2011):

\[
W_s = \frac{4}{3c_d} \left( \frac{P_t}{P} - 1 \right) gd
\]

Equation 2.6

Where:
\( W_s = \) settling velocity of particles (m/s)
\( c_d = \) drag coefficient
\( P_t = \) density of sediment-laden water (kg/m\(^3\))
\( P = \) density of ambient water (kg/m\(^3\))
\( g = \) acceleration due to gravity (m/s\(^2\))
\( d = \) diameter of the particle (m)

2.2.2 Turbidity currents and subaqueous debris flows – differences and similarities

Pratson et al. (2000) used numerical models to illustrate similarities and difference between turbidity currents and debris flows. One of their main similarities is that gravity, fluid pressure and friction determine the momentum of the flow. They are both propelled downstream due to gravity, further propelled by increases in fluid pressure, but become inhibited due to bed friction.
They can be differentiated in terms of flow behaviour and the nature of deposited material. The mud matrix of debris flows often does not allow for seamless exchange of sediment with the original lake bottom sediments (i.e. entrainment and deposition). This is the opposite of ignitive or erosional turbidity currents – non-ignitive turbidity currents are known to deposit their load on the lake bed. Turbidity currents and mud flows are distinguished by how their density changes. Turbidity currents tend to change their densities through deposition and erosion along the flow and with depth whereas debris flows conserve theirs (Pratson et al., 2000).

Furthermore, unlike turbidity currents, debris flows show plastic behaviour and have enough strength to carry larger clasts of material in the current. Debris flows move in a laminar fashion (Re < 0.5). Turbidity currents are much more dilute and all grains are supported equally in its matrix – suspended sediments are held this way due to fluid turbulence. In contrast, debris flows deposits are often poorly sorted and massive (Pratson et al., 2000). Some lakes in western Canada show massive, unstructured debrites in their sedimentary record – for example, debrites have been identified in different Quaternary deposits along the Fraser River Valley and have been interpreted as terrestrial debris flow slides that were triggered by lake level rise. A key criterion to distinguish turbidite sequences from debrites is the grading trend often seen in turbidite sediment cores (Middleton and Hampton, 1973). Mulder et al. (2001) retrieved sediment cores from the Ligurian Sea in the Northwestern Mediterranean to identify possible turbidite sequences.

A fining-upward sequence composed of a fine or coarse sand facies overlain by a silty - clay upper unit was observed (Figure 2.3). At the base of the turbidite is a sharp, coarse-grained erosive flute. This graded sequence reflects a deposit where the current velocity was decreasing, or waning (Mulder et al., 2001). The deceleration of the flow produced this sedimentary facies with an erosive contact at the base of the sequences, as outlined by Bouma (1962). Referred to as the Bouma sequence, a succession of interpretative facies may be formed by low-density turbidity currents (i.e. low-sand concentration) depending on the energy of the flow velocity, where (Bouma, 1962; Shanmugam, 1997, Mulder et al., 2001):
• Ta= intense and quick deposition of particles. This facies is structure-less and massive and is reflective of the point where the turbidity current is at its peak velocity.
• Tb, Tc, Td= reflecting the varying interactions of traction and suspended sediment deposition. Tb facies show planar, parallel laminae. Tc facies contain distinctive ripples or wave-like cross laminae. Td facies contain planar laminated muds resultant from the settling of suspended sediment.
• Te= deposition of turbidite sediment mixing with background, pelagic sediment. This facies is reflective of the point where the turbidity current is at its lowest velocity.

Figure 2.3: Fining-upward turbidite sequence from the Ligurian Sea at 2365 m water-depth. Taken from Mulder et al. (2001).

The sharp, erosive base is a consequence of the erosive waxing head of the current. Facies Ta-Td are resultant of the waning of the flow, while Te represents deposition by the tail of the current and by pelagic sedimentation (Ashley et al., 1985; Mulder et al., 2001). Not all sequences are observed within turbidite sequences. The absence of any of the facies may be due to the location of the deposits. For example, a proximal sediment core may contain only a predominant Ta facies (Shanmugam, 1997).

In contrast, two sediment cores were retrieved from Lake El’gygytgyn located in North-eastern Siberia (Juschus et al., 2009) to determine the significance on gravitational sediment transport on the sedimentary record in the centre of the lake. In the proximal part of the lake,
sediment cores revealed the presence of a debrite. The debrite was characterized as a massive, structureless coarse-grained sedimentary unit with limited sediment mixture.

2.2.3 Geostrophic forces

A common characteristic seen in lacustrine environments in the Northern Hemisphere is that incoming water (i.e. river inflow) is deflected to the right-hand shoreline (Smith, 1978; Atkinson et al., 1994; Wells, 2009; Pilotti et al., 2014) and does not appear to be affected by prevailing wind conditions (Hamblin and Carmack, 1978). This suggests that geostrophic forces associated with the rotation of the earth are important factors in lacustrine sedimentation of large lakes.

To study how the depositional features of turbidites are influenced by Coriolis forces, Wells (2009) ran ten experiments on a rotating platform. A turbidity current was generated by releasing a sediment-rich flow into a corner of a square shaped tank. Keeping the volume and density of the current constant, there was a reduction in the radius of where most of the deposition was occurring as the rotation rate was increased. This resulted in preferential accumulation of sediment deposition along the left hand side of the tank. The turbidity current spread due to geostrophic forces comparable to buoyant river inflow into the denser, salty ocean. A round, large bulge forms where the sediment is depositing with a radius comparable to Rossby’s number < 1 (i.e. the ratio of convection to Coriolis force). Results suggested that depositional patterns are directly related to latitude, with smaller, thicker deposits expected with higher latitudes.

At the field scale, there have been studies that show the effects of Coriolis forces on sedimentation regimes in lakes can be minimal, such as in the case of Bowser Lake. Gilbert and Desloges (1997) noted that there was no tendency of deflected sediment accumulation on the south side of the lake, suggesting that the primary mechanism of sediment deposition is solely from the source stream. However, sub-bottom acoustic profiles taken in Quesnel Lake by Gilbert and Desloges (2012) (Figure 2.4) show low sediment accumulation in the western basin, with more sediment deposited on the right side of the lake. These acoustic
profiles clearly show preferential sediment accumulation, suggesting Coriolis influence (Gilbert and Desloges, 2012).

![Sub-bottom acoustic profiles](image)

**Figure 2.4:** Sub-bottom acoustic profiles from the western basin of Quesnel Lake. Vertical axes show depth (m). Modified from Gilbert and Desloges (2012). Arrow represents groundwater movement. The view of the profile is up-lake (west-basin towards the outlet).

### 2.3 Sedimentary environments and records of lakes

Sediment focusing and diagenesis (compaction and bioturbation) are common occurrences in lakes.

#### 2.3.1 Sediment focusing

Sediment is not necessarily evenly distributed within lakes. Sediment focusing occurs when sediment is moved from shallower zones to deeper zones in a lake, resulting in a preferential accumulation of finer grained sediment in deeper parts of the lake basin (Crusius and Anderson, 1995). Hilton (1985) describes several processes that are most important in predicting the occurrence of sediment focusing. First, sediment sliding and slumping on slopes can move material to deep waters from shallower parts of the lake, which may generate submarine debris flows (Varnes, 1958; Owen, 1991). Another common mechanism
of sediment focusing occurs during lake turn-over, where this causes fine-grained sediment to suspend in the epilimnion. This provides an opportunity for these sediments to be transported to deeper basins by wind or wave action. Lastly, random sediment redistribution in shallow lakes can occur due to the kinetic energy from waves directly suspending sediment from the lake bed. For example, the general pattern of sedimentation accumulation at Kilen Lake, Denmark, shows a higher sediment accumulation rate in the deepest part of the lake, with a decline in sedimentation rates with a decrease in water depths (Lewis et al., 2013). This has been attributed to the large influence of wind-induced waves. These waves are able to re-suspend sediment in the shallow parts (<3 m) of the lake. Sediments in the deeper basin are re-suspended due to internal seiching as wind-induced waves typically are not able to penetrate deeper depths (Lewis et al., 2013). Gradient may play a part in discriminating where sediment is deposited, as sediment focusing does not occur if the slope is too gentle (<4%) (Hilton, 1985).

Other mechanisms of sediment resuspension and subsequent focusing have been noted in the literature. Upwelling events occur when hypolimnic water upwells to the surface and provides a surge of cold water, typically occurring during periods of little or no stratification (Laval et al., 2008; Lisi and Schindler, 2015). The most common trigger for upwelling events is wind action (Laval et al., 2008), when the wind blows over the surface of the water, the water is displaced and the lower mass of water rises up to replace it. Using radionuclides, a study conducted in Lake Michigan showed that coastal sediment resuspension (silt and clay size particles) occurred due to annual upwelling events. These rapidly suspended particles were transported through the coastal margin before being deposited in the deep basins of the lake (Klump et al., 2003). Eadie et al. (2008) noted that winter and spring storms also contribute to sediment resuspension and transport in Lake Michigan. Upwelling events have also been observed in Quesnel Lake (Laval et al., 2008). Episodic wind forcing resulted in sudden cooling and warming events of the water which lasted for up to six days in the west arm of Quesnel Lake.

2.3.2 Flocculation, diagenesis

Within a fluid, aggregation of particles, or flocs, occur as particles collide with one another. The three processes governing flocculation is Brownian motion (i.e.: thermal energy of the fluid, which is considered random in nature), fluid shear and differential settling (large, faster moving
particles may collide into smaller and slow moving particles) (Tsai et al., 1987; Lick et al., 1993; Guo and He, 2011). A breakthrough study using lake bottom sediments from the Detroit River inlet of Lake Erie showed that an increase in fluid shear and sediment concentration (in saline water) resulted in an increase in flocs (Lick et al., 1993). Less information is known about flocculation in freshwater systems, however Guo and He (2011) have observed the presence of large freshwater flocs in the Yangtze River, China (up to 182 µm) due to high suspended sediment concentrations from river inflow. These values were comparable to saline flocs located within the watershed (up to 120 µm). Flocculation has not been investigated in Quesnel Lake. However, Hodder and Gilbert (2007) identified freshwater flocculation in glacier-fed Lillooet Lake, British Columbia. These flocs were observed using microscopy and particle size analysis. It was found that micro-flocs between <4 µm to 30 µm, which were predominantly located in the epilimnion, joined to create macro-flocs that ranged from 200-280 µm in size once they reached the hypolimnion (Hodder and Gilbert, 2007).

In situ changes that sediments undergo post-deposition are referred to as diagenesis. In a lake setting, common changes seen to sediments typically occur due to bioturbation from benthic organisms, chemical reactions such as precipitation of minerals, and from compaction by overlying sediment. After deposition, minerals are altered either biologically or chemically. Diagenesis occurring at or near the sediment-water interface is referred to as early diagenesis (Boudreau, 2000; Rothe et al., 2016). Diagenetic signatures include sediment dissolution or neo-formation of magnetic minerals, and these features have been used to trace paleoclimates (Thouveny et al., 1994; Demory et al., 2005). For example, the presence of vivianite (Fe3(PO4)2*8H2O) in lake sediments have been attributed to diagenetic processes (Rothe et al., 2015). Under reducing conditions, vivianite (a reduced iron phosphate mineral) may form, which only occurs if significant phosphorous is formed during early diagenesis (Rothe et al., 2016). There is currently little information on its exact formation. However, the occurrence of vivianite has been documented in Quesnel Lake (Desloges and Gilbert, 2012). These blue, crystal like structures were associated with woody organic matter, which may have provided the phosphorus.

Bioturbation occurs when there is a resuspension of lake bottom sediments due to benthic organism activity, such as feeding and burrowing or in situ bioturbation. Sediment mixing due to biological activity is quite species specific. Molluscs and oligochaetes are known mix the deeper
sediment and in particular, tubificids oligochaetes have been reported in literature as important agents of sediment mixing (Fisher and Lick, 1980; Matisoff et al., 1999; Boudreau, 2000). Tubificids, which are a part of the oligochaete worms that are commonly found in freshwater systems, ingest sediment at depth and spit up the material mainly at the sediment-water interface (Fisher and Lick, 1980). Evidence of bioturbation can be seen in fossilized markings on soft sediment. Ciutat et al. (2007) determined that tubificid action caused particulate cadmium to be released into the water column due to sediment resuspension. A contrasting experiment done by the authors without bioturbation showed that cadmium release was significantly less. It was only released from its sorption depending on the duration of the experiment. At a macroscale, similar effects of sediment resuspension have been caused by fish (Havens, 1991).

2.4 Research objectives

The central objective of this project is to use the Mount Polley tailings mine spill to understand the impacts of a large catastrophic event on the lake sedimentary record in Quesnel Lake. This spill is a proxy to understand how the input of a mixture of tailings and Hazeltine Creek scour material, a point source, is distributed within a lake setting. Emphasis will be placed on identifying if the large-scaled and rapid sediment input generated either turbidity currents or debris flows and if sediment cores collected at strategic locations along Quesnel Lake can confirm this.

Gaps in the literature that support the novelty of this project include the following:

1) The majority of our understanding of lacustrine depositional mechanisms result primarily comes from low magnitude continuous sediment input from watershed-wide sources, and

2) There are infrequent opportunities to study the effects of high magnitude sedimentation events and this spill can be used as an analogue to study the characteristics and impacts on the prevailing sedimentary environment.
Chapter 3

Study Area

3.1 Introduction

Quesnel Lake is situated in eastern central British Columbia at the western outlet of the Cariboo Mountains (Figure 3.1). While the Mount Polley spill was restricted to the very west arm of Quesnel Lake, the environmental characteristics of the Cariboo Region, the Quesnel Lake watershed and the lake itself are of importance.

3.2 Cariboo Region

3.2.1 Climate

The Cariboo region lies within the Interior Cedar Hemlock Zone (Orbis Consulting, 2009). The area is characterized by dry, warm summers and long, cold winters. Average precipitation is approximately 500-1500 mm annually, where 25-50% of falls in the form as snow. These biogeoclimatic tendencies provide for highly productive vegetation. Common tree species include red cedar, western hemlock, white spruce and hybrid white spruce, and alpine fir (Orbis Consulting, 2009).

3.2.2 Regional Geology

The regional geology of the area is marked by Precambrian and Paleozoic sedimentary rocks overlain by extrusive volcanics from both the Triassic and Jurassic ages (Orbis Consulting, 2009). The boundary between the Omineca Belt and Intermontaine Belt, both characterized by granitic intrusive rocks and basaltic volcanic rocks respectively, runs through Quesnel Lake from northwest to southeast (Rees, 1988). The Intermontane Belt is primarily underlain by Lower Paleozoic to Upper Paleozoic plutonic, volcanic and sedimentary rocks of the Quesnel Terrane. The Quesnel Terrane is made up of a Late Triassic to Early Jurassic magmatic complex which was formed above a subduction zone (Logan and Mihalynuk, 2005). The Triassic Nicola Group,
in the Quesnel Lake region, is made up of a volcanic assemblage of fine-grained sedimentary rocks of Triassic age overlain by a primarily Precambrian metasedimentary unit. Exposed to the east of Quesnel Lake there exists an older Middle to Late Triassic volcanic sedimentary unit, extending as a northwest-trending belt (Logan and Mihalynuk, 2005).

A porphyry Cu-Au deposit occurs on the Mount Polley mine property in the west lake region. It occurs in the Quesnel Terrane of the Intermontaine Belt, which consists of Late Triassic to Early Jurassic volcanic rock. The intrusive complex is described as a subvolcanic composite made up of fine-grained porphyritic diorite and monzonite, with some dikes of syenite and plagioclase porphyry (Logan and Mihalynuk, 2005).

There are no extensive studies of the glacial history of the Quesnel Lake area. However, Desloges and Gilbert (2012) have interpolated information from studies that have examined the glacial history of British Columbia and western Canada as a whole (Clague, 1988; Menounos et al., 2009). Quesnel Lake is one of the deepest lakes in the world, due to tectonic (fault) origins and Pleistocene glacier scouring (Gilbert and Desloges, 2012). Glaciers during the Pleistocene spread westward out of the Cariboo Mountains into the Quesnel River valley and the Fraser Plateau. Thick, Quaternary sediments are present in the Quesnel Lake area that provide a record of the advance and retreat of the Cordilleran Ice Sheet. These include stream valleys carved prior to the final Fraser glaciation (Late Wisconsin), glaciofluvial sands deposited during the early Fraser period by streams within these valleys, glaciolacustrine muds deposited by advancing glaciers and an ice-dammed lake by the end of the recent glaciation (Clague, 1988). Ice cover quickly disintegrated by 10.5 ka BP (Menounous et al., 2009). The central and western regions of Quesnel Lake have terraces of glaciofluvial sediment well above modern lake levels suggesting ice-damming of Quesnel Lake during glaciation. Ice dam failure and lake glacial uplift entrenched the entire lake.

### 3.3 Quesnel Lake – Physical description and hydrology

Quesnel Lake is a “fjord-like”, oligotrophic lake that rests in between the boreal pine forest of the Interior Plateau and the Cariboo Mountains, 70 km southeast of of the town of Quesnel (Laval et al., 2008) (Figure 3.1). Shaped like an exaggerated “w”, it contains long, deep and narrow inlets related to fault lined and deepened by glacial scouring. The lake runs
approximately 100 km east to west, with a surface area of 266 km². Mean depth is 157 m. Depths of 511 m have been reported in the central main lake (Laval et al., 2008), making it one of the deepest lakes in the world.

Elevation increases from approximately 1000 m a.s.l. in the west portion of the lake to a maximum of 3039 m a.s.l. at Mt. Quanstrom in the east. The average elevation is 1375 m a.s.l. (Burford et al., 2009). Almost half of the catchment area is occupied by the Horsefly Basin (2693 km²), with the majority of sediment being from this sub-basin trapped in Horsefly Lake. This explains the low input of clastic material into lower Quesnel Lake. Horsefly River, draining into the interior, is Quesnel Lake’s most significant source of water inflow. Niagara Creek and Mitchell River drain < 600 km² (Laval et al., 2012). However, this upper basin region has 80 km² of mountainous glaciers (1.5% of the drainage area) which are heavily concentrated in the Mitchell River (25 km²) and Niagara Creek (51 km²) sub basins. These glaciers also provide a large inflow of water and sediment (Gilbert and Desloges, 2012). Quesnel River is the major outflow. Average residence time of the lake water in the main body of the lake has been estimated to be is 10.1 years and approximately three months for the smaller west basin (Laval et al., 2008). Mean annual outflow is 131 m³/s (Potts et al., 2004). Peak flows occur in the springtime to early summer (April to June) due to the spring freshet with an average discharge of 689 m³/s (Environment Canada). Flows decline starting in the fall and into the winter. Short peak flows may occur in the fall in response to heavy precipitation events (Potts et al., 2004).

Quesnel Lake experiences lake overturn twice a year, and is thermally stratified during the summer and winter months (Laval et al., 2012). The lake becomes de-stratified in the fall, when air temperatures start to cool the warmer epilimnion, which deepens the epilimnion and initiates an isothermal state. In the west basin, this occurs in late December to early January (Laval et al., 2012). Further along into the winter months, the lake surface in the west basin continues to cool and the water column becomes inversely stratified (i.e. cooler in the epilimnion). The surface water slowly begins to warm and becomes isothermal again in late March and early April. During the spring and early summer months, another (albeit weaker) overturn occurs.

The west basin is also separated from the main Quesnel Lake basin by a 35 m deep sill. The western arm extends to the Quesnel River outlet, and this portion of the lake has a maximum
depth of 115 m (Figure 3.2) and occupies 2.3% of the total Quesnel Lake volume (Laval et al., 2008).

**Figure 3.1: Drainage basin of Quesnel Lake.** The dashed lines separate the Horsefly and Niagara sub-basins. Upper inset shows the location of Quesnel Lake in British Columbia; lower inset shows the stratigraphic geologic terranes of the drainage basin. Arrow on inset shows the direction of thrusting of the Quesnel terrane. Modified from Gilbert and Desloges (2012). Red arrow indicates location of Mount Polley Mine.
Figure 3.2: Bathymetry measurements of the west basin of Quesnel Lake, up the thawleg of the west basin. 0 km represents the Quesnel River outflow. Water depths are in 20 m intervals. Measurements provided by Fisheries and Oceans Canada.

3.4 The Mount Polley tailings spill: failure of the tailings pond

The Mount Polley tailings spill released approximately 18 million m$^3$ of tailings sediment into Quesnel Lake on August 4, 2014 as a subaerial debris flow event (British Columbia Ministry of the Environment, 2015; Golder Associates, 2015). Ten million m$^3$ was deposited into Hazeltine Creek. The addition of approximately 8 million m$^3$ is glaciofluvial sediment eroded from the creek banks and entrained in the debris flow. The trigger of the breach was linked to previous construction at a rock fill zone in the tailings dam which was built at an improper slope (Morgenstern et al., 2015).

Figure 3.3 shows the layout of the Mount Polley failure. The major physical impacts from the tailings failure are as follows: 1) the embankment that separated the tailings pond from Polley Lake failed, 2) 25 million m$^3$ of materials flowed into Polley Lake and subsequently into Hazeltine Creek, and 3) the deposition of these mine materials in addition to woody debris and trees along the now eroded corridor of Hazeltine Creek flowed into the mouth of Quesnel Lake at the Hazeltine Creek delta (Brown et al., 2016).
Figure 3.3: a) Map of Quesnel Lake and Mount Polley mine and tailings pond. Satellite images of Quesnel Lake b) pre-spill and c) post-spill. Taken from Petticrew et al., 2015. Numbers in a) represent coring location from Petticrew et al., 2015. Shaded contours in the lake represent deeper water depths. Taken from Petticrew et al., 2015.
Chapter 4

Methods

4.1 Introduction

Field and laboratory methods were used to investigate and interpret sediments in cores from Quesnel Lake. While sampling was conducted only in the west basin of the lake, sediment data from all other studies (Hazeltine Creek, tailings pond, and other Quesnel Lake studies) are also utilized.

4.2 Field Methods

4.2.1 Sediment cores

Seven sediment cores in the western arm of Quesnel Lake were taken using a Rossfelder submersible vibra corer in July 2015 (Table 4.1). The aluminum core tubes have a diameter of 7.6 cm. The end of each tube was fitted with a core catcher to secure the bottom sediment. Coring locations varied within the western portion of the lake. Sites were chosen based on proximity to Hazeltine Creek (i.e. close to spill input), and on deep, adjacent, flat lake floor sites. Locations were also chosen based on Tetra Tech EBA reporting in Golder Associates (2015) which discussed possible sediment deposit thicknesses. Coring immediately adjacent to Hazeltine Creek was not done to avoid sampling either completely scoured zones or zones with 100% tailings. The coring objective was to capture the contact between the native muds below and the tailings muds above. The length of cores varied from 1.1 to 6.1 m. Cores were cut into 1.5 m lengths to facilitate shipping and analysis.
**Table 4.1**: Coring locations, core lengths, depths and surface water temperature in Quesnel Lake from July 4-17, 2015.

<table>
<thead>
<tr>
<th>Core (Q15)</th>
<th>Core locations (DMM)</th>
<th>Uncut core length (m)</th>
<th>Coring water depth (m)</th>
<th>Lake surface temperature at time of coring (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>N 52° 31.430 W 121° 31.040</td>
<td>3.48</td>
<td>95.7</td>
<td>17.5</td>
</tr>
<tr>
<td>02</td>
<td>N 52° 29.546 W 121° 28.140</td>
<td>4.25</td>
<td>92.1</td>
<td>18.2</td>
</tr>
<tr>
<td>03</td>
<td>N 52° 29.573 W 121° 26.098</td>
<td>2.22</td>
<td>44</td>
<td>18.6</td>
</tr>
<tr>
<td>04</td>
<td>N 52° 30.964 W 121° 30.402</td>
<td>6.11</td>
<td>112</td>
<td>18.5</td>
</tr>
<tr>
<td>05</td>
<td>N 52° 31.946 W 121° 31.319</td>
<td>4.57</td>
<td>82.3</td>
<td>17.9</td>
</tr>
<tr>
<td>06</td>
<td>N 52° 33.164 W 121° 31.775</td>
<td>4.1</td>
<td>50</td>
<td>18.2</td>
</tr>
<tr>
<td>07</td>
<td>N 52° 34.297 W 121° 32.382</td>
<td>1.09</td>
<td>31</td>
<td>19.1</td>
</tr>
</tbody>
</table>

4.3 **Laboratory methods**

Core sections were kept upright, and excess water at the surface was removed using a pipette. The cores were split longitudinally using a table saw, and the halves were separated by running a wire down the middle. Sediment lengths were measured and the cores were photographed. One half was assigned as the working core and the archived half was kept in a cool room at a temperature of 4°C. The working sediment core was allowed to partially dry in order to show any sediment structures such as laminations. Physical characteristics of the cores, such as any distinct layering and colour differences, were recorded manually. All cores were photographed at several stages of drying and as sediment structures became visible.

4.4 **Laboratory Analysis**

4.4.1 **Subsample protocol**

The protocol for subsampling varied for each core. Q15-01 was the focus due to its close proximity to the tailings spill, and because there was less tailings material than expected (i.e. it penetrated the tailings deposit and exposed the basal contact). Loss on ignition and grain size
samples were taken in this core at 2 cm intervals. All other cores were subsampled at 5 cm intervals, with the exception of the upper 20 cm of Q15-05, which was also subsampled at every 2 cm. This was to capture any turbidite/debrite sequences that would not be identified with 5 cm resolutions. Core Q15-07 was not analyzed because this core was short (<50 cm), the most distal and shallow, and contained no significant stratigraphic features.

4.4.2 Loss on ignition

Loss on ignition is a common method used to determine both the organic and the carbonate content of sediment (Dean et al., 1974; Heiri et al., 2001). Approximately 2 g of sample were placed into a crucible of known weight. The samples were placed in a drying oven for 24 hours at 105°C. The crucibles were cooled in a desiccator for 1-2 hours and re-weighed. This dry weight \(W_{dry}\) and the initial weight \(W_{wet}\) were recorded manually along with the crucible weights.

The samples were then burned at 550°C in a muffle furnace for an hour to determine loss on ignition (Heiri et al., 2001). The crucibles were cooled in a desiccator following removal from the furnace and re-weighed. This weight \(W_{LOI}\) was manually recorded.

This first drying removed all moisture, where:

\[
\% \text{ Moisture content} = \frac{(W_{wet} - W_{dry})}{W_{wet}} \times 100
\]

and,

\[
W_{wet} = \text{Weight of wet sample (g)}
\]

\[
W_{dry} = \text{Weight of dry sample (g) burned at 105°C}
\]

The second burn of 1 hour oxidizes the organic matter as CO₂, leaving ash (Heiri et al., 2001), where:

\[
\% \text{ OM} = \text{LOI}_{550} \left( \frac{W_{dry} - W_{550}}{W_{dry}} \right) \times 100
\]

And,

\[
W_{550} = \text{Weight of dried sample after LOI at 550°C}
\]
No sources of carbonates were expected in any samples from Quesnel Lake based on the regional bedrock geology. However, some test samples were burned at 1100°C to determine if residual organic matter content or any significant carbonates were present. This difference was negligible.

### 4.4.3 Grain size analysis

Textural analysis of lake sediments is arguably one of the most important descriptors used in sedimentary analysis. Grain size analysis can be used to infer paleoenvironmental conditions within both the basin and surrounding watershed, and can also shed light on sediment origins and transport as well as depositional mechanisms.

Laser diffraction was used (Malvern Masterizer 3000) because it requires a relatively small amount of sample, it can detect a wide range of grain sizes and has a high repeatability of results with rapid analysis time. The Malvern Mastersizer 3000 was coupled with a Hydro MV allowing for a maximum measurement range of 0.01-3500 µm. Sample preparation and usage of the instrument is outlined below.

#### Sample preparation

Approximately 0.5 g of sample was placed in a 50 mL centrifuge tube. Pretreatment was done on the samples to digest organic material. This is an important step in particle size analysis, as organic matter can bind or aggregate sediment together (Robinson, 1927; Schumacher, 2002). To first remove organic material, drops of stock 30% hydrogen peroxide (H$_2$O$_2$) were added to the centrifuge tube. H$_2$O$_2$ was continuously added until the vigorous reaction was completed (Robinson, 1927). This digestion process was completed in a boiling water bath to speed up the reaction. Once the reaction was complete, the tubes were filled with deionized water to 30 mL and the sample was sedimented by centrifuge at 2800 RPM for five minutes. The deionized water was removed using a pipette.

Following organic matter removal, 3% sodium hexametaphosphate was added to the sample as a dispersant and left overnight for at least 12 hours (Ozer and Orhan, 2015).
**SOP**

Standard operating procedures (SOP) were determined for samples taken from each core. All samples were analyzed for three consecutive measures for 10 seconds and 30% ultrasonication energy. The material property type was silica, which has a refractive index of 1.54, an absorption index of 0.1 and a density of 2.65 g/cm$^3$. The quality of the each result was evaluated using weighted residuals and distribution tests (i.e. low weighting and unimodal).

Samples composed of primarily silt material from preliminary hard textural analysis were set at a stirring rate of 2500 RPM. Samples composed of more sandy material were set at a higher spin speed of 2800 RPM. This was to ensure that all material, no matter how coarse, remained in suspension during laser measurement.

### 4.4.4 ITRAX scanner – XRF, magnetic susceptibility

Split core sections from Q15-01 were scanned on an ITRAX core scanner located at McMaster University, Hamilton. This core scanner is a fast and non-destructive option to determine elemental geochemistry, magnetic susceptibility as well as X-radiograph images (Croudace et al., 2006). Core sections were scanned at a resolution of 200 µm using a Mo tube with a 40 kV voltage, 20 mA current and 10 seconds exposure time. The cores had to be smoothed and relatively dry (with no significant cracks in the sediment surface). Special film was used to cover the core to protect the sensor from contamination. Elements analyzed by the core scanner include Al, Si, K, Ca, Ti, Mn, Fe, Rb, S, Sr and Zr. The ITRAX scanner is semi-quantitative, in that the core scanner presents these elements as counts per second. These counts were plotted down core to determine elemental variation within the core. However, elemental ratios have been widely used in the literature to express these counts in relative terms. Many elemental ratios are commonly used to identify sedimentary sequences such as turbidite beds such as Zr/Rb (Rothwell and Croudace, 2006).

Magnetic susceptibility (MS), a measure for determining the concentration of magnetized minerals in a given sample, can highlight increased inputs of clastic material from terrestrial erosion in lake environments (Nesje et al., 2001). In this study, MS was used as a proxy for inputs of clastic sediment inputs from the tailings, in addition to geotechnical analysis such as particle size and LOI. The mine plume picked up available sediment from Hazeltine Creek,
resulting in a sediment mineralogy reflecting a mix of different mineral signatures between the native creek, lake sediments and heavily re-worked and concentrated tailings spill sediments.

X-ray fluorescence (XRF) is an analytical, non-destructive technique used to determine the elemental composition of sediment. It determines the elemental chemistry of a sample by measuring the fluorescence that is released from a sample when it is excited by an X-ray source. Each element releases a unique fluorescent signature that makes element identification simple.

Mineralogy data can show changes in the detrital sediment input (Kylander et al., 2011). More specifically, both primary elemental and ratios of specific elements can be used to determine changes in sediment input at any time in the sedimentary record (Croudace et al., 2006). Particular elements, notably titanium, potassium, rubidium, and zirconium, are identified as detrital indicators (Karageorgis et al., 2009; Kylander et al., 2011; van der bilt et al., 2015) that can be used to identify foreign sediment inputs into the lake and acts as an indicator for sediment provenance (Croudace et al., 2006).

4.4.5 Microprobe analysis

Two samples (Q15-04B [10 cm], Q15-01B [30 cm]) were submitted for electron probe X-ray microanalyzer (microprobe) analysis. The microprobe captures images of grains at a scale of a few micrometers to millimeters, and can be used to assess the composition of individual particles both for grain shape and chemical properties (Last, 2002). The microprobe allows for the in situ analysis of particle shape, with the added capability of chemical analysis. The principle difference between the microprobe and the ITRAX is the ability to acquire elemental analysis of these individual grains, in addition to microscopic images of the grains to observe grain shape (i.e. elongation, circularity). These images were used to explore any differences in grain shape between Q15-01, which contained mostly non-spill material, and Q15-04 which contained mostly tailings material.

The samples were first subsampled and submitted to the University of Toronto EMPA Laboratory. The samples were cut to size to fit into 1.5” round epoxy mounds, and ground when the samples were dry. An initial polish of 1 micron diamond and a secondary, final polish of 0.3 micron alumnia on cloth were completed on the samples. Carbon was coated on the mounds in order to eliminate surface charging. The accelerating voltage was set to 15.0 kV with
a probe current of 10nA. The dwell time per pixel is 2 ms, while the points were 500 x 500. The signal was backscattered, BSE.

4.4.6 Metals analysis

Discrete sediment samples from all study cores (i.e.: except Q15-07) were analyzed at ALS laboratory group, Vancouver, Canada. Samples were weighed to approximately 5 g and bagged before shipping. The samples were analyzed using ICP-AES and ICP-AS spectrometry (ALS, 2010). Approximately 39 metals were analyzed. However, only selenium (Se), arsenic (As) and copper (Cu) were interpreted. This is because these three metals are commonly associated with the copper gold mine process (Smith and Owens, 2014).
Chapter 5

Results

5.1 Introduction

Overall, all cores contained a basal unit of fine-grained (silt or silty-clay), thinly laminated sedimentary unit that is interpreted as pre-existing, non-spill (herein referred to as “native”) sediment. Each core, apart from Q15-07, was analyzed for grain size, organic matter content and metals concentrations. Three out of the six cores analyzed (Q15-02, Q15-04, Q15-05) were identified as containing some tailings input. Specific tailings signatures include high copper concentrations, lower organic matter content, variances in grain size (coarser in Q15-02, finer in Q15-04 and Q15-05) and distinct differences in mineralogy and magnetic susceptibility. No significant tailings input are observed in Q15-01 (proximal to input location), implying that either the current was eroding the native sediment or the current was retaining its load (i.e. minimal deposition was occurring).

The reaches of the lake where cores were taken can be subdivided into three primary zones, reflecting influence of the spill. Zone 1 encompasses cores Q15-01, Q15-02 and Q15-04 (Figure 5.1). This zone is the deepest section of the western arm at approximately 110 m and most proximal to Hazeltine Creek, within approximately 2 km. It was hypothesized that the flow was most active in this part of the lake and should exhibit highest velocities. The next two zones are represented by the more distal cores from the Hazeltine Creek delta. Q15-03, the most easterly core (Zone 2 – Figure 5.1), was taken close to the Cariboo sill, in shallower, up lake water. The more distal location and much shallower position (approximately 30 m) from zone 1 was thought to have negligible tailings sediment in the core. Lastly, Q15-05 and Q15-06 fall in zone 3 (Figure 5.1). It was thought that these cores should also contain minimal amounts of tailings sediment due to the distance from the delta of up to approximately 7 km. Similar to Zone 2, it is also expected that if there is tailings sediment present, these particles should be the finest in size compared to the pre-existing sediment.
In these sections to follow, the pre-existing (native) sedimentation regime and the sediment structures that reflect this are discussed. This includes previous sedimentary studies conducted and the known pre-spill sedimentary record. The characteristics of the Mount Polley tailings sediment will be explored by identifying distinct sedimentary units that may reflect a tailings deposit within each core zone.
Figure 5.1: Zoning classification of coring locations in Quesnel Lake. Green circles represent core locations.
5.2 Pre-spill sedimentation processes observed in Quesnel Lake

5.2.1 The sedimentary environment and pre-spill state of the water column, in the west arm of Quesnel Lake

A sub-bottom acoustic survey of Quesnel Lake was conducted by Gilbert and Desloges (2012) (Figure 2.2). The basement sedimentary units show acoustically laminated horizontal reflectors that increase in definition up the sediment profile. Sediment below the top 4-5 m is late Pleistocene in origin (Gilbert and Desloges, 2012). This thicker lower package is most likely due to persisting glaciers that lingered in the area of the drainage basin during de-glaciation. Sediment would have been deposited when the glaciers were still active in the lake. Distally this would translate into the deposition of fine-grained silts and clays, as represented by the laminated nature of the acoustic profile. Turbidity currents most likely act as the largest control over sediment deposition during de-glaciation, suggested by the quasi-continuous and unconformable reflectors in this basement unit (Gilbert and Desloges, 2012).

The Holocene (last 10ka) was interpreted to be represented in only the top 4-5 m of the lake bottom sediment in the west arm with an average sedimentation rate of approximately 0.25 mm/year (Gilbert and Desloges, 2012). The similarity in reflector patterns between the lower late de-glacial and upper Holocene sediments signify that sediment deposition patterns in these periods were quite similar, such as a distal open water environment. Sediment sources during deglaciation were most likely para-glacial, where sidewall sediment were exposed and then eroded. During the Holocene, the growth of vegetation alongside the hillslopes reduced sediment input, making these sources less available for lake deposition, resulting in a change to lower accumulation rates (Gilbert and Desloges, 2012).

In most glacier-fed, ice-proximal to ice-distal lakes, in British Columbia, the sediment packages have some similarities: a thick (40-100 m) unit of acoustically laminated sediments that reflect rapid inputs of sand, silt, and clay during deglaciation. The units are often unconformable, burying the uneven bedrock and till terrain below with horizontal beds derived from high energy bottom currents. Overlying these late-glacial to earliest Holocene sediments is a much thinner package of more acoustically transparent sediment reflecting a significant reduction in
accumulation rates during the Holocene. Reduced sediment inputs relate to several factors including: retreat and decline of glaciers, a continual exhaustion of finer glacial sediments and reduced production rates and stabilization of surfaces as vegetation matures. As a result, the entire Holocene sediment package is often no more than 1-4 m thick. Despite the reduced rates of sediment input, there are still distinct laminations in the sediments related to strong seasonality of inputs, frequent high impacts due to major floods and local (allochthonous) processes. These attributes characterize the “native” sediments of the western basin of Quesnel Lake.

5.3 Effects of tailings pond failure on Quesnel Lake

The large plume of material released from the pond resulted in a large lake deposit in the western basin of Quesnel Lake. Petticrew et al. (2015) report the deposit as spanning approximately 600 m long and 1-3 m in depth. The large surge of tailings and eroded material from Hazeltine Creek, as well as the release of water resulted in seiches lasted approximately 12 hours. In the short hours following this event, Quesnel lake level had risen about 7.7 cm. This rise in lake volume was computed to equate to an increase of approximately 21 million m$^3$ of sediment volume to the lake (Petticrew et al., 2015).

Multi-beam sonar was conducted by Tetra Tech EBA a few months following the spill to determine the extent of the spill deposit in the western basin of Quesnel Lake (Golder Associates, 2015). Most of the spill materials were deposited below 100 m in water depth. More importantly, in some areas the thickness of this material was thought to be 10 m deep and over 600 m long (Figure 5.2), which is greater than what was first reported. Below 30 m in the water column, cooler water depths in the west basin were immediately impacted. Hypolimnetic temperatures increased to approximately 7° C below 30 m (Figure 5.3A, 5.3D). In these bottom waters, an increase in turbidity was seen from 1 NTU to over 1000 NTU (Figure 5.2 B), and these elevated levels did not decrease until later in the fall of 2014. Turbidity levels in Hazeltine Creek remained higher than normal (5 NTU) weeks after the spill, which suggests that turbid waters were still flowing into the west basin of Quesnel Lake (Petticrew et al., 2015).
Figure 5.2: Multi-beam and sidescan sonar of the western arm of Quesnel Lake. Deposited sediment is observable in the deepest part of the lake, as indicated by the red square (up to 10 m). Red arrow indicates Hazeltine Creek. Taken from Golder Associates, 2015.
Figure 5.3: Effects of the Mount Polley spill in the western arm of Quesnel Lake showing a) temperature profiles in 2014, b) turbidity in 2014, c) time series of temperature prior to spill (in years), d) temperature data from varying seasons/years. Modified from Petticrew et al., 2015.

5.3.1 Zone 1 – deep west basin proximal to Hazeltine Creek

Cores Q15-01, Q15-02, and Q15-04 were taken in the area most proximal to the Hazeltine Creek (1.5 to 3 km) and in lake depths from 92.1 m to 112 m. It was expected that these three cores would contain the most tailings sediment.
Q15-01 (1.56 km; 95.7 m):

*Core description:*
Most of the sediment in core Q15-01 is fine-grained silts, thinly laminated and dark grey in colour (Gley 2 5/5B) (Figure 5.4). The sediment core exhibits colour banding of primarily dark-coloured laminae, less than 10 mm thick. In contrast, the uppermost 20 cm of the core is coloured as a brown - red (2.5YR 4/4) and is also very fine-grained. The contact point between these two layers is abrupt and planar. The upper 20 cm was initially interpreted as tailings based on colour.

*Organic matter (OM) content, grain-size and magnetic susceptibility results*
Core Q15-01 shows some variance in organic matter contents up-core (Figure 5.4). Low organic matter contents, from 2%-6%, are observed in the lowermost part of the core (from 3 m – 2.34 m). Organic contents gradually increase to a local maximum of 10% by 1.38 m. However, there is a sudden decrease just above this maximum (to approximately 2%) and from there, organic contents remain relatively consistent up core. There is an increase to 13% at 3 cm. However, this declines sharply and remains between 4-6% in the upper 2 cm.
Figure 5.4: Loss-on-ignition, magnetic susceptibility and grain size results for core Q15-01. Black line in LOI represents average.
In the coarser D75 and D90 fractions, there is a slight trend of increasing sediment grain size up-core. However, from 2.5 m to 1.25 m, this increase is most pronounced, whereas above 1.25 m, trends are less obvious with slightly more variability. Grain size results show minimal up-core differences in the finer fractions. These fine fractions (D10, D25; less than 15 µm) show less variation up-core. The MS and grain size curves follow a similar pattern in the lowermost unit of core. Finer grained sediment is expected in the west basin because of its distal location to present-day sediment sources. Sediment in core Q15-01 below 20 cm does not show any significant change in organics with depth except for an abrupt decrease at 1.38 m. Above this peak, organic content slowly increases up-core. This change at 1.38 m is interpreted not as a boundary between the native lake sediments below and the spill debris flow sediments above, but may represent natural changes in past environmental conditions. The average sediment accumulation rate for Quesnel Lake ranges from 0.22 mm/a to 0.72 mm/a, depending on lake location – the western basin has accumulation rates of 0.2 mm/a - 0.4 mm/a (Gilbert and Desloges, 2012). If the spill deposit is restricted to only the upper 20 cm of core Q15-01, then the organic matter change that occurs at 1.38 m is in conjunction with sediment deposited during the mid-Holocene (~ 5500 before present (BP)). Proxy records have indicated that, beginning in the mid-Holocene, southern British Columbia was cooler and wetter than present conditions, with cooler summers and wet winters (Harvey et al., 2012). These conditions were associated with glacier expansion that occurred between 7500-5500 BP (Clague, 2009). Therefore, glacial advancing, coupled with the wet and cold climate observed during the mid-Holocene, may explain the abrupt drop in organic matter content observed in the sediment core.

MS values (unit-less) in this core vary between zero and -918. MS values change from -900 at 1.25 m to near zero at 3 cm. MS values abruptly increases at 1.25 m from -950 to almost zero. Typically lake sediments vary from 0.4-200 (Thompson, 2012), although the samples from this core vary from zero to -1000. Sediment made up of minerals such as basalt show high MS values (130-200), while sediment composed of limestone have values as high as 0.4 (Thompson, 2012). As MS is negatively correlated with organic matter content (Murdock et al., 2013) and
water content (Thompson, 2012), sediments may show extremely negative low MS values if the sediment is saturated or contains “detectable” organic matter. Sediments that also contain particular minerals such as quartz, feldspar, or even trace elements such as arsenic or copper may show diamagnetic properties (and thus negative MS values) due to their inherent diamagnetism (Thompson, 2012).

However, all of the sediments within this core are very negative. This is most likely due to the organic matter within the core (notably the two peaks at 1.25 m and 3 cm). In the rest of the core, the presence of arsenic within the natural sediment muds (Brown et al., 2016) in addition to the water content within the core (the cores were not fully dried prior to ITRAX use to decrease the likelihood of sediment cracking) may be the cause for the very negative values. In this case the negative sign of the values is uninterpretable and unusable due to high amounts of organic matter and water contents.

Despite this, the trends remain interpretable. There is an expected large presence of copper in spill sediments which may relate to the upper 20 cm of this core. Although copper is ferromagnetic (which results in a strongly positive magnetic susceptibility), ore processing at Mount Polley results in a copper sulphide concentration (Kennedy et al., 2016). Any copper present in the tailings is most likely in this state. The magnetic susceptibility of copper (II) sulphide is diamagnetic and should result in a decrease in MS values.

Overall, the diamagnetism of the natural sediment may be attributed to a combination of 1) the presence of arsenic which is found in the natural sediment muds (Brown et al., 2016), and 2) the fact that the sediment core when processed through the ITRAX contained small amounts of water to ensure no cracking in the sediment surface occurred. However, the presence of heavy metals and organics may solely contribute to the very negative MS values in the upper unit.

Mineralogy and metals analysis for core Q15-01

Mineralogy was studied for the entire core using a Cox Analytical Systems ITRAX core scanner.

Figure 5.5 shows the change in four key detrital elements in Q15-01. Zirconium (Zr), rubidium (Rb), titanium (Ti) and potassium (K) were chosen due to the following characteristics:
• Rb = commonly associated with detrital clays, and may be able to distinguish turbidite muds that define an erosional turbidite base (Croudance et al., 2006). It is also present in common clay and mica minerals (Kylander et al., 2011).

• Zr = dominant rock type and overall regional geology of the study site. It is also typically present in poorly weathered minerals.

• Ti, K = Ti is indicative of detrital input (Kylander et al., 2011). Commonly seen with lake sediment abundant elements such as iron. K is also associated with minerogenic input to lakes.

Overall there is a larger count number of Zr and Rb compared to Ti and K. The higher counts of Zr is most likely a reflection of the regional geology of the area from the dominant rock type (igneous). Furthermore, any changes in these two elements up-core due to a possible spill deposit will be negligible in relation to regular, long-term sediment sources because the source of the spill, Mount Polley Mine, reflects the local geology. The mean count profile of Zr and Rb shows minimal variance within the core. From the bottom to 1.45 m, there are a consistent number of counts ranging from 900 to 1400 for Zr and 1100 to 1700 for Rb. At 1.45 m, Rb sharply increases to 3140 counts. There is a less dramatic increase to 2100 counts in Zr at 1.45 m. Above this peak, Rb steadily declines to a range between 1000-1960 counts by the top of the core. There is minimal change in Zr in the upper 1.5 m. In contrast, the profiles of Ti and K show a higher degree of variance in the mean value up-core. In the basement sediment until 2.7 m, there is a sudden decline in counts of these elements, from 5060 to 4600 in Ti counts and 6400 to 3010 in K counts. From 2.7 m to 1.6 m there is minimal change until another sharp decline to near zero values in Ti and in K. This is followed with another sharp increase in K counts to 6500. No observable increase is detected in Ti counts. Counts of K decline steadily until another sharp decline is observed at 0.3 m to 2400 counts. Counts of Ti show little change until 0.3 m to 2600 counts.

As the XRF data are reported in counts/seconds rather than a weight/weight units, it is useful to consider ratios to detect trends. The use of ratios has been heavily relied on to determine changes in sediment sources (Kylander et al., 2011). Figure 5.6 shows the Zr/Rb ratio of only the upper 1.26 m of core in an effort to isolate and observe any potential spill deposit.
Zr is heavily concentrated in coarse-grained fractions while Rb tends to become concentrated in clays. Therefore, an increase in the Zr/Rb ratio will reflect an increase in sediment coarseness. In some studies this has been interpreted as increases in flood discharge (Jones et al., 2010).

Overall, there is minimal change in Zr/Rb up-core. The ratio does not outline a clear, definable turbidite sequence (i.e.: an erosional flute as signified by an increase in the ratio). This further suggests that minimal or no sediment deposition is occurring in this core. This minimal shift may suggest that no significant deposition or scour is occurring at this depth. However, coupled with the slight increase in organic matter content and MS values in the upper 20 cm, only this uppermost sediment may reflect a tailings deposit.
Figure 5.5: XRF data vs. depth profiles of Ti, Zr, Rb, K in Q15-01
Figure 5.6: Zr/Rb ratio of the upper 1.25 m of Q15-01. Red line indicates mean. $R^2=0.17$
Metals analysis for core Q15-01

Metals analysis was conducted on seven discrete samples in Q15-01. These samples were chosen due to variances in colour and grain size. Table 5.1 lists key metals from Smith and Owens (2014) and Imperial Metals (2015) as being significant indicators of contamination from mining activity in the region. Reference levels from Smith and Owens (2014) and regional background levels based on data from the British Columbia Drainage Geochemical Atlas (Lett et al., 2008) are also listed. Regional background levels from the geochemical atlas were determined by sampling stream sediment from undisturbed areas in 1976 (Lett et al., 2008).

**Table 5.1:** Average concentration of all seven samples in Q15-01 (mg/kg) with background levels and regional background levels from Smith and Owens (2014) and from Lett et al. (2008) for Q15-01.

<table>
<thead>
<tr>
<th>Element</th>
<th>Average metals Concentration in Q15-01 (mg/kg)</th>
<th>Background levels, from Smith and Owens (2014) (mg/kg)</th>
<th>Regional background levels, from Lett et al. (2008) (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>14.2</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Cu</td>
<td>192.4</td>
<td>92</td>
<td>35</td>
</tr>
<tr>
<td>Se</td>
<td>0.98</td>
<td>1.5</td>
<td>--</td>
</tr>
</tbody>
</table>

Arsenic and selenium are both products of the gold and copper mining process (Leybourne and Cameron, 2008; Smith and Owens, 2014), and a percentage of copper sulfide materials end up in tailings pond during ore processing. Thus, if there are observed higher levels of these metals against both the reference levels determined by Smith and Owens (2014) and regional background levels, then it is possible to infer contamination.
Table 5.2 shows the change in metal concentration with depth in this core. Almost all arsenic values exceed background levels. Copper values in the upper 5 cm of core show enormously high values (924 mg/kg), exceeding both the reference levels and regional background levels. This is in conjunction with a peak in organic matter and low MS values (Figure 5.3). Cu values in the rest of the core remain above the reference level.

**Table 5.2:** Concentrations (mg/kg) of As, Cu, and Se and depths in core Q15-01.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Arsenic (As), mg/kg</th>
<th>Copper (Cu), mg/kg</th>
<th>Selenium (Se), mg/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>16.1</td>
<td>924</td>
<td>1.45</td>
</tr>
<tr>
<td>1.16</td>
<td>6.51</td>
<td>52.1</td>
<td>0.27</td>
</tr>
<tr>
<td>1.34</td>
<td>9.12</td>
<td>65.9</td>
<td>1.28</td>
</tr>
<tr>
<td>1.58</td>
<td>7.58</td>
<td>72.3</td>
<td>0.91</td>
</tr>
<tr>
<td>2.8</td>
<td>13.0</td>
<td>64.0</td>
<td>0.95</td>
</tr>
<tr>
<td>2.88</td>
<td>17.7</td>
<td>73.8</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Copper-rich sediment in the uppermost 6 cm of core suggests significant tailings material present. The increase in metals concentration may be due to the tendency of heavy metals to bind to organic carbon. In lake sediments metals are adsorbed to organic matter via electrostatic attraction (Matagi et al., 1998). Copper and selenium are reported as having an affinity for organic compounds in aqueous environments (Breault et al., 1996). Moore and Ramamoorthy (1984) report that organic matter in lake sediments is less significant in the sorption of arsenic compounds to most metals including selenium and copper. The organic matter in this core would have been introduced during the breach flood.
It is interesting to note that selenium values do not exceed background levels anywhere in the core. Imperial Metals (2015) determined that within the tailings mixture, selenium was more soluble, therefore more mobile, than other metals such as copper. This may explain lower than expected levels in the lake muds present in Q15-01. Overall, the evidence presented here suggests the upper 20 cm of Q15-01 is tailings mud.

**Q15-04 (1.5 km, 112 m):**

*Core description*

Q15-04 is the most proximal core to the point of the Hazeltine Creek inflow (~1.52 km) and, at a depth of 112 m, was taken from the deepest section of the western Quesnel Lake basin. Most of the sediment observed in the upper 3.5 m of the core consists of very fine-grained silts that are massive in structure and light brown to beige in colour (5Y 6/4). There are no laminae present in this unit. From the bottom of the core at 4.4 m to 3.5 m, the remainder of sediment consists of fine-grained silts, laminated (<10 mm) and dark grey in colour (Gley 2 5/5B). This portion of the sediment core exhibits colour banding of primarily dark-coloured laminae. The contact between these two sections at 3.5 m of core is gradual and non-planar, extending over approximately 30 cm. This signifies intense mixing during sediment deposition.

*Loss on ignition (LOI), grain-size, and metals*

Grain size results show significant changes in grain size with depth (Figure 5.7). At the base of the core, particle size gradually increases until a sharp increase at 3.5 m. At this point, grain size gradually decreases until 2.1 m, where there is a steep decline in particle size. The upper 2 m is marked by very small particle sizes (mean particle size is approximately 4.54 µm) that slowly decrease in size until the top of the core.

Low organic matter, with a range of 0.9%-4.6%, characterizes the entire sediment core profile. From the base of the core until 3.20 m, organic contents increase from 2.6 % to 4.4 %. Above this, there is a significant decrease to an average of 2.8 %. There is
minimal change up-core from this range except for a dip to 1.3 % at 0.5 m. At the top of the core organic contents increase to 3%.

Low copper concentrations (< 50 mg/kg) mark the bottom sediment. There is an obvious and dramatic increase in copper concentrations up-core, starting with the first sample at 2.15 m, with the highest concentration at 1130 mg/kg in the uppermost sediment. The decreasing and overall small grain size above 2.5 m, along with the low organic matter contents and high copper concentrations indicates that this upper 2 m is tailings mud, with a mixing zone from 3.1-2.1 m. The large concentration of copper in this tailings deposit is most likely due to the affinity of metals to fine-grained clays (Paksad et al., 2014). As is somewhat higher above 2 m, the concentration of selenium shows less variation throughout.
Figure 5.7: Organic matter content (%), grain size and metal concentrations (As, Se, Cu) in core Q15-04
As this core was retrieved from the deepest part of the west arm of Quesnel Lake, it was hypothesized that this core would exhibit large amounts of the mine tailings material due to the proximity to Hazeltine Creek. The metals analysis, grain size in the mixing zone and organic matter change supports this.

Unlike Q15-01, the sediments showed large amounts of variability in colour and texture. There are two distinct colours in the sediment core. A lower, laminated grey unit (Gley 2 5/5B) from 4.5 m to 3.5 m and an upper, massive unit 3.5 m to the top of the core that was beige/light brown in colour (5Y 6/4). In between, from 3.5 m to 2.1 m, is a mixing zone. The finest sediment is restricted to the uppermost sediment. This apparent fractionation is typical of sediment deposited by a turbidity current (a turbidite sequence), with a lower, coarse-grained erosive base at the bottom of the turbidite followed by an uppermost fine-grained cap. The middle layer with the non-planar boundaries between the native and non-native sediment indicates intense mixing. This may signify that the energy of the current peaked at this depth.

Grain shape – Q15-01 and Q15-04

Cores Q15-01 and Q15-04 are proximal, deep and contain both the native muds and tailings deposits. A further test using grain shape, signifying different erosion and deposition processes, was undertaken. An Electron Probe X-ray micro-analyzer was used on one sample taken from Q15-01 (i.e. native muds) at 3.50 m and one sample from Q15-04 at 10 cm (i.e. tailing muds) to analyze grain shape of the particles. ImageJ, which is open source software that determines circularity, was used to generate particle counts. The native muds should represent how most of the natural sediments in the lake are shaped, with an exception that mine tailings mud may be different.

Means of the number of particles for each “bin” of shape, per particle size (per sample), are tabulated in Table 5.3 and Table 5.4. Grain size distributions were chosen based on the median diameter (D_{50}, \mu m) of the sample. Respective “bins” represent the varying degrees of circularity: 0.00-0.30 is defined here as “straight” particles; 0.71-1.00 is
defined as “circular” particles. The counts of particles are per image captured by the microprobe.

The generalized estimating equation (GEE) approach was used for statistical analysis in SPSS. The data presented from the image software used to count the particle shapes per grain size bin is nested. This means that the data are collected from multiple parameters (individual data is considered nested in that group). GEEs are best conducted for data analyzed in clusters where relationships within clusters are expected (Larsen et al., 2008). Since the data are inherently fractionated into separate bins per individual microprobe image, it proved difficult to conduct traditional analyses that allow for the prediction of changing covariates on one given individual (i.e. regression). Furthermore, because there is an expected relationship between the variants, this violates assumptions of regression, justifying the need to use an alternative approach.

Table 5.3: Mean counts of particles for each bin and according grain size for sample taken from Q15-01 (native lake muds).

<table>
<thead>
<tr>
<th>Bin</th>
<th>0-2</th>
<th>2-4</th>
<th>4-6</th>
<th>6-9</th>
<th>9-infinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00-0.30 (Rod like)</td>
<td>8.40</td>
<td>10.47</td>
<td>13.60</td>
<td>12.80</td>
<td>23.73</td>
</tr>
<tr>
<td>0.31-0.50</td>
<td>76.07</td>
<td>123.27</td>
<td>86.13</td>
<td>63.40</td>
<td>114.73</td>
</tr>
<tr>
<td>0.51-0.70</td>
<td>274.67</td>
<td>224.27</td>
<td>114.13</td>
<td>71.13</td>
<td>101.00</td>
</tr>
<tr>
<td>0.71-1.00 (Circle like)</td>
<td>3044.87</td>
<td>307.4</td>
<td>89.80</td>
<td>35.73</td>
<td>31.33</td>
</tr>
</tbody>
</table>
Table 5.4: Mean counts of particles for each bin and according grain size for sample taken from Q15-04 (suspected tailings spill muds).

<table>
<thead>
<tr>
<th>Bin</th>
<th>0-2</th>
<th>2-4</th>
<th>4-6</th>
<th>6-9</th>
<th>9-infinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00-0.30 (Rod like)</td>
<td>2.87</td>
<td>19.93</td>
<td>27.2</td>
<td>21.33</td>
<td>21.93</td>
</tr>
<tr>
<td>0.31-0.50</td>
<td>116</td>
<td>219.07</td>
<td>133.33</td>
<td>82.93</td>
<td>112.27</td>
</tr>
<tr>
<td>0.51-0.70</td>
<td>475</td>
<td>359.2</td>
<td>159</td>
<td>97.07</td>
<td>109.53</td>
</tr>
<tr>
<td>0.71-1.00 (Circle like)</td>
<td>4744.33</td>
<td>538.73</td>
<td>132.47</td>
<td>53.53</td>
<td>35.53</td>
</tr>
</tbody>
</table>

Circularity is a measure of how closely a particle resembles a circle. It is defined by the degree of abrasion of a particle based on sharpness of the particle’s edges and corners (Wadell, 1932). As the particle shape approaches 1, it is defined to have an overall circular shape. Counts, or particles, that are closer to 0 are defined as straight lines. Sphericity, in contrast, takes into account the symmetry of the x, y and z axes of a particle (Bates and Jackson, 1980). When the three axes of a particle are equal, it is a perfect sphere.

Within the finest fraction of both samples, most particles fall into the 0.71-1.00 shape bin, defined as circular. The highest difference (p < 0.05) between the bins per grain size classification exists only in the two finest fractions. There is little significant difference in the 4-6 um, 6-9 um and 9-infinity fractions between the bins to suggest differences in sediment transport mechanisms (p > 0.05).
The emphasis of fine, circular grains in both samples suggest high abrasion during natural transport processes and/or the mining process. However, there is a clear distinction between the amounts of circular grains that were found within both samples per unit area. The sample taken from Q15-04 (tailings) contains more circular particles (in the finer <4 µm bins).

Clay minerals (<2 µm), in aqueous environments, result from weathering and the dissolution of minerals. Shape, as well as size, of these minerals is controlled by various factors such as the crystallographic structure of the particles and stress applied on the particle (i.e. interaction with other particles). Normally, the smaller a particle is, the lower the probability of mechanical weathering will influence its shape (Santamarina and Cho, 2004). In aqueous solutions, effects of particle-to-particle interaction are lower due to the presence of water. This does not apply to chemical weathering, in which smaller particles have higher probabilities for chemically controlled features. In larger grains, shape is dictated by mechanical and some chemical effects. As more circular grains were found in the tailings sample, this most likely reflects the rigorous ore processing that occurs at Mount Polley as previously explained. This may also be due to the intense sediment mixing that occurred down Hazeltine Creek and when entering the western basin of Quesnel Lake. These grain shape results (in specific size ranges) may discriminate between natural and ore-processed muds.

**Q15-02 (2.38 km, 92.1 m):**

*Core description*

In core Q15-02, two sedimentary units are observed. In the lowermost 2 m of core, the sediment consists of fine-grained silts, thinly laminated and dark grey in colour (Gley 2 5/5B). This portion of the sediment core exhibits colour banding of primarily dark-coloured laminae (<10 mm). The upper 2 m sediment consists of medium to coarse-grained silts, massive in structure and dark red/brown in colour (2.5YR 4/4). No laminae are present in this upper sediment unit. The contact between these two sections of core is gradual, extending over approximately 9 cm.
Loss on ignition (LOI), grain-size, metals results

Grain size results show significant fluctuations with depth, but this is more pronounced in the coarser grained fraction (Figure 5.8). Particle size is small in the basement sediment, fluctuating consistently from the base of the core until 2 m. There is a sharp increase in particle size in all fractions at 2 m, with an apparent fining upward trend observed with some variation. Nonetheless there is a defined coarse-grained base at 2 m and a fine-grained sediment cap observed in the uppermost sediment.

In this core, organic matter content appears to be inversely related to changes in grain size. Organic matter contents range from 5% to 7% in the bottom 2 m of sediment, with one sudden peak to 17% at 3.7 m. However, this declines sharply to 1.3 % by 2 m, coinciding with the sudden increase in grain size. Organic contents ranging from 0.9 % - 2.1% are seen in the uppermost sediment.

Copper concentrations vary with core depth. The lowest concentrations (< 80 mg/kg) are observed in the bottom sediment below 1.5 m. There is a notable increase in the upper 3 most samples to almost 500 mg/kg above 0.6 m. The sample at 1.6 m was expected to be higher. This may imply more mixing with native muds in this zone. All arsenic values are greater than background levels, further suggesting a large tailings presence.

Colour, grain size, organic matter content and metals analysis indicate the upper 2 m of this core is tailings sediment. Sediment below 2 m is interpreted as pre-existing natural sediment. Low organic matter in this upper unit suggests a large input of clastic material. There is an apparent fining upward in the upper 2 m unit with a coarser grained base from 2 m to 1.5 m, reflecting the characteristics of a turbidite deposit. The contact point between underlying native and overlying tailings sediment is abrupt at 2 m based on LOI and particle size analysis results. As the contact between the native and tailings deposit extends over 9 cm, this suggests some mixing occurring during deposition as seen in Q15-04. Furthermore, the presence of this large turbidite deposit is indicative of turbidity current waning in flow or declining in velocity as the mixing zone is much thinner than in Q15-04.
Figure 5.8: Loss-on-ignition, grain size and metal concentrations (As, Se, Cu) of core Q15-02.
Thus far, erosive, coarser-grained bases within cores Q15-02 and Q15-04 have been observed, implying the presence of a turbidite deposit in these locations. However, particle size above this erosive flute in Q15-02 remained coarse, while particle size significantly decreased above this base in Q15-04, which is coupled with a large difference in sediment colour (Figure 5.9).

![Figure 5.9](image)

**Figure 5.9**: Upper cores of Q15-01, Q15-02 and Q15-04 showing the native mud zone, the mixing zone and turbidite zone. These turbidite sequences, albeit a result from the same mine breach, show differences in colour and grain size.
5.3.2 Zone 2 – Q15-03 (up-lake from Hazeltine Creek – 4.69 km, 44 m):

Turbidity currents have been known to deaccelerate in nature due to physical changes in bathymetry. The distance from the point of flow (Hazeltine Creek) and the difference in elevation from this point to the deepest lake bottom suggests that this core should contain minimal to no tailings sediment inputs. The following section presents the findings from this core, taken 4.69 km away from Hazeltine Creek at a depth of 44 m.

Core description

The sediment in Q15-03 consists of thinly laminated (< 10 mm) fine-grained silts that are dark grey in colour (Gley 2 5/5B). The colour is similar to the native sediments in the cores of Zone 1. There are no apparent colour differences throughout this core. However, intermittent sand beds within the silt sediment matrix are observed below 2 m that vary from 5-10 mm in thickness.

Loss on ignition (LOI), grain-size, metals results

Overall, there is minimal variation in grain size and organic matter content in comparison with Q15-02 and Q15-04 (Figure 5.10). Reduced particle size fluctuations are reflected in the lower 1.50 m. However, there is a significant peak in particle size at 1.95 m, related to thin, intermittent sand beds within the silt-dominated matrix. Variation in particle size is more pronounced from 0.4 m to the top of the core.

Organic matter content also shows minimal variation up-core. In the bottom 1.5 m of the core, organic contents are low and range from 0.7 % to 4 %. There is a dramatic peak to 23 % at 0.3 m before it declines suddenly to 6 % at the top of the core. This peak in organics may represent a thin lamina of organic rich sediment, although no woody debris or other macro-organic fragments were observed. The low organic contents at the base of the core coincide with the intermittent sand layers.

Metals concentrations in this core are lower than concentrations seen in cores from Zone 1. Copper concentrations in the upper sediment are approximately 80 mg/kg, an order of magnitude less than Zone 1 cores such as Q15-04. Nonetheless, copper concentrations
increase up-core. Selenium and arsenic concentrations vary with depth – arsenic concentrations increases at 1 m but tapers off down core. Selenium slightly increases at 1 m. Overall there is a less pronounced variation in metals concentrations with depth.

This core is interpreted as having negligible tailings input, most likely due to the distal and shallower location of the core from Hazeltine Creek and higher lake bottom elevation from the point of inflow. This site is most likely beyond the bottom current travel distance.
Figure 5.10: Loss-on-ignition, grain size and metal concentrations (As, Se, Cu) of core Q15-03.
5.3.3 Zone 3 – Q15-05, Q15-06

Q15-05 and Q15-06 fall in zone 3 (Figure 5.1). These cores were taken from the most distal, down-lake position from the Hazeltine Creek delta (approximately 6 km away), in water depths of 82.3 m and 50 m respectively. It was expected that the tailings spill current had already deposited the majority of the sediment it entrained. Given their distal position and higher elevation, it was expected that there should be negligible new sediment deposition in these cores.

Q15-05 (82.3 m, 4.21 km):

Core description

Similar to other cores, the sediment in Q15-05 consists of thinly laminated (< 10 mm) fine-grained silts that are dark grey in colour (Gley 2 5/5B). There are no apparent colour differences throughout this core. Intermittent sand intrusions of 1-5 cm thickness occur within the silt sediment matrix below 2 m.

Loss on ignition (LOI), grain-size, metals results

Q15-05 exhibits highly variable particle size values throughout the sediment package (Figure 5.11). In order to determine if any spill sediments occurred in the upper sediment, the upper 20 cm was subsampled more frequently at every 2 cm.

This upper portion of sediment has distinct variations in grain size. The coarsest sediment is found in the underlying sediment at the base of the core. Particle size decreases gradually, with a high degree of variance, from the bottom of the core to 1.1 m. This decrease is related to a reduced frequency of the coarser grained laminae. A finer-grained sediment unit is observed from this point to 0.4 m. Two increases in particle size are observed at 0.4 m and again at 0.2 m. Grain size decreases gradually until the top of the core.

Like Q15-02, organic matter inversely mirrors the trend in grain size. Low organic contents characterize the base of the core, starting from 0.4 % below 4 m. Organic
content gradually increases up-core to a maximum of 7.8% at 0.2 m. A sharp decline in organic content to approximately 2% coincides with many of the sharp increases in particle size at peak values.

Similarly to cores in Zone 1, copper concentrations increase at the top of the core above at least 1.5 m. At lower depths, concentrations decline and remain constant. The highest concentrations of up to 400 mg/kg are seen in the upper sediment. Arsenic and selenium concentrations gradually increase up-core, with a slight decrease in the middle of the sediment package.

In this core, the upper 10 cm is interpreted as the non-native tailings sediment from the mine spill. The increase in particle size at 0.2 m is interpreted as an erosive base, with a fining upwards trend observed in the uppermost 20 cm of sediment. This suggests the presence of a weak turbidite. This turbidite unit is small, however the coinciding low organic matter suggests a higher than normal sediment yield. Although there is no difference in colour, the combination of elevated levels of copper, fining upward sediment with a coarse base in this upper portion, and low organic matter content suggests an increase in clastic material. Grain sizes of these materials are finer than sediment seen in other cores (i.e.: Q15-02). This is most likely the remnants of the finest suspended sediment still remaining in the flow that settled between August 2014 and sampling in July 2015.
Figure 5.11: Loss-on-ignition, grain size and metal concentrations (As, Se, Cu) of core Q15-05.
**Q15-06 (50 m, 6.12 km):**

This is the most distal core at 6.8 km from Hazeltine Creek. It was taken from a water depth of 50 m.

*Core description*

Most of the sediment in core Q15-06 is fine-grained silts, thinly laminated and dark grey in colour (Gley 2 5/5B). The sediment core exhibits colour banding of primarily dark-coloured laminae (<10 mm). There are no apparent colour differences throughout this core. However, similar to core Q15-05, intermittent sand intrusions within the silt sediment matrix are observed below 2 m (1-4 cm).

*Loss on ignition (LOI), grain-size, metals results*

Grain size results for Q15-06 show highly variable particle sizes throughout the core, similar to Q15-05 (Figure 5.12). All fractions are somewhat coarser and more variable below 2.3 m, and the particle size values decrease gradually until 1.5 m. At this point, particle size gradually increases to the top of the core.

In contrast, organic matter contents range from 1.5 % - 5% in the lower 2.2 m of the core. Organic contents increases from 1.4% after 2 m before consistently increasing to 7% by the top of the core.

Metals concentrations show relatively low values in comparison cores from Zone 1. Copper values remain below 100 mg/kg throughout the core, however the bottom sediments contain less copper than the uppermost sediment at about 1.5 m. Copper values increase from 4 mg/kg at 3.2 m to 90 mg/kg at 0.5 m. Arsenic and selenium steadily increase with depth, but remain significantly lower than observed in Zone 1 cores.

This core is interpreted as having very minor to no tailings input. This is most likely due to the flow deaccelerating completely at this point in the lake. This is further justified by low inputs of elatic material and the low concentrations of copper.
Figure 5.12: Loss on ignition, grain size and metal concentrations of core Q15-06.
Chapter 6

Discussion

6.1 Introduction

Due to its large size and the fact that it has remained relatively undisturbed throughout its existence, Quesnel Lake is commonly referred to as “pristine” in the literature (Potts et al., 2014; Petticrew et al., 2015).

On the morning of August 4, 2014, a tailings pond adjacent to the lake failed due to an unstable embankment. This complex tailings mixture resulted in a debris flow that travelled down Hazeltine Creek, scoured the banks of the creek and deposited a mixture of tailings sediment, water, and glaciofluvial sediment into the west arm of Quesnel Lake (Golder Associates, 2016).

Approximately 10 million m$^3$ of water and 4.5 million m$^3$ of tailings slurry entered north into Polley Lake (Golder Associates, 2016). This material formed a barrier at the opening of the lake, blocking the flow of water. The debris flow then flowed south-east, scouring the channel of Hazeltine Creek and enlarging it from 2 m to 25 m. The flow immediately destabilized the banks, removing native glaciofluvial sediment, soil and even larger trees from the floodplain. Some tailings sediment was deposited in the riparian zone of the creek.

A final debris flow volume of 18.6 million m$^3$ of mixed tailings, soil and water flooded into Quesnel Lake. The setting for the flow to plunge to the lake bottom was ideal: the sediment concentration of the flow was orders larger than the concentration of the Quesnel Lake freshwater. Although the exact temperature of this tailings pond is unknown, tailings ponds normally see temperatures ranging from 30-60º C (Penner and Foght, 2010). Higher temperatures are often observed with depth in the pond due to a lack of surface cooling and higher heat retention capacity (Penner and Foght, 2010). The average temperature of Hazeltine Creek in August is approximately 16.1º C (Environmental Canada, 2017). Given that the debris flow had to travel through colder river water (Hazeltine Creek), the temperature of the flow had most likely dropped to a temperature more comparable to Hazeltine Creek. The average surface
temperature of Quesnel Lake in August is 17º C, and with depth, this temperature drops significantly to a minimum temperature of 4º C in the lowermost lake water (Petticrew et al., 2015). Therefore the flow may not have had enough of a thermal gradient to displace the colder bottom water of Quesnel Lake. Rather, the sediment concentration was the driving force for the flow to plunge as a bottom current.

In this study, six cores were analyzed to characterize the turbidity current that deposited this sediment. This study provides a unique opportunity to 1) understand point source, large-scaled sedimentary inputs into untouched, pristine lakes, and 2) observe the behaviour of a large turbidity current entering a deep lake and subsequent sedimentation processes associated with the current.

6.2 The effects of the mine spill on the sedimentary record – analysis from sediment cores

Sediment cores were strategically taken from various points and depths in the lake. For comparison purposes, cores were categorized in three zones. Zone 1 encompasses the deepest part of the lake with a maximum depth of 115 m (Gilbert and Desloges, 2012).

Cores Q15-01, Q15-04, and Q15-02 ranged from 92 m to 112 m in water depth. Organic matter contents of the native sediment (i.e. lower sediment) typically ranged between 3-10%. However, organic matter contents varied in the upper sediment in each core. In the upper 2 m of Q15-02, organic matter contents ranged from 1-2%, which is significantly lower than the native sediment. This was also seen in the upper 4 m of sediment in Q15-04 (albeit with some variation).

In conjunction with low organic matter, the uppermost 2 m of sediment in Q15-02 contained coarse grained sediment with a mean particle size of approximately 19 µm. Mean particle size in the lower 2 m of sediment is approximately 8 µm. In contrast, Q15-04 contained fine particle size with an average of 4.5 µm in the uppermost 3.5 m of core. Furthermore, copper concentrations increase up core in both Q15-02 and Q15-04 – the highest amount of copper are observed in this uppermost sediment and exceed regional background levels.

Q15-01 was taken from 95.7 m water depth, 2.8 km away from Hazeltine Creek. The ITRAX core scanner was used on this core to examine XRF and magnetic susceptibility. MS trends show
significant difference in the uppermost 20 cm of the core. Copper concentrations, similar to Q15-02 and Q15-04, also show the highest copper concentrations in this upper unit.

Evidence points to the presence of tailings deposits in each core in Zone 1. Q15-04 and Q15-02 contain the largest tailings deposit. Mixing is observed in Q15-04, with a non-planar and expansive contact zone between the native sediment below and non-native sediment. Variances in organic matter contents and grain size further depict this. Q15-02 contains a less extensive mixing zone – there is some sediment mixing from sediment texture. However, grain size and organic matter contents show an abrupt change at 2 m. The uppermost sediment in all three Zone 1 cores contained copper concentrations that exceed both background levels and are significantly higher than the basement native sediment, indicating Zone 1 contains much of the tailings both upstream and downstream of Hazeltine Creek.

Q15-03 (4.69 km, 44 m) was representative of Zone 2, while Q15-05 (82.3 km, 4.21 m) and Q15-06 (6.12 km, 50 m) were in Zone 3. These zones are both in the shallowest portion of the west basin – Zone 2 is up lake to the spill point and proximal to the Cariboo sill.

In Q15-03, there is no evidence from grain size or organic matter contents that suggest the presence of tailings in the upper sediment. Rather, there are textural anomalies in the basement sediment of this core that point to Holocene changes of sediment input. Stratigraphic analysis indicate the presence of 5 mm to 10 mm sand laminae in the base of the core, in conjunction with low organic matter contents.

Copper concentrations also do not suggest any significant inputs of sediment from the pond breach. Therefore the current responsible for depositing sediment in Zone 1 was unable to rise up and deposit sediment at this location. This is most likely due to an increase in elevation from 112 m in the deepest part of the lake (Zone 1) to 44 m closer to the sill at Q15-03.

There is evident variance in grain size and organic matter contents up core in Q15-05 and Q15-06. Smaller sampling increments were used in the upper 20 cm of Q15-05 to isolate for any tailings sediment given that copper concentrations in the uppermost 20 cm of core were higher than background values. It was found that a small amount of tailings deposit was observed in this uppermost sediment of Q15-05 at 20 cm.
A key question in this study is whether the debris flow that entered Quesnel Lake from Hazeltine Creek generated a turbidity current or if it became a subaqueous debris flow. Four out of the six cores (Q15-01, Q15-02, Q15-04, Q15-05) contained turbidite sequences, characteristic of a turbidity current. In the classic model (Komar, 1985; Kneller, 1995; Mulder et al., 2001), normally graded sequence (fining upwards in grain size) are associated with a typical sediment sequence deposited by a current with waning flow, where a sharp, erosional contact is seen at the base of the sequence with an uppermost, fine-grained cap. The tailings deposit observed in the uppermost sediment of Q15-02, Q15-04, and Q15-05 exhibited this normal gradation.

Sediment concentration plays a large role in the classification of a sediment gravity flow. Subaqueous debris flows have sediment concentrations up to 70%, while in turbidity currents, they typically do not reach over 10% (Knoblauch, 1997). Turbidity currents, in essence, are much more dilute than debris flows. The large volume of both interstitial water and tailings water compared to sediment supports the idea that a turbidity current was generated rather than a debris flow.

Turbidites are commonly associated with particular facies that reflect the velocity and overall status of the current at that depth. Ta facies are massive, structureless and represents the point where the turbidity current is at its peak velocity; deposition is quick and is commonly seen proximal to the inflow point (Bouma, 1962; Shanmugam, 1997, Mulder et al., 2001). Tb, Tc and Td reflect the interactions between traction and suspended sediment deposition, and can be identified by distinct features such as ripples and wave-like cross laminae (Mulder et al., 2001). Lastly, Te facies is reflective of turbidite sediment mixing with pelagic (background) sediment. Here, the current is at its lowest velocity (Mulder et al., 2001).

Q15-04 contained definite Ta and Te facies. A Ta facies exists between 3.5 m and 2.9 m. This is apparent because of the extensive mixing of native and tailings sediment. In contrast, Te is the mixing of background sediment and the last remnants of sediment from the waning turbidity current. This is observed in the uppermost 1 m of sediment. There exists a mixture of tailings sediment, evident from the finer grained particles with low organic matter, with the native sediment.
No ripples or sediment features were observed in this core; the tailings sediment were structureless and massive. Thus it is difficult to identify distinct Tb, Td and Te facies. If these facies were present they would fall in between the weak mixing zone between the Ta and Te facies. Furthermore, not all facies need to be present in order to identify a turbidite sequence. The absence of any of the facies may be due to the location of the deposits relative to the inflow point; a proximal sediment core may contain only a predominant Ta facies (Shanmugam, 1997; Mulder et al., 2001).

There is a weak mixing zone observed at 1.90 m to approximately 2 m in Q15-02. Although sediment texture shows a 10 cm contact point between the native and non-native sediment, grain size and loss on ignition results at this contact zone are less definitive. There is a clear distinction between the two sediment types above and below 2 m. The varying degrees of mixing observed in each core suggest that the velocity of the turbidity current was at its peak in the deepest part of the lake. The current lost momentum with distance.

Figure 6.1 shows a schematic diagram of thicknesses of the observed turbidite sequences in this study, including the direction of the turbidity current (with arrows indicating relative velocities). Absolute velocities of the current at each core location and depth are unknown in this study. However, it is known that the current velocity was at its peak proximal to Hazeltine Creek (and thus proximal to Q15-04 and Q15-02). Therefore this diagram, although speculative, is an approximation of relative current velocities based on turbidite thicknesses.
**Figure 6.1:** Thicknesses of turbidite sequences in sediment cores represented by red bars, and speculated relative velocities of the turbidity current, represented by black arrows.
6.3 Long Term Effects and Geologic Implications of the Breach

Given how recent the spill occurred, there exists no study that aims to undergo the legacy effects of the Mount Polley Mine on the Quesnel watershed. However, although mine spills are infrequent, there are many studies in literature that examine long-term effects of point source pollution into river and lake systems (Reardon et al., 2014).

One important factor in determining the significance of environmental disasters over time are the particle size of the sediment released into the water column (Reardon et al., 2014). Fine grained sediment pose as a threat to remediation because they do not readily settle to the lake bottom. Large portions of the tailings sediment from Mount Polley are indeed fine-grained; the finest sediment observed in Zone 1 is approximately 4 µm. From an environmental standpoint, this introduces the likelihood of the deposited clay to silt size sediment being re-released into the water column. Given the depth of Quesnel Lake, these sediments are most likely to re-suspend due to lake turnover and not currents (Hilton, 1985). Suspension in the upper water column is maintained by winds. The long, thin, east to west running arms of Quesnel Lake provide an avenue for strong winds to force water to accumulate at one end of the lake, generating a seiche. Winds from the east may also push these fine-grained sediments towards the Quesnel River outflow. This is especially problematic given that toxic metals (i.e. copper) from the tailings sediment bind readily to fine particulate sediment (i.e. concentrations are higher in fine sediment).

Another important factor is the sediment deposition that occurred in the terrestrial areas of the catchment. This would create an opportunity for the sediment along the floodplain to be re-mobilized during spring snow melt and enter the lake. Some mixed tailings materials were deposited along the floodplains of Hazeltine Creek in the riparian zone (Golder Associates, 2006). This represents a secondary source of pollution for the sediment not trapped in the newly re-engineering channel (Golder Associates, 2016) until the sediment source is exhausted. How this will be reflected in the sedimentary record will vary depending on seasonal factors that control these sediment inputs. Additionally, extensive reconstruction of lower Hazeltine Creek channel, and the construction of sediment traps at the Hazeltine Creek outlet, may affect this.
Another consideration for long term effects of the spill is the geochemistry of the tailings sediment. In a tailings pond, mine waste is saturated with water in order to prevent it from reacting with oxygen, which maintains copper in an insoluble form (Gandy et al., 2007). Mount Polley Mine Corporation, using this rationale, emphasize that these toxic copper metal concentrations in the lake sediments should therefore remain immobile and thus do not pose a spatial threat (Golder Associates, 2016). However, it is difficult to predict the fate of these sediments (both the terrestrial tailings deposit and the deposit in Quesnel Lake) in a natural, biotic setting that are not fully accounted for in laboratory studies (i.e. with changes in sunlight, temperature, microbial activity, etc).

A final consideration in the spatial distribution of the sediment is Coriolis forces, which can result in right hand deflection of sediment plumes (northern hemisphere) and sediment accumulating along the right hand side of tributary outlets of Quesnel Lake (Gilbert and Desloges, 2012). The Rossby number is an expression that determines whether geostrophic forces such as Coriolis or inertial forces dominate accumulation. The Rossby number can be expressed as follows:

\[
Ro = \frac{U}{L \cdot f}
\]  
(Equation 6.1)

Where:

Ro= Rossby number (dimensionless)

\(U\)=velocity, m/s

\(L\)= width of Quesnel Lake at outflow point, m

\(f\)=Coriolis parameter, which is approximately \(10^{-4}\) at 60° latitude

With a \(U\) value estimated at 1 m/s, which is the approximate flow velocity of the current (Sussbauer, 2013), and an \(L\) of 2000 m, a Rossby’s number of approximately 5 is obtained. Rossby’s numbers of > 1 suggest that Coriolis forces on sediment accumulation are minimal.
Geological considerations: diagenesis

Currently, the majority of the tailings sediment is present in the deep lake bottom of Zone 1. The sediment grains will become more consolidated together with a reduction in pore space and elimination of pore water. Eventually, compaction will make this sediment unavailable to be re-suspended into the water column. Sediment accumulation over the next 1000 years will “seal” the tailings. Eventually, as with all lake sediments, the tailings deposits will become buried and lithified into rock, a long (i.e. millions of years) process.

The thickest deposit seen in this study is approximately 4 m. Other results for Quesnel Lake have suggested deposits up to 10 m (Petticrew et al., 2015). These thicknesses were not seen in these cores. The natural rate of sediment accumulation in Quesnel Lake is low, especially in the west basin (0.2 mm/a). In essence, the thickness of the sediment deposits from the breach is equivalent to the amount of sediment that took would have taken 20 000 years to accumulate, assuming accumulation Holocene rates apply. Moreover there is a possibility that seasonally more tailings sediment will be introduced into the lake from the Hazeltine Creek floodplain. Within the first five months of the breach, channel stabilization work was completed along the Hazeltine Creek margins in an attempt to contain the deposited tailings sediment. First, a significant volume of sediment that was deposited along the creek margins were physically removed and hauled off-site. Next, creek stabilization commenced. This work involved reconstructing the channel to pre-existing conditions; a low flow channel (i.e. mean annual flood) and two tiers of floodplains were created to mimic pre-spill Hazeltine Creek (Allan et al., 2016).

Although the primary rationale for this work was to reestablish and restore fish habitat, it also served as a means to control sediment movement by creating a engineered channel resistant to erosion. Restoration efforts such as these are able to entrain large sediment clasts such as gravel. Finer sediments like clay and silt, given that they enter the lake as suspended load, are harder to contain. These sediments pose the greatest pollution risk. This means may not be effective for the long-term, and fine grained tailings sediment may still enter Quesnel Lake.

Nonetheless, compressed and lithified sediment will retain some of the original characteristics of the deposit. Many turbidites have distinctive beds or laminae characteristic to the nature of the turbidity current that deposited it (i.e. velocity, duration).
The Mount Polley mine is strategically located in an area with high copper rich ore content. Although the spill materials contained high concentration of toxic metals, the mine uses local bedrock. Thus there are similarities between the background sediment concentrations and the tailings sediment. Nonetheless, copper and other elements of the tailings sediment significantly exceeds the regional background levels of the entire Quesnel watershed. The lake deposit will show a higher than normal copper and arsenic concentration despite future diagenesis. These copper rich beds will act as a mining signal that can be traced back to this single catastrophic event.

*Uniformitarianism and Catastrophism*

Uniformitarianism is an important concept in the geosciences. Developed in the late 1700s but brought to the forefront of geology in the mid-1800s, this ideology suggests that the landforms that exist on Earth’s surface are not created by catastrophic events and regimes. Rather, slow geomorphic processes were responsible for the development of Earth’s landscape (i.e. gradual increments). It implies that the same geologic processes at work in the past continue to be at work in present day. Catastrophism is a theory contrary to uniformitarianism, which supports the idea that Earth was predominately formed by short-lived, dramatic events. Catastrophic events are usually unusual occurrences and are often seen as outliers in the geologic record.

Both theories have geological evidence that support each claim. A key idea is that uniformitarianism is gradual over long time scales. In the context of the Mount Polley mine spill, this sudden event will appear as an outlier in the sedimentary record of Quesnel Lake. Although anthropogenic activity (i.e. forestry, agriculture and mining) are not uncommon in the Quesnel River watershed (Smith and Owens, 2010), the lake itself has been relatively undisturbed since deglaciation.

The preserved sedimentary sequence of lake bottom sediments in the west basin of Quesnel Lake will appear as follows. First, a thick, 20-40 m deglaciation package of ice proximal sediment composed of silt and some sand will underlie the upper units. A fine, thinly laminated unit of silts and clays deposited during the low energy Holocene will overlie the late Pleistocene basement sediment. This Holocene sediment will be capped by a very thick and spatially isolated
graded turbidite unit. The sequence will represent high magnitude (glacial), low magnitude (Holocene) and “catastrophic” (mine spill) sources.
Chapter 7

Summary and Conclusion

• The acoustic record for all of Quesnel Lake (Gilbert and Desloges, 2012) suggests large-scale sedimentary events during the Holocene are rare occurrences in Quesnel Lake. Likely natural causes during the lake’s history include volcanic activity, hillslopes destabilized by earthquakes and glacier ice-dam failures during deglaciation. Occurring on the morning of August 4, 2014, the Mount Polley spill provided a rare opportunity to explore the sedimentary effects of a large-scale, catastrophic event into a large, deep, pristine fjord-like lake.

• Approximately 14.5 million m$^3$ of water and tailings slurry entered into Hazeltine Creek as a debris flow. The plume scoured the banks of Hazeltine Creek, widening its margins. The flow eroded the pre-existing glaciofluvial sediments that infilled the creek valley and also deposited some tailings material along the creek margins. This material from the creek contributed approximately 8 million m$^3$ of sediment and water to the sub-aerial debris flow. The final destination of the debris flow was into the western basin of Quesnel Lake. This zone is the deepest part of the western basin with a maximum depth of 112 m.

• As much as approximately 4 m of the mixed tailings mud was deposited in the deep basin in just a few days. By contrast, average sediment accumulation in the entire Quesnel Lake basin is 0.4 mm/a depending on proximity to point of inflow. In the western basin it is 0.2 mm/a due to the distal location of the west basin.

• The question remained as to whether the underflow that entered the lake from Hazeltine Creek generated a turbidity current or debris flow. To test this, six sediment cores were taken from strategic points along the west basin of Quesnel Lake to identify any turbidite or debrite sequences. Turbidite sequences are normally graded, and often contain ripples, waves or other cross-like stratigraphic features that reflect the velocity conditions of the current. Massive, structureless features are diagnostic of debrites.
The stratigraphic properties of cores were categorized into three zones: Zone 1 was located in the deepest part of the lake - proximal to Hazeltine Creek. Zone 2 was up-lake from the inflow point closer to Cariboo sill, while Zone 3 was furthest downlake from Hazeltine Creek and closer to the Quesnel River outflow. The flow deposited the majority of its sediment load in Zone 1. Metals concentrations, namely copper, were critical for distinguishing native and non-native (i.e. tailings) sediment.

Although both fine grained and coarse grained tailings sediment were observed in Zone 1 and Zone 2, all the tailings deposits displayed a normally graded sequence of fine-grained silts and coarse-grained silts. Therefore, the tailings deposits observed in Zone 1 and Zone 2 (Q15-05) cores are indicative of turbidite deposits. Q15-04 contained an expansive mixing zone between the native and tailings sediment. The non-planar, thick expanse of this point suggests that the turbidity current had peaked in velocity at this depth. From this, it can be concluded that although a debris flow event transported the tailings materials from the tailings pond to Quesnel Lake, a turbidity current was favoured over a sub-aqueous debris flow. Both thermal stratification and a high sediment load provided conditions ideal for the turbidity current.

The thickest turbidite sequences were located in the proximal lake zone. There are apparent differences in physical and mineralogical properties amongst these sediment cores that help discriminate the turbidity process. Distally there is a decline in mine sediment due to an extensive difference in lake-bottom elevation. Due to negligible sediment deposition outside of the deep proximal lake zone, the energy of the turbidity current declined sharply as it encountered the steep lake bottom gradients going both up-lake and down-lake.

A Rossby number of at least 5 suggests that geostrophic forces do not play a large role in the sediment accumulation in the lake. Therefore, right hand tailings accumulation is not expected.

The stabilization of Hazeltine Creek occurred within the first five months after this spill. First, all non-consolidated sediment that were deposited along the margins by the debris flow were physically removed. Next, a low-flow channel with two levels of floodplain was engineered to mimic the conditions of the pre-spill creek. This was predominately done to control sediment erosion along the creek banks. However, as the majority of the
The spatial distribution of the spill sediments in the west basin of Quesnel Lake have been partially mapped in this study. Not enough data are presented here to fully understand the flow dynamics of the turbidity current once it entered into the lake. Only limited parameters of flow dynamics are explored here. Nonetheless, this thesis acts as a starting point to understand the flow dynamics of the turbidity current.
References / Bibliography


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