EVOLUTION OF THE NORTHEAST ZONE BRECCIA BODY, MOUNT POLLEY MINE, BRITISH COLUMBIA

by

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ABSTRACT

The Mount Polley deposit in north-central British Columbia is a Cu-Au porphyry system related to alkaline magmatism. The deposit is composed of numerous discrete zones of Cu-Au mineralization related to bodies of hydrothermal breccia, including the Northeast zone which hosted a pre-mining proven and probable reserve of approximately 11 Mt of ore averaging 0.88% Cu and 0.28 g/t Au. The polylithic breccia body at the Northeast zone is irregular in shape and intruded by multiple generations of post-mineral dykes. Post-mineral faults cut the breccia, making the original breccia geometry unclear. 11,000 meters of core logging along two vertical sections perpendicular to the long axis of the orebody show that a significant percentage (locally >50%) of the breccia is composed of K-feldspar-phryic monzonite porphyry clasts. Many of these have globular shapes, implying that this material was ductile at the time of brecciation. Cu-sulfides are most abundant in and immediately above zones containing the greatest concentration of K-feldspar-phryic monzonite porphyry clasts. This relationship suggests that the fluids responsible for both mineralization and brecciation originated during this phase of intrusion. Most of the Cu-Au-bearing sulfide minerals form hydrothermal chemical infill in the breccia. Where fine-grained clastic material is abundant or where movement of clasts was minimal, sulfides are generally less abundant or absent. The entire breccia body of the Northeast Zone at Mount Polley appears to be the result of a single brecciation event. Variation in breccia character within the body is attributable to variations in fluid flux, pre-existing rock character, and fluidization processes. Furthermore, the permeability structure established during the brecciation event exerted the fundamental control over ore distribution within the breccia body.
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DEDICATION

This thesis is dedicated to the night people and to the siren tribe;

the fact that they don't understand what we're doing,

means we're doing it well.
Chapter 1 - Significance of the Mount Polley deposit

Introduction

Porphyry Cu-Au mineralization is the product of physical and chemical interactions between intrusions, country rock, and fluids (Guilbert and Clark, 1980). Hydrothermal, magmatic, and tectonic breccias are common features of these systems (Sillitoe, 1985). Breccia formation in magmatic-hydrothermal systems reflects not just the chemistry of the fluids responsible, but also the timing and the energetics of the system (McPhie et al., 1993). Detailed description of breccia characteristics can lead to enhanced understanding of not only the chemical but the physical evolution of fluids within a hydrothermal system (McPhie et al., 1993). Breccias are data-rich geological features resulting from complex and often spatially and temporally overlapping processes. In mineralizing systems, breccias can enhance, inhibit or destroy the deposition of economic minerals (Burnham, 1979; Burnham, 1985; Sillitoe, 1985; Bushnell, 1988; Zweng and Clark, 1995; Serrano et al., 1996). Describing the features, internal organization, and ultimately the genesis of breccia features can be a powerful tool in understanding a hydrothermal system. The hydrothermal system that produced mineralization at Mount Polley is particularly important because Mount Polley represents an example of a little-examined class of porphyry deposits related to alkaline, rather than calc-alkaline, rocks (Sillitoe, 2002; Holliday and Cooke, 2007).

The Mount Polley Cu-Au porphyry

The Mount Polley Cu-Au mine in central British Columbia (figure 1.1) exploits an orebody consisting of at least five discrete porphyry Cu-Au-Ag ore zones (figure 1.2)
associated with magmatic-hydrothermal breccias (Barr et al., 1976; Lang et al., 1995b; Logan and Mihalynuk, 2005). These breccias are coeval with monzonitic intrusions emplaced into the alkaline volcanic rocks of the Quesnel terrane (Hodgson et al., 1976; Fraser, 1994a and b; Fraser et al., 1995; Rees et al., 2005, 2006; Logan and Mihalynuk, 2005; Logan et al., 2007). The Northeast ore zone, on which this study is focused, provides evidence of the direct connection between the intrusion, brecciation, and mineralization processes.

The Northeast Zone is important because it represents a small yet high grade ore zone (Deyell, 2005; Deyell and Tosdal, 2005; Jackson et al., 2007; Pass et al., 2007; Imperial Metals Corporation, 2007). The processes which resulted in the Northeast Zone mineralization may provide clues to mechanisms which concentrate and focus fluid flow in other alkaline porphyry systems. Recognizing focused fluid flow guides exploration keyed to finding economic mineralization. Due to their atypical alteration expression as compared to calc-alkaline systems, finding the zone of most focused fluid flow in alkaline hydrothermal systems is not straightforward; additional guides to exploration in prospective zones of alkaline magmatism would add value to both academic and economic comprehension of these systems.
1. Red Chris
2. Rugged Mountain
3. Ten Mile Creek
4. Butterfly Pluton
5. Zippa Mountain
6. Hogem Batholith
7. Chuchi
8. Peach
9. Rayfield River
10. Kamloops Syenite
11. White Rocks Mountain
12. Averill Pluton
13. Copper Mountain/Irigerbelle
14. Kruger Syenite
Figure 1.1- The location of Mount Polley and other alkalic porphyry deposits and alkalic intrusive centers in the Quesnel and Stikine terranes. Inset shows the location of British Columbia (green). Redrafted from www.mapplace.bc.ca.
Quaternary: Till, glaciofluvial, glaciolacustrine deposits.

Quartz latite (Early Jurassic, 197 Ma)
Breccia, conglomerate. Polymictic, intrusive-clast rich, matrix-supported.

Augite-porphyry and mafic dikes.
Polymictic fragmental hydrothermal breccia, minor jigsaw-fit breccia and igneous breccia.
Hydrothermal breccia in Core Zone of Mount Polley Complex. Red indicates Cu-Au min.

Potassium feldspar-(plagioclase-)phyric monzonite.

Plagioclase feldspar porphyry (monzodiorite).
Non-bedded, matrix-rich fragmental breccia of monzonitic material.

Monzodioritic porphyry fragmental breccia, clast-supported.

Monzodiorite and monzonite, undivided.
Igneous (and hydrothermal) breccia in mixed monzodiorite, diorite.

Uneven-textured diorite to monzodiorite.
Even-textured equigranular augite-(biotite) diorite to monzodiorite.
Pyroxenite.

Basaltic to andesitic intrusive and extrusive rocks.
Figure 1.2- Geologic map of the Mount Polley Property, with ore zones delineated by red rectangles. Mineralized zones within breccia bodies are shown in red. Map courtesy of Chris Rees, Imperial Metals.
The primary goal of this study is to clarify the connection between magmatism, brecciation, and mineralization. This study includes examination of 10,340 meters of core, 142 thin sections, and 58 major and trace element chemical analyses. Two cross-sections perpendicular to the apparent long axis of the breccia body were constructed, concentrating on the description and internal architecture of the breccia, and on the pre-, syn-, and post-breccia intrusive rocks. Spatial and temporal relationships between mineralization, intrusion, brecciation and alteration are described.

The first and second chapters of the thesis address the general characteristics and regional geology of the Mount Polley area, and summarizes previous studies undertaken in the area. The third chapter addresses the igneous rocks and magmatic evolution of the Northeast Zone at Mount Polley. The features and internal organization of the breccia body, making the connection between the magmatic and the hydrothermal systems, are described in the fourth chapter of the thesis. This chapter also includes evidence contributing to describing the energetics of the breccia system. The fifth chapter of the thesis describes the alteration zonation observed within and around the breccia body, and presents data contributing to deciphering the chemical evolution of the fluids responsible for brecciation and mineralization. The sixth chapter presents the conclusions of the thesis, and advances a hypothesis explaining the observed features.

**The significance of alkaline hydrothermal systems**

The majority of porphyry and epithermal copper and gold deposits currently known are associated with rocks of medium to high-K calc-alkalic composition (Sillitoe, 2002, Holliday and Cooke, 2007). A minority of volcanoplutonic hydrothermal deposits, the alkaline porphyry and epithermal deposits, are spatially and temporally associated with
arc-related volcanic and intrusive rocks of alkalic composition (Lang e et al., 1995, Jensen and Barton, 2000, Sillitoe, 2002, Holliday and Cooke, 2007). Due to their comparative rarity, alkalic porphyries have not received the same attention that led to the systematic description of the calc-alkalic deposit class (Holliday and Cooke, 2007).

![Figure 1.3 - Major alkalic related Au deposits of the world. The red line divides porphyry from epithermal systems. From Jensen and Barton, 2000](image)

Although less common than their calc-alkalic cousins, alkalic Cu-Au deposits are of economic significance (Lang et al., 1995, Jensen and Barton, 2000). They include some of the world’s highest grade and largest porphyry-related gold resources (figure 1.3 and Table 1.1), as well as some of the largest gold accumulations in epithermal settings (Jensen and Barton, 2000). Though alkalic porphyry Cu-Au deposits occur in relatively few districts, they are still attractive exploration targets due to their high grades, high Au:Cu ratios, and potential for valuable co-product commodities, including platinum group elementss (Eliopoulos and Economou-Eliopoulos, 1985; Thompson et al., 2002).
Table 1.1- Characteristics of some alkalic-related mineral deposits.

<table>
<thead>
<tr>
<th>DEPOSIT</th>
<th>TYPE</th>
<th>TONNAGE</th>
<th>CU</th>
<th>AU</th>
<th>MO</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>British Columbia</td>
<td>Porphyry</td>
<td>241.7 Mt</td>
<td>0.345</td>
<td>0.18</td>
<td>--</td>
<td>Abacus Mining Corp, 2008</td>
</tr>
<tr>
<td>Afton/Ajax</td>
<td>Porphyry</td>
<td>129 Mt</td>
<td>0.393</td>
<td>0.155</td>
<td>--</td>
<td>MINFILE, 1996</td>
</tr>
<tr>
<td>Similco</td>
<td>Porphyry</td>
<td>130 Mt</td>
<td>0.393</td>
<td>0.155</td>
<td>--</td>
<td>Imperial Metals, 2007</td>
</tr>
<tr>
<td>Mount Polley</td>
<td>Porphyry</td>
<td>Undefined</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>Jonnes et al., 2007</td>
</tr>
<tr>
<td>Mount Milligan</td>
<td>Porphyry</td>
<td>205.9 Mt</td>
<td>0.25</td>
<td>0.6</td>
<td>--</td>
<td>Jago et al., 2007</td>
</tr>
<tr>
<td>Lorraine</td>
<td>Porphyry</td>
<td>32 Mt</td>
<td>0.66</td>
<td>0.25</td>
<td>--</td>
<td>Eastfield Group, 1998</td>
</tr>
<tr>
<td>Red Chris</td>
<td>Porphyry</td>
<td>276 Mt</td>
<td>0.349</td>
<td>0.266</td>
<td>--</td>
<td>Imperial Metals, 2007</td>
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<tr>
<td>Galore Creek</td>
<td>Porphyry</td>
<td>786 Mt</td>
<td>0.52</td>
<td>0.29</td>
<td>--</td>
<td>NovaGold, 2008</td>
</tr>
<tr>
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<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Lachlan Fold Belt</td>
<td>Porphyry</td>
<td>54 Mt</td>
<td>0.77</td>
<td>2.5</td>
<td>132.6</td>
<td>Wilson et al., 2007</td>
</tr>
<tr>
<td>Ridgeway</td>
<td>Porphyry/epithermal</td>
<td>767 Mt</td>
<td>--</td>
<td>--</td>
<td>586</td>
<td>Wilson et al., 2007</td>
</tr>
<tr>
<td>Cadia (district)</td>
<td>Porphyry</td>
<td>30 Mt</td>
<td>0.91</td>
<td>0.5</td>
<td>--</td>
<td>Heithersay and Walsh, 1995</td>
</tr>
<tr>
<td>Cowal</td>
<td>L.S. Epithermal</td>
<td>32 Mt</td>
<td>0.4</td>
<td>0.07</td>
<td>&gt;13</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Goonumbla</td>
<td>L.S. Epithermal</td>
<td>&gt;211 Mt</td>
<td>--</td>
<td>&gt;1</td>
<td>583</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Endeavour</td>
<td>L.S. Epithermal</td>
<td>63.6 Mt</td>
<td>1.1</td>
<td>0.5</td>
<td>--</td>
<td>Jensen and Barton, 2000</td>
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<tr>
<td>Great Plains Margin</td>
<td>L.S. Epithermal</td>
<td>3.2 Mt</td>
<td>--</td>
<td>7.2</td>
<td>&gt;33</td>
<td>Jensen and Barton, 2000</td>
</tr>
<tr>
<td>La Plata/Allard stock</td>
<td>L.S. Epithermal</td>
<td>32 Mt</td>
<td>0.4</td>
<td>0.07</td>
<td>&gt;13</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Central City</td>
<td>L.S. Epithermal</td>
<td>3.2 Mt</td>
<td>--</td>
<td>7.2</td>
<td>&gt;33</td>
<td>Jensen and Barton, 2000</td>
</tr>
<tr>
<td>Boulder County</td>
<td>L.S. Epithermal</td>
<td>&gt;211 Mt</td>
<td>--</td>
<td>&gt;1</td>
<td>583</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Cripple Creek</td>
<td>L.S. Epithermal</td>
<td>30 Mt</td>
<td>0.91</td>
<td>0.5</td>
<td>--</td>
<td>Jensen and Barton, 2000</td>
</tr>
<tr>
<td>Rosita Hills</td>
<td>L.S. Epithermal</td>
<td>3.2 Mt</td>
<td>--</td>
<td>7.2</td>
<td>&gt;33</td>
<td>Jensen and Barton, 2000</td>
</tr>
<tr>
<td>Elizabethtown-Baldy</td>
<td>L.S. Epithermal</td>
<td>&gt;211 Mt</td>
<td>--</td>
<td>&gt;1</td>
<td>583</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Cerillos</td>
<td>Epithermal</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>15</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Old Placers district</td>
<td>Epithermal/porphyry</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;9.7</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>New Placer</td>
<td>Skarn/porphyry</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>3.6</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Jicarilla</td>
<td>Epithermal/porphyry</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;2.5</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>White Oaks</td>
<td>Epithermal</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>5.1</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Nogal-Bonito</td>
<td>Porphyry</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;9.7</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Orogrande</td>
<td>Porphyry</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>3.5</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Organ Mountains</td>
<td>Porphyry</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>3.4</td>
<td>Kelly and Luddington, 2002</td>
</tr>
<tr>
<td>Villa Ahumada</td>
<td>Porphyry</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Golden Sunlight</td>
<td>Porphyry</td>
<td>4.7 Mt</td>
<td>1.6</td>
<td>--</td>
<td>--</td>
<td>Jensen and Barton, 2000</td>
</tr>
<tr>
<td>Republic</td>
<td>Porphyry</td>
<td>Undefined</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Papua New Guinea</td>
<td>Porphyry</td>
<td>51.5</td>
<td>0.23</td>
<td>--</td>
<td>--</td>
<td>Richards and Ledlie, 2003</td>
</tr>
<tr>
<td>Mount Kare</td>
<td>Porphyry</td>
<td>51 Mt</td>
<td>--</td>
<td>7</td>
<td>--</td>
<td>Lihir Gold Limited, 2007</td>
</tr>
<tr>
<td>Porgera</td>
<td>Epithermal</td>
<td>258 Mt</td>
<td>--</td>
<td>2.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lihir/Ladolam</td>
<td>Porphyry/Epithermal</td>
<td>--</td>
<td>--</td>
<td>7.3</td>
<td>40</td>
<td>Zhou et al., 2002</td>
</tr>
<tr>
<td>China/Southeast Asia</td>
<td>Porphyry</td>
<td>206 Mt</td>
<td>0.54</td>
<td>0.8</td>
<td></td>
<td>Eliopoulos and Economou-</td>
</tr>
<tr>
<td>Phu-phu</td>
<td>Skouries</td>
<td>14.7 Mt</td>
<td>8.1</td>
<td>--</td>
<td>--</td>
<td>Eliopoulos, 1985</td>
</tr>
<tr>
<td>Yulong</td>
<td>PorphyrY</td>
<td>206 Mt</td>
<td>0.54</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yao'an</td>
<td>Emperor</td>
<td>14.7 Mt</td>
<td>8.1</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>Emperor</td>
<td>14.7 Mt</td>
<td>8.1</td>
<td>--</td>
<td>--</td>
<td>Jensen and Barton, 2000</td>
</tr>
<tr>
<td>Malmbjerg</td>
<td>Porphyry</td>
<td>&gt;150 Mt</td>
<td>--</td>
<td>--</td>
<td>0.23</td>
<td>Brooks et al, 2004</td>
</tr>
<tr>
<td>Almaden (Hg)</td>
<td>Epithermal</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Palabora</td>
<td>Carbonatite</td>
<td>850 Mt</td>
<td>0.5</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Bingham</td>
<td>Carbonatite</td>
<td>&gt;1000 Mt</td>
<td>0.56</td>
<td>0.35</td>
<td>0.035</td>
<td>Groves and Veilreicher, 2001</td>
</tr>
<tr>
<td>Mountain Pass (REE)</td>
<td>Carbonatite</td>
<td>34 Mt</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>

Alkalic deposits are imperfectly represented by models based on calc-alkaline porphyry deposits (Jensen and Barton, 2000). Part of the difficulty in describing and
interpreting the common features of alkalic porphyries lies in the rocks themselves. Alkaline rocks are believed to compose only 1/1000th of the igneous rocks in the earth's crust, yet they are described using 17% of igneous nomenclature (Sørenson, 1974). The rarity and complexity of the alkalic rocks results in a poor understanding of the chemical, physical, hydrothermal, and tectonic properties and affiliations of these rocks (Lueck and Russell, 1994, Lang et al., 1995). Instead, models based on porphyry systems in calc-alkalic rocks have driven models of alkalic deposits (Sillitoe, 2002). Increased awareness of the economic importance of the alkalic class of porphyry and epithermal deposits emphasizes the need to produce more representative models of these anomalous, but economically attractive mineralizing systems (Holliday and Cooke, 2007).

Alkalic porphyry systems are typically high-grade porphyry-style deposits associated with small volume pipe-like intrusions that have surface expressions of only a few hundred square meters (Lueck and Russell, 1994, Lang et al., 1995, Lickfold et al., 2007; Holliday and Cooke, 2007). Characteristics of some orebodies associated with alkaline rocks are summarized in Table 1.2. Especially in the silica-undersaturated systems of British Columbia (Figure 1.1), alkalic porphyries are associated with complex composite intrusions, some including both alkaline and calc-alkaline rocks (Lueck and Russell, 1994, Lang et al., 1995). Despite the fact that alkalic melts are generally higher in CO₂, SO₄, and halogens than their calc-alkaline equivalents, areas of mineralization in alkaline rocks typically feature restricted alteration haloes as well (Bailey and Hampton, 1990, Sillitoe, 2002). This small footprint makes them difficult exploration targets, so practical guides and accurate deposit models are required to assist exploration (Holliday and Cooke, 2007).
Table 1.2- Characteristics of alkalic porphyry systems

<table>
<thead>
<tr>
<th>Feature</th>
<th>Deposits</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Igneous features</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petrogenetically associated volcanic rock</td>
<td>Cadia, Mount Polley, Galore Creek</td>
<td>Logan and Bath, 2005, Lickfold et al, 2007</td>
</tr>
<tr>
<td>Mineralization associated with the most evolved intrusive phase</td>
<td>Cadia, Mount Polley</td>
<td>Logan and Bath, 2005, Lickfold et al., 2007</td>
</tr>
<tr>
<td>Silica-saturated intrusions</td>
<td>Cadia, Mount Milligan</td>
<td>Lang et al., 1995, Lickfold et al., 2007</td>
</tr>
<tr>
<td>Silica-undersaturated intrusions</td>
<td>Mount Polley, Galore Creek</td>
<td>Lang et al., 1995, Logan and Bath, 2005</td>
</tr>
<tr>
<td><strong>Alteration features</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argillic assemblages restricted to late structure penetrating the orebody</td>
<td>Mount Polley, Cadia</td>
<td>Lickfold et al., 2007, Logan et al., 2007, Logan and Bath, 2005</td>
</tr>
<tr>
<td>K-silicate constructive alteration associated with ore</td>
<td>Mount Polley, Galore Creek, Cadia</td>
<td>Lickfold et al., 2007, Logan et al., 2007, Logan and Bath, 2006</td>
</tr>
<tr>
<td>Large volumes of K-metasomatism surrounding the orebody</td>
<td>Galore Creek, Cadia</td>
<td>Lickfold et al., 2007, Logan et al., 2007</td>
</tr>
<tr>
<td>“Reddening”; hematite dusting of feldspars</td>
<td>Mount Polley, Afton-Ajax, Cadia</td>
<td>Lickfold et al., 2007, Logan et al., 2007</td>
</tr>
<tr>
<td><strong>Tectonic associations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complex island arcs with alkaline and calc-alkaline magmatism</td>
<td>BC porphyries, Lachlan foldbelt porphyries</td>
<td>Lang et al., 1995, Logan and Bath, 2006, Logan and Mihalynuk, 2005</td>
</tr>
<tr>
<td><strong>Other associated mineralization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-sulfidation alkaline epithermal</td>
<td>La Plata, Cadia</td>
<td>Jensen and Barton, 1995, Lickfold et al., 2007</td>
</tr>
<tr>
<td>Skarn (developed in carbonate and reactive volcanic rocks</td>
<td>Mount Polley, Galore Creek</td>
<td>Rees et al., 2006, Logan et al., 2007</td>
</tr>
</tbody>
</table>
Unlike calc-alkaline porphyry systems, the alkaline systems do not usually have associated advanced argillic alteration assemblages, and no connection to high sulfidation epithermal deposits has been demonstrated (Lang et al., 1995, Jensen and Barton, 2000, Sillitoe, 2002, Holliday and Cooke, 2007). These features are attributed to the high neutralization capacities of the alkaline host rocks, which reduce the lateral mobility of acidic fluids (Jensen and Barton, 2000, Sillitoe, 2002). Phyllic alteration in alkaline porphyry systems is typically restricted to late fault and vein zones that penetrate the waning hydrothermal system. The subtle nature of the peripheral hypogene alteration assemblages (variants on potassic, calc-potassic, sodic, calc-sodic and propylitic alteration) makes identifying the focus for fluid flow difficult further than a few hundred meters away from the mineralized center. Research has suggested that a systematic vertical and lateral zonation in sulfur isotopic composition surrounds some mineralized porphyry complexes (Deyell, 2005; Wilson et al., 2003), and mineralogical changes have also been noted (Sketchley et al., 1995; Lang et al., 1995b; Wolfe et al., 1996; Wilson et al., 2003; Gifkins et al., 2005).

Certain alteration assemblages in alkaline systems are distinct from those found in calc-alkaline systems. In the porphyry environment (e.g. Lang et al., 1995; Wilson et al., 2003), these include a Cu-Au-Ag and Mo-Au associations, and distinctive alteration assemblages characterized by high-temperature Na- (albite) and Ca-bearing (diopside, actinolite, and/or garnet) minerals (Jensen and Barton, 2000, Holliday and Cooke, 2007 and references therein).
Alkalic porphyry-related mineral deposits as a class have been examined by a number of researchers. Sillitoe (2002) discussed a variety of characteristics and localities distinguishing alkalic from calc-alkaline porphyry deposits worldwide. On more restricted scales, Cooke et al. (2006) examined the alkalic porphyry related mineralization of the Lachlan fold belt in great detail, Kelly and Ludington (2002) and MacLemore (2002) synthesized research undertaken on the Great Plains margin alkalic-related epithermal and porphyry deposits, and the characteristics of deposits in the Quesnel and Stikine terranes of British Columbia were summarized by Lang et al. (1995).

Other alkalic-related mineral deposits that have been covered in great detail on a deposit scale include Porgera (Ronacher et al., 2004, Ronacher et al., 2002, and references therein), Skouries (Frei, 1997, and Eliopoulos and Economou-Eliopoulos, 1995), Lihir (Gemell et al, 2004, Carman, 1994 and 2003 and Mueller et al., 2002) and Cadia-Ridgeway (Wilson et al., 2003, Wilson et al., 2007 Lickfold et al., 2007 and references therein).

The Mount Polley system

Describing the mineralization at Mount Polley requires some adaptation of common terminology. Although a number of economic ore zones exist on and around the Mount Polley property, none of the ore zones, independent of the others, would represent minable reserves. Thus, each mineralized zone does not constitute an ore body. Similarly, the group of ore zones does not meet the legal description of a mining district. Thus, the Mount Polley “orebody” consists of multiple deposits, referred to here as ore zones and distinguished more on the basis of engineering (planned pits) than geological discontinuity. The cluster of ore zones is referred to as the Mount Polley deposit or
orebody. The term Mount Polley district is not used, as this formal legal designation has not been adopted for Mount Polley or the presently unexploited present in the surrounding area.

In British Columbia, individual alkaline deposits represent a range of depths and temperature of formation, from the “magmatic” environment of Lorraine (Nixon and Peatfield, 2003) through the “typical” porphyry environment of Mt. Milligan and the Cariboo-Bell zone of Mount Polley (Enns et al., 1995; Fraser et al., 1995; Sketchley et al., 1995) to the potentially shallower breccia environment at the top of the systems potentially represented by the Northeast zone of Mount Polley.

The widespread presence of hydrothermal breccia in the ore zones of Mount Polley distinguish this alkaline system from many of the other alkaline porphyry systems in British Columbia. Hydrothermal breccias are reported to be common at Galore Creek (Enns et al., 1995), where they in part host Cu-Au ore but they can also lack any significant Cu and Au values (Lang et al., 1995). Of the many deposits around the Iron Mask batholith, only the DM and Crescent deposits are hosted in significant hydrothermal breccia (Lang et al., 1995). Hydrothermal breccias are present but reportedly insignificant at Copper Mountain or Mount Milligan (Lang et al., 1995; Sketchley et al., 1995). Although the tonnage of the various deposits varies considerably; grade correlates with the presence of significant breccia at Mount Polley and Galore Creek, with the highest grades occurring in breccia bodies (see Table 1 in Lang et al., 1995).

Hydrothermal breccia forms where the ambient fluid pressure exceeds the lithostatic load of the overlying rock column coupled with the tensile strength of the
surrounding rock (Burnham, 1985 and 1997). Thus, breccias should be more common in shallow upper crustal environments. As such, it is tempting to suggest that Mount Polley represents one of the shallower alkalic porphyry deposits in BC. As an analogy, Zweng and Clark (1995) used fluid inclusions from the breccia-hosted >800 Mt Toquepala porphyry Cu-Mo system in southern Peru to suggest that it formed at much shallower depths than the nearby vein-dominated >1,200 Mt Cuajone porphyry Cu-Mo deposit. Unfortunately, the lack of appropriate minerals in most alkalic porphyry systems in British Columbia from which depth of formation can be determined, coupled with limited geologic constraints on the scale of post-mineral erosion and deformation of the Triassic and Early Jurassic deposits, has to date precluded establishing any independent constraints on their depth of formation (Lang et al., 1995).

The Mount Polley orebody is hosted within one of many alkalic intrusions emplaced into volcanic rocks of the Quesnel terrane (Figure 1.4) (Lang et al., 1995). These intrusions range in composition from orbicular pseudoleucite syenite to diorite (Bath and Logan, 2006). Mineralization associated with these intrusions is generally breccia and vein-hosted chalcopyrite with lesser bornite and associated gold, commonly with K-feldspar-magnetite alteration assemblages (Panteleyev et al., 1996). The intrusive complex is a north to northwest-trending body composed primarily of equigranular to porphyritic diorite, monzodiorite, and monzonite intruded by syenite dikes. U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology from several of the intrusive phases in the complex give ages between 201 and 205 Ma, indicating a Late Triassic age (Bailey and Archibald, 1990; Mortensen et al., 1995; Logan et al., 2007).
Figure 1.4- Terrane map showing Triassic-Jurassic alkaline intrusions and porphyry Cu-Au deposits and prospects in the Mount Polley Area; redrafted from www.mapplace.bc.ca
The porphyry system at Mount Polley involves a number of discrete ore zones within a post-mineralization north-plunging syncline (Hodgson et al., 1976; Fraser, 1994a, b; Fraser et al., 1995; Rees et al., 2005, 2006; Logan and Mihalynuk, 2005, Tosdal et al., 2008). The area is highly faulted, but it is possible that the ore zones represent different stratigraphic levels of a series of spatially related porphyry-style deposits (Logan and Mihalynuk, 2005). Cu:Au:Ag:Mo ratios differ from ore zone to ore zone, as does alteration, petrology, and the role of hydrothermal and igneous cemented breccia (Rees et al., 2005 and 2006). Average grades, alteration, and host rock types vary as well. If true, each center may have formed at slightly different crustal depths. This supposition is supported by the relative positions of the ore zones with respect to the regional stratigraphy. The Nicola Volcanic group rocks closest to the Northeast Zone are substantially higher in the section than those adjacent to the Southeast zone.

The Northeast Zone has the highest Ag content of the ore zones and shows the most clearly hydrothermal features in the breccia. The Northeast zone is the only ore zone in the cluster with widespread sericite-bearing alteration assemblages. In the deepest observed portions of the Northeast zone, K-feldspar constructive alteration is similar to that reported in the central ore zones (Fraser et al., 1995, Panteleyev et al. 1996, Rees et al., 2005).

The Cariboo-Bell and Springer zones in the center of the group contain hydrothermal and intrusion-cemented breccia- and vein-hosted sulfide minerals associated with roughly concentric alteration assemblages around a Cu-Au–rich core (Fraser et al., 1995). The central potassic (including albite, biotite, and actinolite subfacies) core is surrounded by an intermediate garnet-epidote zone and an outer propylitic zone (Figure 1.5).
Chalcopyrite and minor bornite are the main sulfide minerals. Sparse pyrite is present distal to the core of the deposit, and magnetite is abundant in the central and deep portions of the orebody. Sulfide deposition accompanies K-feldspar veins and wall rock replacement. Alteration and sulfide deposition can be sequenced by multiple K-feldspar phryic porphyry intrusions (Figure 1.6). Cu:Au:Ag ratios are intermediate between the Northeast and Southeast zones.

Fraser (1994a, b; Fraser et al., 1995) divided the hydrothermal breccias in the Cariboo-Bell and Springer deposits into four types, based on dominant silicate cement mineralogy: biotite, actinolite, albite and magnetite. Albite-cemented breccia in the Springer ore zone is characterized by the presence of tabular albite and lesser biotite, magnetite and sulfides as breccia cement. Clast boundaries are diffuse and albite has extensively replaced the clasts. Biotite- and actinolite-cemented breccia characterize the Cariboo and Bell zones. The actinolite-cemented breccia dominates the Bell ore zone, whereas the biotite-cemented breccia dominates the Cariboo zone (Figure 1.5). Fraser et al. (1995) reported that the transition between the two breccia cements is gradational. Actinolite or biotite forms the dominant breccia cement and contains Cu-Fe sulfide minerals in varying amounts. In the actinolite breccia, K-feldspar replaces breccia clast margins and also forms alteration selvages around actinolite-sulfide veins that cut the country rock and breccia. In the biotite-cemented breccia, the clasts are moderately to completely replaced by K-feldspar (Fraser, 1994b). Albite-cemented breccia overprints actinolite-cemented breccia in the northern part of the Bell pit.

Magnetite-cemented breccias are uncommon (Fraser, 1994b). Where present, however, they are commonly associated with elevated Cu concentrations (Imperial Metals
Clasts in these breccias are also partially replaced by K-feldspar. Sulfide and sparse pyroxene are also present as breccia cement. Another notable feature which supports this zoning is the unconformity present at the northern end of the Mount Polley property. This unconformity juxtaposes 205.2 ± 1.2 Ma Mount Polley Intrusive Complex Monzonite with a 196.7 ± 1.7 Ma clastic-infill dominated breccia of unknown origin (Bailey and Archibald, 1990; Mortensen et al., 1995; Logan et al., 2007). The Northeast Zone is the closest (<500 m), spatially and stratigraphically, to this unconformity, and the Southeast zone is the farthest (3.5 km) (Figure 1.2).
Figure 1.5 - Alteration in the Central Zone at Mount Polley, redrafted from Fraser, 1995.
Figure 1.6-Lithology of the Central Zone at Mount Polley, redrafted from Fraser, 1995.
The inferred vertical positions of the ore zones are also based on their positions relative to regional stratigraphy (Panteleyev et al., 1996; Logan and Mihalynuk, 2005). The regional volcanic stratigraphy is folded into a moderately dipping post-mineral syncline plunging to the north-northwest (Logan et al., 2007). Extending this structure into the MPIC, the Northeast zone is located stratigraphically high within the regional syncline, and the Southeast zone is located the deepest within the regional syncline (Rees et al., 2005). Alteration characteristics of each ore zone, as discussed above, are consistent with this structural reconstruction and with alteration zoning observed at other Cu-Au porphyry deposits (Holliday and Cooke, 2007; Lickfold et al., 2007; Logan et al., 2005).

Alteration zonation in alkalic porphyry systems is relatively consistent worldwide (Jensen and Barton, 2000; Holliday and Cooke, 2007) (figure 1.5, 1.7). Mineralization is commonly associated with potassic and calc-potassic alteration assemblages within and surrounding small volume alkalic intrusions (Jensen and Barton, 2000, Sillitoe, 2002, Deyell and Tosdal, 2005). Mineralization is associated with hematite dusting of the feldspars in the rock, negative S isotopes, increased magnetic susceptibility, and anomalous Pb-Zn (Holliday and Cooke, 2007 and references therein). Mineralization is surrounded by a propylitic halo featuring albite-actinolite (inner) and albite-epidote (outer) zones. Argillic alteration occurs above the stratigraphic level of ore deposition and along structures penetrating the ore body (Holliday and Cooke, 2007).
Figure 1.7- Common characteristics of mineral deposits related to alkalic intrusions. A: Complex, small volume alkalic intrusions (Cadia/Ridgeway, Goonumbla, Skouries, Mount Polley); B: Hydrothermal and magmatic breccias (Mount Polley, Galore Creek); C: Fault and vein systems (Nogal-Bonito, NM); D: Subvolcanic breccia systems that fail to breach the surface (Bessie G, CO); E: Shallow, large volume volcanic and subvolcanic breccia systems, including intracaldera structures (Cripple Creek, CO, Ladolam, PNG); F: Flat lying intra volcano and intracaldera vein and fracture systems (Emperor, Fiji); G: Steep vein and fracture systems (La Plata, CO); H: Deposits with magmatic and near-magmatic sulfide textures (Lorraine, BC, Bootjack Stock, BC); I: Deposits with both hydrothermal and magmatic characteristics (Lorraine, BC); J: “Typical” alkalic porphyry deposits associated with potassic and propyllic alteration (Mount Polley, Galore Creek, Mt. Milligan, Cadia-Ridgeway); K: Proximal skarn deposits developed in carbonate or reactive volcanic rocks (Pond Zone at Mount Polley, Galore Creek); L: Distal skarn and carbonate replacement deposits, ‘telethermal’ deposits related to alkalic magmatism M: Alkaline-related VHMS deposits N: Epithermal mineralization infilling subvolcanic breccias (Bessie G., CO); O: Epithermal mineralization infilling diatreme breccias (Cripple Creek, CO) P: Low-sulfidation epithermal systems with sericite-roscoelite-fluorite-carbonate assemblages (Ladolam, Emperor, Porgera)
Describing the alteration, mineralization and brecciation processes which formed the Northeast Zone orebody at Mount Polley will provide clues to what may be the shallowest depths of an alkalic porphyry system. Analysis of this portion of the system, its relationship to the deeper portions of the same system (represented by the other ore zones in the group), and how it compares to and contrasts with similar portions of calc-alkalic systems, will increase understanding of the upper portions of alkalic orebodies as a class. Analysis of the uppermost levels of the porphyry system may also provide clues to the linkage between porphyry and epithermal ore deposition environments, aiding exploration for epithermal systems in porphyry districts and vice versa.

**Thesis objectives**

The Northeast Zone at Mount Polley presents an unusual view of an unusual type of porphyry deposit. This thesis describes previous work performed on the Mount Polley deposit, its regional setting, and the ore deposit itself. The igneous rocks that surround and cut the hydrothermal breccia body, which hosts mineralization, are described, and the characteristics and internal architecture of the breccia body are presented. Description of the breccia body yields insights into the physical evolution of the fluid system; description of the associated alteration assemblages yields insights into the chemical alteration of the fluid system. Finally, a hypothesis is advanced to explain the relationship between intrusion, brecciation, alteration, and mineralization.
Chapter 2-Background and Previous Work

Introduction

The Mount Polley deposit has been known since the 1960s, and since that time a considerable mass of work has been produced addressing the geology and geologic setting of the deposit. This chapter addresses the previous body of geologic literature dedicated to the Mount Polley area, the exploration and production history of the Mount Polley mine, and summarizes the regional and local geology of the Quesnel and adjacent terranes in which the Mount Polley deposit formed. Research carried out by other workers on the Mount Polley deposit and internal research undertaken by Imperial Metals and the Mount Polley Mining Corporation is summarized here to provide a deposit-scale and regional-scale context for discussion of the Northeast Zone.

This chapter introduces the magmatic evolution of the igneous rocks spatially, genetically and temporally associated with the Mount Polley deposits. This magmatic evolution is more fully developed in Chapter 3.

Previous Work

Literature review

Placer gold localities in the Quesnel Lake/Cariboo Mining district were documented as early as 1877 (Dawson, 1877; Bowman, 1895), describing activity beginning in around 1859. The volcano-sedimentary package in the Quesnel River area was first described and ascribed a Mesozoic age by Bowman (1889). Studies in the 1950s and 1960s, conducted mainly by the Geological Survey of Canada, formalized and refined this stratigraphy, recognizing that the “Quesnel River Beds” defined a volcanic belt that was
nearly contiguous throughout the Canadian Cordillera (Tipper, 1959, 1978; Campbell, 1961, 1963; Campbell and Campbell, 1970; Campbell, 1978). The regional-scale syncline in which the Mt. Polley deposit sits was first described as the “Quesnel Trough” by Roddick et al. (1967).


examined the alteration and igneous fertility of the intrusive rocks associated with the Mount Polley deposits in comparison with those of other alkalic porphyries in BC.

**History of the Mount Polley Deposit**

**Property Discovery**

Although placer gold was known in the Mount Polley area in the 19th century and hydraulic mining was widespread and productive (Cockfield and Walker, 1932; Cockfield, 1948; Levson and Giles, 1993), heavy cover, both vegetative and fluvioglacial (Blackwell and Stubley, 2005; Levson, 2001; Tipper, 1971), inhibited the discovery of lode deposits despite known copper occurrences. A follow-up prospecting study conducted after a government airborne magnetic survey map issued in 1963 showed an aeromagnetic anomaly and demonstrated the existence of the Mt. Polley/Cariboo-Bell Cu-Au deposit (Panteleyev et al., 1996).

**Exploration**

Initial development and prospecting on the property was done by Mastodon Highland Bell Mines Limited and Leitch Gold Mines, which merged to form Cariboo-Bell Copper Mines Limited in 1966. In 1969, control of the property was taken by the Teck Corporation, and work continued intermittently until a Teck affiliate, Highland Crow Resources, acquired control in 1978 (Rees et al., 2005). In 1981, the property was optioned by E&B Explorations, which acquired 100% interest in 1982. Imperial Metals Corporation and Geomex Partnerships joined the project as joint venture partners in 1987, but intensive evaluation work on the property did not begin until 1990 (Caldwell, 2005). In 1990, a feasibility report on the property was completed by Wright Engineers,
proposing a 5 million tonne/year plant. E&B Explorations merged with Mascot Gold Mines, which in turn merged with Corona Corporation and ultimately became Homestake Canada. Between 1987 and 1992, Imperial Metals bought out the interest held in the Mt. Polley property by Homestake Canada and others, acquiring Geomex partnerships in 1992 to become the sole owner of the deposit. A downturn in metals prices resulted in the project being furloughed. In 1994, Imperial Metals merged with Bethlehem Resources, which had a long-standing relationship with Sumitomo Corporation (Rees et al., 2005; Caldwell, 2005).

Development

The decision to pursue further development of the Mt. Polley property was made in 1996, and financing was arranged through the Sumitomo Corporation. Imperial Metals retained 55% interest and operational control over the project, and Sumitomo retained 45% interest (Caldwell, 2005). This joint venture, incorporated as the Mt. Polley Mining Corporation, commenced mining activities in 1997. Between 1997 and 2001, mining from the Cariboo and Bell pits produced 133 million pounds of copper and 370,000 ounces of gold from 27.7 million tones of ore milled (Rees et al., 2005). In 1998, Imperial Metals merged with Princeton Mining Corporation, thus assuming operational control over the Huckleberry Mine, near Houston, BC (Rees et al., 2005). In 2001, Sumitomo Corporation sold its interest in the Mount Polley property to Imperial Metals for $11 million. Shortly thereafter, having exhausted the reserve in the Cariboo pit and facing a $15 million pre-strip on the Springer pit, Mount Polley was placed on care and maintenance pending a rebound in metals prices (Caldwell, 2005).
Discovery of the Northeast zone

In 2003, on-site exploration resumed and a small, high-grade Cu-Au-Ag resource was discovered 1.5 km northeast of previously known mineralization (Rees et al., 2005). The area was previously mapped as volcaniclastic rock and included with the post-mineral cover located farther to the north and west (Figure 1.2), (Bailey and Hodgeson, 1979, Fraser et al., 1995). In 2003, reconnaissance exploration aimed at identifying possible oxide-ore reserves discovered an area of high grade oxidized float. Tracing this float back to its origin, an outcrop of breccia grading 3% Cu was discovered. The first hole drilled in this zone intersected 57 meters grading 2.54% Cu, 1.15 g/t Au, and 17 g/t Ag. This hole was located 2 km northeast of the existing mill. The discovery of the Northeast Zone and subsequent expansion of proven and probably reserves under the Springer pit prompted an influx of capital in the project and into the company, bringing the operation back into active status. This deposit, initially called the Northeast zone or the Wishbone, is in the process of being developed as the Wight Pit. Pit development began in March, 2005.

Development of the Northeast zone

In 2005, the Mount Polley mine milled 4,814,084 tonnes of ore from the Wight Pit, the Bell pit, and low-grade stockpiles (Imperial Metals, 2007a). Separated statistics for the Wight pit alone are not available; the mill in place at Mount Polley was designed for the lower-grade ore produced by the Cariboo, Bell and Springer pits, and ore from the higher-grade Wight pit was diluted for metallurgical reasons. This milled tonnage resulted in the recovery of 30,328,771 lbs Cu, 30,635 oz Au, and 234,355 oz Ag in 2005. In 2006, 6,235,221 tonnes were mined, again dominantly from the Wight Pit, but
augmented from the Bell Pit and low-grade stockpiles. This milled tonnage resulted in the recovery of 55,548,194 lbs Cu, 38,164 oz Au, and 422,588 oz Ag (Imperial Metals, 2007a and b). As of the date of writing, production has not been announced for 2007.

**Reserves and resources at Mount Polley**

Overall, the various deposits constitute proven and probable reserves of 59.9 Mt of ore containing 0.36% Cu, 0.27 g/t Au and 0.73 g/t Ag (Imperial Metals, 2007a) (Table 2.1). Measured and indicated resources include 73.570 Mt of ore at 0.356% Cu, 0.302 g/t Au, and 1.426 g/t Ag. The Northeast zone orebody, the focus of investigation during this project, contains a proven and probable reserve of 4.31 Mt of ore at 0.829% Cu, 0.268 g/t Au, and 5.929 g/t Ag. Measured, indicated and inferred resources outside the planned pit in Northeast zone total 17.520 Mt of 0.8% Cu, 0.2 g/t Au and 4.4 g/t Ag (Imperial Metals, 2007). This resource excludes the results of two years of production, totaling 11.049 Mt of 0.438% Cu and 0.278 g/t Au.
Table 2.1: Reserves and resources for the Mount Polley orebody, from [www.imperialmetals.com](http://www.imperialmetals.com)

<table>
<thead>
<tr>
<th>Zone/Zone</th>
<th>Wight</th>
<th>Bell</th>
<th>Springer</th>
<th>Southeast</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tonnes Ore</strong></td>
<td>7,935,000</td>
<td>6,675,500</td>
<td>24,266,000</td>
<td>2,100,402</td>
<td>40,976,902</td>
</tr>
<tr>
<td><strong>Copper %</strong></td>
<td>0.871</td>
<td>0.297</td>
<td>0.367</td>
<td>0.273</td>
<td>0.448</td>
</tr>
<tr>
<td><strong>Copper (lbs)</strong></td>
<td>152,323,086</td>
<td>43,768,815</td>
<td>196,270,751</td>
<td>12,641,391</td>
<td>405,004,043</td>
</tr>
<tr>
<td><strong>Gold g/t</strong></td>
<td>0.282</td>
<td>0.316</td>
<td>0.313</td>
<td>0.514</td>
<td>0.318</td>
</tr>
<tr>
<td><strong>Gold (oz)</strong></td>
<td>72,040</td>
<td>67,773</td>
<td>244,458</td>
<td>34,710</td>
<td>418,980</td>
</tr>
<tr>
<td><strong>Silver (oz)</strong></td>
<td>1,621,772</td>
<td>n/s*</td>
<td>n/s*</td>
<td>81,238</td>
<td>1,703,010</td>
</tr>
</tbody>
</table>

**MEASURED, INDICATED AND INFERRED RESOURCES, BY ZONE**
(excludes pit reserves)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Tonnes</th>
<th>Copper Equivalent</th>
<th>Copper %</th>
<th>Gold g/t</th>
<th>Silver g/t</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Northeast</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>14,297,702</td>
<td>0.779</td>
<td>0.609</td>
<td>0.190</td>
<td>4.384</td>
</tr>
<tr>
<td>Indicated</td>
<td>1,387,308</td>
<td>0.830</td>
<td>0.636</td>
<td>0.221</td>
<td>4.616</td>
</tr>
<tr>
<td>Inferred</td>
<td>1,835,195</td>
<td>0.773</td>
<td>0.600</td>
<td>0.197</td>
<td>4.160</td>
</tr>
<tr>
<td><strong>Bell</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>9,562,373</td>
<td>0.420</td>
<td>0.233</td>
<td>0.238</td>
<td>n/s*</td>
</tr>
<tr>
<td>Indicated</td>
<td>976,160</td>
<td>0.376</td>
<td>0.227</td>
<td>0.190</td>
<td>n/s*</td>
</tr>
<tr>
<td>Inferred</td>
<td>828,312</td>
<td>0.372</td>
<td>0.236</td>
<td>0.174</td>
<td>n/s*</td>
</tr>
<tr>
<td><strong>Springer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>20,033,640</td>
<td>0.554</td>
<td>0.342</td>
<td>0.270</td>
<td>n/s*</td>
</tr>
<tr>
<td>Indicated</td>
<td>12,865,244</td>
<td>0.531</td>
<td>0.318</td>
<td>0.272</td>
<td>n/s*</td>
</tr>
<tr>
<td>Inferred</td>
<td>23,055,896</td>
<td>0.519</td>
<td>0.282</td>
<td>0.302</td>
<td>n/s*</td>
</tr>
<tr>
<td><strong>C2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured/Indicated</td>
<td>5,891,159</td>
<td>0.475</td>
<td>0.236</td>
<td>0.304</td>
<td>n/s*</td>
</tr>
<tr>
<td>Inferred</td>
<td>1,448,995</td>
<td>0.450</td>
<td>0.223</td>
<td>0.288</td>
<td>n/s*</td>
</tr>
<tr>
<td><strong>Southeast</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured/Indicated</td>
<td>14,229,738</td>
<td>0.622</td>
<td>0.247</td>
<td>0.462</td>
<td>1.338</td>
</tr>
<tr>
<td><strong>Total Resource</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured/Indicated</td>
<td>79,243,324</td>
<td>0.584</td>
<td>0.352</td>
<td>0.287</td>
<td>n/s*</td>
</tr>
<tr>
<td>Inferred</td>
<td>27,168,398</td>
<td>0.528</td>
<td>0.299</td>
<td>0.290</td>
<td>n/s*</td>
</tr>
</tbody>
</table>

n/s* - Silver only economically significant in the Northeast Zone
Regional geology

Geology of Quesnellia

The Quesnel terrane is an accreted island arc terrane characterized by alkalic and lesser calc-alkaline volcanism and magmatism that extends from south of the U.S. border to north-central British Columbia (Lang et al., 1995). Quesnel rocks range in age from 230 to 180 Ma (Bailey and Archibald, 1990; Mortensen et al., 1995; Logan et al., 2007). The latter date may reflect the date of docking with the North American craton (Mortensen et al., 1995). The characteristic components of Quesnellia are Middle Triassic to Early Jurassic volcanic, sedimentary and plutonic assemblages, which formed in an island arc volcano-plutonic tectonic setting. The Quesnel arc is similar in age and chemistry to the Stikine arc to the west.

Quesnellia hosts several major porphyry copper deposits of both alkaline and calc-alkaline affinity, such as Highland Valley, Copper Mountain, Afton-Ajax and Mount Milligan, all generated by early Mesozoic, island-arc magmatism (McMillan et al., 1995).

Extrusive rocks of the Mount Polley Area

The regional and district scale lithology at and around Mount Polley has been examined in detail by Panteleyev et al. (1996), Logan and Mihalynuk (2004), Logan and Bath (2005 and 2006), and Bath and Logan (2006). The subdivision of the stratigraphic units as described here is that of Panteleyev et al (1996), as modified by Rees et al. (2005) based on Imperial Metals mapping of the Mount Polley property (Figure 2.1, Table 2.2). The regional ‘basement’ in the Mount Polley area consists of the Nicola Group.
<table>
<thead>
<tr>
<th>Period</th>
<th>Deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cretaceous</td>
<td>Polythic conglomerate, Calc-alkaline Quartz Monzonite, Cu-Mo mineralization @ Gavin Lake (unconformity)</td>
</tr>
<tr>
<td>Post-Early Jurassic</td>
<td>Conglomerate Sandstone and Siltstone (unconformity)</td>
</tr>
<tr>
<td>Early Jurassic</td>
<td>Sandstone and siltstone, with analcime-olivine basalt</td>
</tr>
<tr>
<td></td>
<td>Polythic conglomerate (see discussion in text) Dacite</td>
</tr>
<tr>
<td></td>
<td>Polythic breccia with abundant monzonite clasts (see discussion in text) (unconformity)</td>
</tr>
<tr>
<td>Late Triassic-Earliest Jurassic (Norian)</td>
<td>Basaltic to intermediate clast breccia</td>
</tr>
<tr>
<td></td>
<td>Intermediate, silica-understaurated intrusions and associated breccias (Mount Polley Complex, Bootjack stock)</td>
</tr>
<tr>
<td></td>
<td>Analcime basalt, andesite, breccias and tuffs; interbedded limestone</td>
</tr>
<tr>
<td></td>
<td>Pyroxene phryic basalt flows, tuff, and breccia; minor hornblende phryic basalt</td>
</tr>
<tr>
<td></td>
<td>Olivine-pyroxe-pyrific basalt (pillow basalt, breccia, tuff)</td>
</tr>
<tr>
<td>Middle-Late Triassic (Anisian to Carnian)</td>
<td>Carbonaceous siltstone and phyllite sandstone, volcaniclastic tuffs and breccia</td>
</tr>
<tr>
<td>Upper Paleozoic</td>
<td>Au-mineralization @Spanish Mountain (thrust)</td>
</tr>
<tr>
<td>Paleozoic-Proterozoic</td>
<td>Slide Mountain Terrane (thrust)</td>
</tr>
<tr>
<td></td>
<td>Kootenay/Barkerville Terrane</td>
</tr>
</tbody>
</table>

Figure 2.1-Stratigraphy of the Mount Polley Area; from Logan et al., 2007; Logan and Bath, 2005 and 2006; Rees et al, 2005; Logan and Mihalynuk, 2004; Panteleyev, et al., 1996; Bloodgood, 1990; Bailey, 1978
Table 2.2 - Selected geochronology of the Nicola group, MPIC, and associated rocks; timescale in accordance with Okulich, 2001

<table>
<thead>
<tr>
<th>UNIT</th>
<th>ROCK TYPE</th>
<th>DATE</th>
<th>DATING METHOD</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Limestone</td>
<td>Anisian-Ladinian</td>
<td>Conodonts</td>
<td>Orchard, 1995; Bloodgood, 1990</td>
</tr>
<tr>
<td>1a</td>
<td></td>
<td></td>
<td></td>
<td>Panteleyev et al., 1996</td>
</tr>
<tr>
<td>2</td>
<td>Limestone</td>
<td>Norian</td>
<td>Fossils</td>
<td>Orchard, 1995</td>
</tr>
<tr>
<td>2a</td>
<td>Pyroxene basalts</td>
<td>Carnian-Norian</td>
<td>Fossils</td>
<td>Panteleyev et al., 1996</td>
</tr>
<tr>
<td>2b</td>
<td></td>
<td></td>
<td></td>
<td>Rees et al., 2005</td>
</tr>
<tr>
<td>2c</td>
<td></td>
<td></td>
<td></td>
<td>Rees et al., 2005</td>
</tr>
<tr>
<td>2d</td>
<td></td>
<td></td>
<td></td>
<td>Rees et al., 2005</td>
</tr>
<tr>
<td>2e</td>
<td></td>
<td></td>
<td></td>
<td>Rees et al., 2005</td>
</tr>
<tr>
<td>MPIC</td>
<td>Diorite</td>
<td>201.7±4 Ma</td>
<td>U-Pb zircon</td>
<td>Mortensen et al., 1995</td>
</tr>
<tr>
<td></td>
<td>Plagioclase</td>
<td>204.7±3 Ma</td>
<td>U-Pb zircon</td>
<td>Mortensen et al., 1995</td>
</tr>
<tr>
<td></td>
<td>Porphyry</td>
<td>165.2±1.8 Ma</td>
<td>40Ar/39Ar</td>
<td>Logan et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Pyroxene</td>
<td>205.01±0.3 Ma</td>
<td>U-Pb zircon</td>
<td>Logan et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Monzonite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>K-feldspar syenite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>porphyry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Misc.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper Triassic</td>
<td>200.7±2.8 Ma</td>
<td>Pb-Pb titanite</td>
<td>Mortensen et al., 1995</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bootjack Stock</td>
<td>C.g. Syenite</td>
<td>203.1±2.0 Ma</td>
<td>40Ar/39Ar</td>
<td>Bailey and Archibald, 1990</td>
</tr>
<tr>
<td></td>
<td>Orbulcular syenite</td>
<td>202.7±7.1 Ma</td>
<td>U-Pb zircon</td>
<td>Mortensen et al., 1995</td>
</tr>
<tr>
<td></td>
<td>Pseudoleucite syenite</td>
<td>200.7±2.8 Ma</td>
<td>U-Pb zircon</td>
<td>Mortensen et al., 1995</td>
</tr>
<tr>
<td>Other local stocks</td>
<td>Shiko Lake stock</td>
<td>196±7 Ma</td>
<td>K/Ar</td>
<td>Panteleyev et al., 1996</td>
</tr>
<tr>
<td></td>
<td></td>
<td>192±10 Ma</td>
<td>K/Ar</td>
<td>Panteleyev et al., 1996</td>
</tr>
<tr>
<td></td>
<td></td>
<td>182±6 Ma</td>
<td>K/Ar</td>
<td>Panteleyev et al., 1996</td>
</tr>
<tr>
<td></td>
<td>Woodjam stock</td>
<td>193.0±1.2 Ma</td>
<td>40Ar/39Ar</td>
<td>Logan et al., 2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>192.2±1.1 Ma</td>
<td>40Ar/39Ar</td>
<td>Logan et al., 2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>161.77±0.99 Ma</td>
<td>40Ar/39Ar</td>
<td>Logan et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Gavin Lake stock</td>
<td>162.5±0.86 Ma</td>
<td>40Ar/39Ar</td>
<td>Logan et al., 2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>160.0±2.3 Ma</td>
<td>U-Pb zircon</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>Rees et al., 2005</td>
</tr>
<tr>
<td>3a</td>
<td></td>
<td></td>
<td></td>
<td>Rees et al., 2005</td>
</tr>
<tr>
<td>3b</td>
<td>Dacite</td>
<td>196.7±1.3 Ma</td>
<td>U-Pb zircon</td>
<td>Logan et al., 2007</td>
</tr>
<tr>
<td>3c</td>
<td></td>
<td></td>
<td></td>
<td>Rees et al., 2005</td>
</tr>
<tr>
<td>4</td>
<td>Limestone</td>
<td>Sinemurian</td>
<td>Fossils</td>
<td>Bailey, 1988</td>
</tr>
</tbody>
</table>

*Most units within the Nicola Group have not been dated near the latitude of Mount Polley.
The basal unit of the Nicola Group (unit 1) is a 2,500-4,000 m thick sequence of fine grained graphitic to quartzose sedimentary rocks, which grade upwards into the basal unit of the overlying volcanic sequence. Unit 1 is referred to as the “basal black phyllite” and is dominated by black phyllites, siltstones, and shales. Locally, near the contact between the Quesnel terrane and the eastward Cariboo-Kootenay terrane rocks, this unit is highly deformed. The basal black phyllite hosts gold-bearing quartz-pyrite veins at the Spanish Mountain prospect, owned and operated by Skygold Ventures Ltd. The basal black phyllite is described in more detail by Bloodgood (1987a-c, 1988, 1989 and 1990), Rees (1987) and Panteleyev et al. (1996). The unit 1 sedimentary rocks are deposited onto ocean floor rocks of the Slide Mountain terrane. They are interpreted to reflect sedimentation into a low-energy, comparatively deep-water sedimentary environment, probably a restricted marginal basin environment (Rees et al., 2005).

The basal black phyllite is conformably overlain by and grades into mafic hornblende and pyroxene volcaniclastic breccia, conglomerate and tuffaceous argillite. Clasts of the volcanic rocks are found within the uppermost sedimentary beds of unit 1, suggesting that earliest volcanic activity occurred during latest sedimentation. Logan and Bath (2005) identify this unit as unit 1A. The rocks of unit 1A, referred to by Logan and Bath (2005) as the Eastern arc basalt, are petrochemically and stratigraphically distinct from the other volcanic rocks in the sequence (Panteleyev et al., 1996). Unlike the later rocks in the sequence, the volcanic rocks of unit 1A are tholeiitic rather than alkaline in composition. These rocks are interpreted to represent the onset of arc volcanism in a marginal basin setting (Logan and Bath, 2006). The rocks of unit 1A are found entirely within the sedimentary rocks of unit 1.
Conformably overlying the rocks of unit 1 and 1A is a 3,000 m sequence of subaqueous and lesser subaerial volcanic and volcaniclastic rocks (Panteleyev, 1987 and 1988; Panteleyev and Hancock, 1989). These rocks are defined by Logan and Bath as unit 2 and subdivided by Rees et al. (2005) as units 2a-e. The base of this sequence is dominated by fine- to medium-grained volcaniclastic rocks with lesser volcaniclastic breccia. Coherent fine to medium grained volcanic flows are volumetrically minor. Compositionally, this unit is dominated by green and maroon olivine-pyroxene phryic basalt. Pillow basalt is locally present, but the unit is dominated by fine- to medium-grained volcaniclastic breccias and fine-grained basaltic tuffs. The olivine-pyroxene units (unit 2A, figure 2.2) are conformably overlain by pyroxene-phyric flows, tuffs, and breccias, with minor hornblende-bearing basalt. This sequence is subdivided by Panteleyev but that subdivision was abandoned by Rees et al. (2006) and Logan and Bath (2006), who preferred the general term “pyroxene basalt”. The pyroxene basalt has a higher proportion of flows and coherent rocks than the breccia-dominated olivine-pyroxene basalt, and less abundant volcaniclastic breccias. Pillows are rarer in the pyroxene basalt than in the underlying pyroxene-olivine basalt. The pyroxene basalt is conformably overlain by analcime basalt and basaltic-andesite. The upper units of the analcime basalt are interbedded with and locally capped by thin lenses of limestone, which locally form mappable units (Logan and Mihalynuk, 2004; Logan et al., 2007). The analcime basalt (unite 2e, Panteleyev et al., 1996) is dominated by subaqueous flows with minor pillows, volcaniclastic breccia, and tuffs. The analcime basalt is defined as unit 2e by Panteleyev et al (1996).
The volcanic succession is cut by a series of intrusions, most notably the Mount Polley Intrusive Complex (MPIC), which will be reviewed in more detail below, and the Bootjack stock. The Bootjack stock, as described by Bath and Logan, 2006, is a complex intrusion dominated by coarse-grained nepheline syenite with lesser K-feldspar syenite and fine-grained melasyenite. Both suites and their relationship to each other will be discussed in more detail below. The Bootjack stock, the MPIC, and the basalt sequence of Panteleyev's unit 2 are truncated by an unconformity juxtaposing 205 Ma intrusive rocks with 196 Ma breccia of unknown origin (Logan et al., 2007). This sequence, from the onset of olivine-pyroxene basalt volcanic activity through the end of analcime-basaltic andesite volcanic activity, is interpreted to reflect the main stage of arc activity. These rocks are alkaline in composition and share petrogenetic affinities (Logan and Bath, 2005).

Unconformably overlying the analcime basalt and the intrusive suites is a breccia of uncertain origin. Panteleyev et al. (1996) identify it as a volcanioclastic unit, unit 3A. The breccia is maroon in color, matrix-dominated and polylithic. It contains both volcanic- and intrusion-derived clasts and the geometry and contract relationships of the unit are still unclear (Logan et al. 2007). This breccia unit is conformably overlain by a thin unit of dacite tuff, which is in turn conformably overlain by a unit of volcanioclastic conglomerate containing rounded clasts of monzonite and underlying volcanic units. These two units are defined by Panteleyev et al. (1996) as units 3B and 3C. The conglomerate unit is similar in composition and internal organization to the breccia underlying the dacite, with the exception of having rounded rather than angular clasts (Panteleyev et al., 1996).
These units are believed to reflect the mature stage of arc formation and to be related to the erosion and redistribution of volcanic-derived material (Panteleyev et al., 1996). The conglomerate grades into a series of sandstones and siltstones interbedded with thin beds of analcime basalt. This unit is in turn overlain by a series of sedimentary conglomerates, sandstones and siltstones.

**Mount Polley Intrusive Complex**

All known mineralization in and around the Mount Polley property is located within 2-3 km of Mount Polley Peak, and is associated with the igneous rocks and breccias of the Mount Polley Intrusive Complex (MPIC) (Imperial Metals, 2007a). This study uses the term MPIC as advocated by Rees et al. (2006) in preference to the term Mount Polley Stock used by other workers (Panteleyev et al., 1996), as it better reflects the complex construction of this multi-generational pluton. The MPIC is a compound intrusion dominated by nepheline-normative monzonites, monzodiorites, diorites and syenites. Outside this intermediate to felsic volcanic center, the geology is dominated by intermediate to mafic volcanic rocks as summarized previously. Rees et al. (2006) divided the complex into a number of subunits (Figure 2.2). These subunits range from diorites through K-feldspar and psuedoleucite porphyries.
Figure 2.2. Intrusive rocks of the Mount Polley Intrusive Complex. Abbreviations explained below.
**Augite-biotite diorite (PD1)**
The oldest generation of intrusive units is an equigranular augite-biotite diorite dominated by augite and plagioclase but containing up to 20 vol. % K-feldspar (figure 2.3). Minor biotite, hornblende, and magnetite are present, generally composing <5 vol. % of the rock. This unit may be equivalent to the augite monzonite of Fraser (1994), although the profusion of augite-bearing equigranular monzonites and monzodiorites of various relative ages throughout the complex make direct correlation difficult. Disseminated pyrite is present in the PD1 but not common, and sparse disseminated chalcopyrite in present in the unit within the Springer pit and adjacent to the Bell pit.

**K-feldspar-bearing diorite (PD2)**
A more feldspar-rich diorite unit (PD2) is inferred to intrude PD1. The unit contains rocks with varying textures, all of dioritic, leucodioritic to monzodioritic composition (figure 2.3). Intrusive contacts with other units are not observed. Instead, PD2 contacts are gradational with intruding units, especially with the Polley monzodiorite (PMDu) (see below). PD2 is distinguished from PMDu by its lower K-feldspar content. Overall, PD2 rocks are variable, ranging from fine to coarse grained, and dominantly inequigranular, with slightly coarser plagioclase phenocrysts in a finer grained groundmass. Plagioclase phenocrysts are generally not more than 2-3 mm long. Slightly more mafic xenoliths, possibly of PD1, are common in the PD2 and contribute to the textural and compositional heterogeneity of the unit. Some xenoliths have gradational contacts with the bulk of the rock, whereas others are resorbed, suggesting reaction between xenoliths and magma.
Locally, PD2 is contains up to 5 vol % pyrite in leucodiorite. Distinguishing the PD2 from the PMdu is complicated by the presence of K-feldspar alteration, which alters plagioclase to K-feldspar, giving the rocks a creamy pink color.

**Undifferentiated Monzodiorite (PMdu)**

Polley monzodiorite (PMdu) represents the bulk of the igneous complex. Equigranular augite-bearing monzonite dominates the unit, with lesser K-feldspar-bearing diorite, monzodiorite, and K-feldspar-phyric monzonite porphyry. The PMdu is differentiated from the PD2 by the presence of primary K-feldspar, although K-feldspar is usually less abundant than plagioclase where this rock is comparatively unaltered. The PD2 and the PMdu are juxtaposed by the East Cariboo fault (Fraser, 1994). In the Springer area, PMdu intrudes PD1, establishing the igneous chronology.

The PMdu is extremely variable and encompasses rock units defined by other workers as diorites, monzodiorites, or “plagioclase porphyry” (Fraser, 1994). The PMdu is creamy grey to pinkish grey where least altered. The PMdu is equigranular to microporphyritic, and can range from fine- to coarse-grained. Albite-constructive alteration and weathering of this unit can cause plagioclase phenocrysts to stand out, resulting in the identification of this unit as plagioclase porphyry by other workers (e.g. Fraser, 1993). Augite is the most common mafic mineral in the PMdu, with hornblende locally abundant along with sparse primary, euhedral biotite. Locally, hornblende is more abundant than augite.

Xenoliths of more mafic rock are common in PMdu. These locally compose up to 25% of the rock. Inclusions are most commonly angular or irregular in shape, although smaller inclusions are frequently rounded or even amoeboid. Most inclusions are fine-grained to
aphanitic and pyroxene-rich. They may be glomerocrysts of mafic minerals, enclaves of mafic material, or xenoliths of fine-grained mafic rock. Other medium- to coarse-grained inclusions contain plagioclase and/or K-feldspar. Texturally and mineralogically, these inclusions resemble the PD1 and PD2 units. Disseminated pyrite and thin (<1 mm) pyrite veins are common in the PMdu, generally composing <1% of the rock.

**Monzonite (PMz)**
More homogenous, less-inclusion-rich monzonite (PMz) intrudes PMDu. These rocks are grey to pale pink, locally stained red or reddish orange. They are medium- to coarse-grained, generally coarser grained than PMdu, and contain more abundant mafic minerals (>10% augite and some primary biotite) than older rocks. Hornblende is not reported in PMz rocks. Where contact relationships are observed, PMz cuts PMdu.

**K-feldspar monzonite porphyry (Pkm)**
Locally, PMz and PMdu rocks are cut by dykes and irregular bodies of K-feldspar-phyric porphyry, known as Pkm. These bodies are generally elongate and less than a few tens of meters in map dimension. They trend NNW and dip steeply, often near-vertical. Pkm rocks are divided by Rees and Ferriera (2006) into two groups, the “coarser” Pkm and the “finer” Pkm.

The coarser Pkm is distinguished by K-feldspar phenocrysts 1-4 cm long. The K-feldspar phenocrysts are notably stubby or blocky in appearance and set in a coarse to medium grained groundmass. Phenocrysts are frequently aligned parallel to the margins of the intrusive bodies; in smaller dykes the texture is strongly trachytic. Phenocryst content varies markedly. In some areas, Pkm only contains 1-2% phenocrysts and appears to grade into the PMdu, especially in the Southeast zone. The groundmass of the coarser
Pkm contains plagioclase subequal to K-feldspar where least altered. The main mafic mineral in the Pkm is augite with lesser hornblende. Biotite commonly forms crystals up to 5 mm across.

The Pkm is almost always strongly altered; K-feldspar-constructive alteration with disseminated hematite is most common. Disseminated pyrite is common as is fine-grained disseminated chalcopyrite. Chalcopyrite is locally present, but is never abundant enough to constitute ore grades.

The finer Pkm is distinguished by phenocrysts ranging from a few mm to 1 cm in length. Phenocrysts are generally more abundant than those in the coarser Pkm, rarely composing more than 30% of the rock. Alignment of phenocrysts is common. Plagioclase phenocrysts are rare and generally smaller than K-feldspar phenocrysts where present (1-2 mm vs. 3-5 mm). The groundmass is finer than that of the coarser Pkm, and K-feldspar constructive alteration may make the ground mass appear finer still. As in the coarser Pkm, K-feldspar alteration is associated with hematite dusting, coloring the rock red or red-orange. In least-altered examples of this rock type, the groundmass of the rock is creamy to pinky grey and K-feldspar phenocrysts are pale pink. In most examples, the rock is red orange with pale orange or pink phenocrysts. The finer Pkm generally contains more xenoliths than the coarse Pkm. Lithic fragments resembling PMdu are most common, but medium- and coarse-grained lithic fragments resembling PD1 and PD2 are present as well. Fine-grained mafic inclusions such as those common in the PMdu are rare; local mafic inclusions are present within monzonitic xenoliths.
Augite Porphyry (AP)
Mafic to intermediate augite-phyric porphyry dykes are widespread in the Mount Polley complex (Rees et al., 2005; Ross, 2004a and b; Gillstrom, 2004). These dykes crosscut mineralized breccias and are generally unaffected by hydrothermal mineralization (Rees et al., 2005). The augite porphyry dykes vary more in orientation than any other dykes in the MPIC, and are generally controlled by faults. The augite porphyry dykes are characterized by a fine-grained, pale-green to pinkish-green groundmass containing 20-60% euhedral black augite phenocrysts. Sparse olivine phenocrysts have also been reported, typically replaced by iddingsite (Rees et al., 2005).

Bootjack Stock
To the south of the MPIC, the Bootjack stock is dominated by psuedoleucite syenite, orbicular psuedoleucite syenite, and melasyenite (Bath and Logan, 2005). The Bootjack stock is more silica-undersaturated than the MPIC, but U-Pb dates are within the error of dates from the MPIC (Table 2.2; Bath and Logan, 2005; Logan et al., 2007). The Bootjack stock is not spatially associated with economic Cu-Au mineralization or extensive hydrothermal alteration (Rees et al., 2005).

Summary
Regional volcanic rocks surrounding the MPIC reflect a trend of increasing differentiation (Logan et al., 2007). This pattern is continued within the MPIC, with the most mafic rocks (PD1 and PD2) occurring early in the development of the complex and the most feldspathic (Pkm) occurring closest to the time of brecciation and mineralization.
Chapter 3-Intrusive Rocks of the Northeast Zone

**Introduction**

The most salient feature of the Mount Polley deposit is the hydrothermal breccia (Rees et al., 2005; Bailey, 1978). This breccia hosts the majority of economic mineralization and presents the most striking visual feature of the deposit (Fraser, 1993, 1994 a and b; Fraser et al., 1995; Tosdal et al., 2008). The breccias at Mount Polley are, however, the product and the reflection of igneous as well as hydrothermal processes (Burnham, 1979 and 1985; Sillitoe, 1985; Jebrak, 1997; Cox et al., 2001; Gonnerman and Manga, 2003). These rocks reflect a physical and chemical evolution from the volcanic rocks into which the intrusive complex was emplaced, the intrusive complex itself and the intrusions that triggered brecciation, to the post-breccia and post-mineral intrusions which cut the breccia.

The rocks that make up the bulk of the Mount Polley Intrusive Complex (MPIC) were summarized in Chapter 2. Here, physical characteristics and cross-cutting relationships of the igneous rocks for the Northeast zone are presented, based on observations in core and hand sample. The physical and chemical evolution of the igneous rocks in the Northeast zones highlights the unusual nature of the syn-breccia intrusive phase, as well as the continuity of evolution from the earliest to the latest intrusive rocks.

**Northeast Zone**

**Field relations**

Igneous rocks examined in the Northeast zone are divided into four broad groups, according to their timing relative to the mineralized breccia (Table 3.1). The oldest rocks,
as determined by field relationships, were xenoliths observed as inclusions in the various igneous rocks. Xenoliths are included within pre-breccia rocks. This group includes the various rock types, which were observed as angular, mechanically-derived clasts within the breccia. The syn-brecciation group includes those rocks that were ductile or fluid at the time of the brecciation event. Post-breccia rocks cut the breccia. In some cases, particular rock types were observed both as dykes cutting the breccia and as clasts within the breccia (equigranular augite-bearing monzonite and equigranular hornblende-bearing monzonite). Despite their similarities, these rocks were considered as separate units based on their contact relations. In other cases, substantial intercepts of a single rock type which occurred both pre- and post-breccia were observed in core. Where these intercepts showed fine-grained or chilled margins against the breccia, they were considered to be post-breccia; where no obvious intrusive contact was observed, the intercept was assumed to reflect the presence of an oversized clast.

### Table 3.1- Timing of rock types observed in the Northeast zone

<table>
<thead>
<tr>
<th>TIMING</th>
<th>ROCK TYPES</th>
<th>EVIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenoliths in pre-breccia rocks</td>
<td>Fine-grained mafics, horblende mafics, diorite, monzodiorite</td>
<td>Xenoliths in breccia clasts, syn-breccia clasts, and post-breccia dykes</td>
</tr>
<tr>
<td>Pre-breccia rocks</td>
<td>Equigranular monzonite, equigranular hornblende monzonite</td>
<td>Breccia clasts</td>
</tr>
<tr>
<td>Syn-breccia rocks</td>
<td>Megacrystic K-feldspar monzonite porphyry</td>
<td>Juvenile clasts in breccias</td>
</tr>
<tr>
<td>Post-breccia rocks</td>
<td>Multiple post-breccia dykes</td>
<td>Chilled/fine grained margins against breccia and other post-breccia dykes</td>
</tr>
</tbody>
</table>

**Xenoliths**

Four distinct xenolith types are present within pre-breccia rocks. The most common are angular, rounded and irregular "mafic" xenoliths as described by Rees et al. (2005, 2006) in the undifferentiated monzonite unit. Diorite and monzodiorite xenoliths are less
common. Hornblende-bearing mafic porphyry xenoliths were observed only in two locations. The xenoliths are most common in the pre-mineral equigranular monzonite, although they occur in the megacrystic monzonite porphyry as well. A few xenoliths are observed in the crowded K-feldspar porphyry. Xenolith abundance varies from absent to 5-7%, averaging around 1%. There is no systematic variation with depth or location; xenoliths occur in clusters throughout the pre-mineral equigranular monzonite and equigranular monzonite clasts within the breccia.

**Biotite-magnetite “mafics”**

“Mafic” xenoliths are common in the equigranular monzonite rock, which formed the majority of breccia clasts and of breccia country rock (figure 3.1). These xenoliths are most commonly angular to subrounded and 1-3 cm in diameter; in rare cases xenoliths up to 20 cm in diameter were observed. Irregular and ellipsoidal xenoliths were also observed; some of the xenoliths are tabular (figure 3.2). The mafic xenoliths are fine-grained and magnetic. In thin section, the xenoliths are composed of polycrystalline aggregates of secondary biotite, chlorite and magnetite, with rare pyrite (figure 3.3). The original mineralogy of the xenoliths, although certainly mafic, has been obscured by alteration.

The origin of the mafic xenoliths is unknown.
Figure 3.1; Photographs of mafic xenoliths in equigranular monzonite clasts in breccia (a) and in equigranular monzonite xenoliths in post-breccia K-feldspar porphyry dykes (b).

Figure 3.2-Photographs of angular (a,b) rounded (a,b) and tabular (c) mafic xenoliths. Line drawings included to highlight xenolith shapes. Scale bar equals 1 cm.
Figure 3.3-Photomicrographs of xenoliths in plane (left) and cross (right) polarized light. A; xenolith replaced by chlorite and pyrite and crosscut by a post-mineral carbonate vein; b; Xenolith replaced by chlorite, with reaction rim between xenolith and host rock; c; partially replaced xenolith with some remnant plagioclase; d; higher magnification image of xenolith rim showing raggedness caused by polycrystalline replacement of orginal mafic minerals by chlorite and magnetite.
Diorite

A much rarer group of xenoliths are coarse grained, with 40-50% mafic minerals and 50-60% plagioclase that resemble Diorite 1 (figure 2.2). A few xenoliths show variable alteration, which might be truncated veins (figure 3.4a,b). In some cases, xenoliths show reaction rims against the surrounding rock (figure 3.4c,d). These features suggest that the xenoliths were not in chemical equilibrium with the host rock.

Figure 3.4-Photographs of diorite xenoliths. a; Diorite xenolith with truncated K-feldspar vein; b; diorite (?) xenolith with K-feldspar alteration; c; Diorite xenolith with mafic rim; d; diorite xenolith with reaction rim against monzonite.
Monzodiorite

A minority of coarse grained xenoliths contain K-feldspar as well as plagioclase. These monzodiorite xenoliths closely resemble Diorite 2 (figure 2.3 b-c). These xenoliths usually contain 30-40% mafic minerals, 30-50% plagioclase, and ~20% interstitial K-feldspar (figure 3.5).

![Figure 3.5-Photograph of monzodiorite xenolith](image)

Hornblende mafic porphyry

The rarest xenoliths are dark green hornblende mafic porphyry. Only two hornblende mafic porphyry xenoliths were found. The groundmass of these xenoliths is fine-grained, dark blue-green, and crowded with 2-3 mm hornblende phenocrysts. These xenoliths were found only within syn-breccia megacrystic K-feldspar porphyry. The hornblende mafic xenoliths have coarse grained equigranular reaction rims against the K-feldspar porphyry (Figure 3.6).
Figure 3.6-Photograph of hornblende mafic porphyry xenolith in megacrystic monzonite porphyry dyke. Note the reaction rim around the xenolith on the right side of the image.

Due to the small size of these xenoliths, and their small volumetric contribution to the ore body, no chemical analyses were done on xenoliths.

**Pre-breccia rocks**

**Equigranular Monzonite**

Approximately 90% of the clasts in the hydrothermal breccia (Figure 3.7) consist of xenolith-bearing equigranular monzonite derived from the surrounding country rock. This monzonite is very similar to the PMdu and PMz units, and to some post-breccia dykes. The equigranular monzonite clasts consist of ~90% K-feldspar, and <10% mafic minerals, mostly altered to chlorite, magnetite, and pyrite. This rock is described here as a monzonite rather than a syenite due to the presence of widespread K-feldspar constructive alteration in the MPIC.

Figure 3.7-Photograph of variably altered equigranular monzonite clasts in breccia
Like the undifferentiated monzonite of the MPIC in general, the equigranular monzonite described here shows significant textural variation. K-feldspar microporphyry or fine-phenocryst K-feldspar porphyry forms <5% of breccia clasts, but locally can form 40-50% of clasts (Figure 3.8). There are two distinct subtypes of this rock. The K-feldspar microporphyry contains 20-30% 1-2 mm K-feldspar phenocrysts in a fine-grained K-feldspar and plagioclase groundmass. The phenocrysts are not substantially larger than the average crystal size in the groundmass, but they are visually distinct as euhedral phenocrysts among the subhedral groundmass grains. In fine-phenocryst porphyry, the K-feldspar phenocrysts are ~3 mm in length and typically <1 mm wide, giving them an elongate aspect. The groundmass is fine-grained (<2mm). The equigranular monzonite, microporphyry and the fine-phenocryst porphyry grade into each other, even within a single clast. In thin section, monzonite, which appears equigranular in hand sample, shows microporphyry textures (Figure 3.9) and as such they are considered here as a single rock type.
No systematic variation in grain size, porphyryitic or trachytitic nature of the equigranular monzonite was observed within the breccia body. Petrography examination also shows Carlsbad twinning in the feldspar phenocrysts, indicating that the K-feldspar is primary, not potassic alteration of albite or another feldspar (Figure 3.9). The groundmass of the equigranular monzonite was too fine-grained to distinguish K-feldspar alteration from primary K-feldspar, especially given the presence of abundant hematite staining. Hematite staining was most distinct along grain boundaries, suggesting that it is of hydrothermal rather than magmatic origin (Figure 3.9). Zoning of hematite staining within K-feldspar phenocrysts suggests control of hematite staining by compositional banding within the grains. Hematitic alteration is discussed more fully in Chapter 5.
Figure 3.9-Photomicrographs of equigranular monzonite showing microporphyry textures (a). Note the hematite staining on the crystal margins (b,c,d), and Carlsbad twinning of microphenocrysts (b,d), indicating that the K-feldspar composition is original and not the effect of post-intrusion K-feldspar constructive alteration. Images e and f show chlorite altered and biotite-altered augite phenocrysts.

Monzonite clasts in the breccia are generally angular to subangular. Locally rounded clasts are present (see Chapter 4). The lack of globular or fluidal clast shapes or chilled or fine grained margins indicate that the monzonite was crystalline prior to brecciation.
Coherent equigranular augite monzonite surrounding the breccia is locally mineralized, usually as crackle-breccia infill (figure 3.10).

Figure 3.10-Chalcopyrite and bornite mineralization in equigranular monzonite. Scale bar equals 1 cm.

Mafic

Mafic clasts, very similar to the mafic xenoliths described above, are also observed within the breccia. Composing 1-2% of breccia clasts, these clasts locally composed up to 20% of the breccia (figure 3.11). The mafic clasts in breccia are generally smaller than clasts of other rock types, usually less than 2 cm in length. They are dark in color, fine-grained, and typically preferentially altered (see Chapter 5). Mafic clasts are most common where the average clast size of the breccia is smallest (see Chapter 4). The mafic clasts may represent re-worked xenoliths originally included within the monzonite clasts.
Figure 3.11-Mafic clasts in breccia. A; mafic clasts with equigranular and monzonite microporphyry clasts; b; predominantly mafic clasts. Note replacement of mafic clasts by chalcopyrite.

Altered mafic

The most distinctive group of clasts within the breccia are altered green to green-grey mafic clasts. Alteration has obscured the primary mineralogy of the clasts (the clasts are composed of secondary actinolite, albite, and minor epidote). They contain magnetite and K-feldspar veins truncated at the clast boundaries, indicating the presence of a pre-breccia hydrothermal system (figure 3.12).
Although the edges of these magnetite veins are in some cases replaced by Cu-sulfides, no primary Cu-sulfides were observed associated with this generation of veins.

The tabular distribution of the altered mafic clasts within the breccia (figure 3.13) suggests that the altered mafic clasts may be the disaggregated remains of a sill-like body within the monzonite. This tabular geometry is well defined, with no altered mafic clasts outside the margins of the body shown, and up to 90% altered mafic clasts within it.
Figure 3.12-Distribution of altered mafic clasts on section 29. Altered mafic clasts were not observed on Section 18.

**Syn-breccia**

Between 10 and 20% of the clasts within the breccia, locally ranging from 1% to >90%, are composed of megacrystic (>1.5 cm phenocryst) K-feldspar monzonite porphyry. These clasts are most commonly angular to subrounded, but also occasionally include
complex clast shapes indicating that the unit was plastic when brecciated (Figure 3.14a and b).

Figure 3.14a-Juvenile megacrystic porphyry clasts. Image courtesy of Dr. Kirstie Simpson.
Figure 3.14b- Juvenile megacrystic monzonite porphyry clast. Note how the clast has been squeezed between several equigranular porphyry clasts. Hole WB-04-99, 444.5 m. Field of view equals 2 cm.

Megacrystic K-feldspar monzonite porphyry clasts contain 10-15% euhedral K-feldspar phenocrysts, commonly with starburst-shaped agglomerations of phenocrysts and irregular glomerocrysts (figure 3.15). The phenocrysts are commonly broken (figure 3.15). In thin section, phenocrysts show patchy hematite dusting and oikocrystic textures (figure 3.16). The groundmass of the megacrystic K-feldspar monzonite porphyry is fine-to medium-grained, containing <5% mafic minerals. Mafic minerals within the K-feldspar monzonite porphyry are blocky in shape, suggesting that the original mineral
may have been biotite or augite, but mafic minerals are mainly altered to chlorite. The groundmass feldspar appears to be mainly K-feldspar, but the original mineralogy has probably been modified by syn- and post-breccia K-feldspar-stable alteration. Very similar megacrystic K-feldspar porphyry intrusive bodies are cut by drillholes outside the area of the breccia (figure 3.17). Cu-Au mineralization is not spatially associated with the K-feldspar monzonite dykes which cut breccia.

Figure 3.15-Broken phenocrysts (a, bottom left) and glomerocrysts (a and b) of K-feldspar in the megacrystic monzonite porphyry; phenocrysts are stained with hematite and locally altered to albite.
Figure 3.16-Photomicrographs of a single K-feldspar megacryst showing K-feldspar chadacrysts within the K-feldspar oikocryst, and patchy hematite dusting concentrated along fractures. Image on the right traced to show detail; vein at upper right is post-mineral calcite.

Figure 3.17a-Distribution of megaerystic porphyry dykes on Section 29.
Post-breccia Intrusive rocks

The hydrothermal breccias are cut by a host of post-breccia dykes. All the units addressed in this section have intrusive margins against the breccia or against each other. The dykes are presented in chronologic order, based on cross-cutting relationships either by direct intrusive contacts or by the presence of xenoliths of one unit in another.

The post-breccia intrusive rocks can be subdivided into compositional groups with sequential timing (Table 3.2). These dykes document chemical and physical changes both
within and between compositional groups, reflecting an overall trend of increasingly mafic compositions and decreasing grain size for each generation of dykes.

**Table 3.2a: Trends in the composition and texture of post-mineral dykes**

<table>
<thead>
<tr>
<th>COMPOSITIONAL GROUP</th>
<th>DYKES</th>
<th>TRENDS WITHIN THE GROUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equigranular augite monzonite</td>
<td>Mineralized equigranular augite monzonite</td>
<td>Decreasing grain size with time</td>
</tr>
<tr>
<td>Post-mineral equigranular augite monzonite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-feldspar porphyries</td>
<td>Syn-breccia megacrystic monzonite porphyry</td>
<td>Decreasing phenocryst size and abundance over time</td>
</tr>
<tr>
<td>Post-mineral crowded K-feldspar monzonite porphyry</td>
<td></td>
<td>Increasing phenocryst aspect ratio over time</td>
</tr>
<tr>
<td>Post-mineral moderate K-feldspar monzonite porphyry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-mineral sparse K-feldspar monzonite porphyry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-mineral K-feldspar trachyte porphyry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-feldspar and plagioclase porphyry</td>
<td>Post-mineral K-feldspar and plagioclase porphyry</td>
<td></td>
</tr>
<tr>
<td>Hornblende-bearing equigranular monzonite</td>
<td>Hornblende and augite-bearing equigranular monzonite</td>
<td>Increasing proportion of hydrous minerals over time</td>
</tr>
<tr>
<td>Hornblende-bearing equigranular monzonite</td>
<td></td>
<td>Decreasing grain size</td>
</tr>
<tr>
<td>Hornblende-bearing equigranular monzonite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hornblende and biotite-bearing equigranular monzonite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biotite trachyte</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plagioclase (diorite) microporphyry</td>
<td>Plagioclase (diorite) microporphyry</td>
<td></td>
</tr>
</tbody>
</table>
### Table 3.2b: Trends in the composition and texture of post-mineral dykes

<table>
<thead>
<tr>
<th>COMPOSITIONAL GROUP</th>
<th>DYKES</th>
<th>TRENDS WITHIN THE GROUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mafic dykes</td>
<td>Plagioclase-phyric mafic microporphyry</td>
<td>Increasingly mafic composition</td>
</tr>
<tr>
<td></td>
<td>Plagioclase and augite-phyric mafic microporphyry</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Augite-phyric mafic microporphyry</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Augite and olivine-phyric mafic microporphyry</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Olivine-phyric mafic microporphyry</td>
<td></td>
</tr>
<tr>
<td>Augite porphyry</td>
<td>Augite porphyry</td>
<td>Exploits faults; often highly deformed and gougy on at least one contact.</td>
</tr>
</tbody>
</table>

**Equigranular augite monzonite**

The oldest generation of post-breccia dykes is equigranular augite-bearing monzonite very similar to the country rock of the breccia. These dykes occur repeatedly throughout the sequence of dykes, generally becoming finer grained over time. The oldest of these dykes are presumed to be the oldest post-breccia dyke generation because they are the only dykes that contain chalcopyrite as veinlets and replacing mafic minerals (figure 3.18).

The equigranular monzonite dykes were too numerous and difficult to distinguish from clasts within the breccia to be shown on cross sections.
Figure 3.18-Chalcopyrite and bornite mineralization in post-breccia equigranular augite-bearing monzonite. A; Bornite-chalcopyrite vein-breccia, b; chalcopyrite replacing mafic minerals, c; chalcopyrite vein crosscutting finer-grained equigranular monzonite, and d; a diffuse chalcopyrite vein with replacement of mafic sites by chalcopyrite. Scale bar is 1 cm.
K-feldspar phric monzonite porphyry

The equigranular augite monzonite dykes are cut by K-feldspar-phric monzonite porphyry dykes (figure 3.19). These dykes generally have phenocrysts between 5 and 7 mm long in a fine-grained to aphanitic groundmass. This family of dykes contains no visible plagioclase either as phenocrysts or in the groundmass. The K-feldspar-phric monzonite porphyry dykes can be divided into three subtypes based on the phenocryst percentage. Generally, the greater the percentage of phenocrysts in the porphyry, the larger and blockier the phenocrysts and the greater the amount of disseminated pyrite in the groundmass of the dyke.
Figure 3.19a-Distribution of K-feldspar-phyric monzonite porphyry dykes on section 29
Figure 3.19b-Distribution of K-feldspar-phyric monzonite porphyry dykes on Section 18.

The dykes generally have a branching morphology and are interpreted to be approximately vertical. They are more common, and more varied, in Section 29 than Section 18.

The oldest K-feldspar porphyry is phenocryst-crowded, with >30% phenocrysts. Flow alignment of phenocrysts is common, especially around xenoliths and at the dyke margins (figure 3.20). The dykes have chilled margins against the breccia and against equigranular monzonite. They contain xenoliths of equigranular monzonite and fine-grained mafic rock.
Although no direct crosscutting relationships were observed in core, a family of K-feldspar-phyric monzonite porphyry dykes containing 15-20% K-feldspar phenocrysts are assumed to be the next generation of dykes cutting the breccia. This conclusion is based on the apparent regular progression of decreasing phenocryst percentage in the K-feldspar porphyries. The phenocrysts in these dykes are more elongate than those in the phenocryst-crowded dykes. Disseminated pyrite was less abundant, and fewer equigranular monzonite xenoliths were observed. Some flow textures are present in these
dykes. In contrast to the crowded K-feldspar-phyric dykes, which generally had uniformly sized, shaped, and distributed phenocrysts throughout the dyke, the moderate K-feldspar-phyric monzonite porphyry dykes showed significant variation in phenocryst size and aspect ratio. Generally, phenocrysts are sparser, larger and blockier toward the center of the dykes, and more common, smaller, and more elongate toward the dyke margins. The margins of the crowded K-feldspar-phyric porphyry were also typically smooth, whereas the margins of the moderate K-feldspar-phyric porphyry are in many cases highly irregular, in many cases with apparently disaggregated fragments. Glomerocrysts and starburst-shaped phenocryst clusters are less common in the phenocryst-moderate dykes than in the phenocryst crowded ones, but still present (figure 3.21).

Figure 3.21-K-feldspar glomerocrysts in moderately K-feldspar-phyric monzonite porphyry. A; glomerocryst made up of larger crystals than the surrounding phenocrysts; b; glomerocryst made up of crystals the same size as the surrounding phenocrysts; c; glomerocryst overprinted by hematite-carbonate alteration. Scale bar equals 1 cm.
The youngest and most common group of K-feldspar-phyric monzonite porphyry dykes contains less than 5% phenocrysts. These are volumetrically the largest dykes in the system. The phenocryst-poor K-feldspar-phyric monzonite porphyry dykes are notably darker in color than the other dykes of the group, with a finer grained groundmass and more pronounced chilled margins. The phenocrysts in the dykes are generally more elongate than those in the moderate or the crowded K-feldspar-phyric monzonite porphyry.

Another dyke included within this larger family is the trachyte porphyry dyke observed in Section 18. Although its position on the far side of the Green Giant fault and its lack of cross-cutting relationships makes establishing the timing of this dyke problematic, the apparent trend in dyke character (finer grained groundmass, sparser and more elongate phenocrysts) suggest that the trachyte porphyry is the latest in the series. The trachyte porphyry has an aphanitic groundmass and contains 2-3% extremely elongate (1-2 mm wide by 7-15 mm long) phenocrysts. In contrast to the dark red to orange fine-grained groundmass of the other K-feldspar-phyric monzonite porphyry dykes, the groundmass of the trachyte porphyry dyke is aphanitic and dark brown in color, closely resembling the chilled margins of the phenocryst poor K-feldspar-phyric monzonite porphyry dykes. Starburst and cross-shaped phenocryst clusters were observed in the trachyte porphyry, but more complex glomerocrysts were not.

As a group, the K-feldspar phyric-dykes show a progression over time of decreasing phenocryst size and abundance, and increasing phenocryst aspect ratio (figure 3.22). This trend will be discussed in more detail below.
Figure 3.22-Progressive changes in dyke texture over time. A; Megacrystic K-feldspar phryic monzonite porphyry, b; crowded K-feldspar-phryic monzonite porphyry, c; moderate K-feldspar-phryic monzonite porphyry, d; sparse K-feldspar-phryic monzonite porphyry, and e; K-feldspar-phryic trachyte porphyry. Scale bar equals 1 cm.
K-feldspar- and plagioclase-phyric monzonite porphyry dykes

Cutting the K-feldspar-phyric porphyry dykes are K-feldspar- and plagioclase-phyric monzonite porphyry dykes. These dykes have 10-15% 5-8 mm orange K-feldspar phenocrysts and 5-10% 3-5 mm grey or cream-colored plagioclase phenocrysts in a fine-grained to aphanitic dark red groundmass (Figure 3.23). These dykes have a conspicuous “two-toned” appearance, but the presence of plagioclase may be the result of preservation rather than original compositional distinctiveness. The dominant mafic mineral in the dykes is biotite. It is possible that the K-feldspar-phyric dykes in which plagioclase is not observed may have simply experienced pervasive K-feldspar constructive alteration, converting plagioclase to K-feldspar, and that the biotite is secondary and replacing augite. The plagioclase- and K-feldspar-phyric monzonite porphyry dykes, like the dykes with only K-feldspar phenocrysts, commonly have disseminated pyrite in the groundmass of the rock. Although encountered in three drillholes, this rock type is probably a single dyke (Figure 3.24). This rock type was not encountered in section 18.

Figure 3.23-Plagioclase- and K-feldspar-phyric monzonite porphyry, cut by a multi-generation pyrite vein. Scale bar equals 1 cm.
Figure 3.24-Plagioclase- and K-feldspar-phyric porphyry dyke in section 29.
Equigranular hornblende and hornblende-biotite monzonite

Equigranular augite-bearing monzonite dykes occur sporadically throughout the igneous sequence of the Northeast zone, locally with small amounts of hornblende. In a few dykes deep in Section 29, equigranular monzonite containing no visible augite and an abundance of hornblende were observed. These dykes cut K-feldspar constructive alteration, which overprints the K-feldspar-phyric and the K-feldspar- and plagioclase-phyric dykes in both Section 29 and Section 18 (figure 3.25 a and b), so they are assigned a post-K-feldspar- and plagioclase-phyric dyke timing, although direct cross-cutting relationships were not observed.

This family of dykes contains 2-5% <3mm euhedral hornblende laths in a fine grained K-feldspar and plagioclase groundmass (figure 3.26). Disseminated pyrite is not observed in these dykes, but fine-grained disseminated magnetite is present. The hornblende bearing equigranular monzonite is cut by a second generation of hornblende-bearing equigranular monzonite, distinguished from the first by the presence of 1-2% primary biotite. Primary biotite forms <2mm euhedral crystals. Secondary biotite forms felty black or green-black crystalline aggregates replacing augite or hornblende. The biotite and hornblende-bearing monzonite also contains xenoliths of biotite-free hornblende-bearing monzonite, confirming the timing relationship between biotite-bearing and biotite-free hornblende monzonite. In section 18, hornblende-bearing monzonite forms a larger body than those observed in Section 29. In section 18, hornblende monzonite is cut by trachyte and diorite dykes and by faults exploited by augite porphyry dykes.
Figure 3.25a-Hornblende and hornblende-biotite dykes in Section 29.

Hornblende and hornblende-biotite dykes in section 29 cut K-feldspar constructive alteration, but are cut by albite-epidote alteration. This suggests that the hornblende-biotite dykes occurred late in the development of the hydrothermal system, and were post-mineral, but were not post-hydrothermal. Minor pyrite is present replacing mafic minerals in these dykes (figure 3.26).
Figure 3.25b-Hornblende and hornblende-biotite bearing equigranular monzonite on section 18.
The most common, although not the most voluminous, dykes in the Northeast zone are trachyte dykes (figure 3.27). No trachyte dykes of mappable scale were observed in section 29, but they were abundant in section 18. These dykes are dark brown in color, aphanitic, and are observed cross-cutting all but the mafic and augite porphyry dykes. The term “trachyte” is used here in the sense of an aphanitic equivalent of monzonite, not as a textural term denoting flow alignment of phenocrysts (Bateman et al., 1989). They commonly form 2-5 cm ‘microdykes’ cutting other units (figure 3.28). These dykes are commonly vesicular or amygdaloidal (figure 3.29). The trachyte also commonly forms local intrusive infill breccias where it cross-cuts breccia or fractured
monzonite units (figure 3.30). The trachytes also frequently form the clasts of carbonate and gypsum-cemented mosaic and jigsaw breccias related to the latest stages of hydrothermal activity in the Northeast zone (figure 3.31, see chapter 5).

Figure 3.27-Trachyte dykes on Section 18.
Figure 3.28- Trachyte microdykes cutting hydrothermal breccia. a; trachyte microdyke cutting breccia; note the irregular margin on the right controlled by the breccia texture. b; irregular trachyte microdyke controlled by fractures in coherent equigranular monzonite. c; trachyte microdyke with chilled margin against megacrystic monzonite porphyry. Scale bar equals 1 cm.
Figure 3.29-Carbonate and carbonate-silicate amygdules in trachyte. A; small, irregular amygdules in even-textured, aphanitic trachyte; b; small, rounded amygdules in even-textured, fine-grained trachyte; c; large, irregular amygdules filled with multiple minerals. Scale bar equals 1 cm.

Figure 3.30-Trachyte infill, monzonite clast breccia. Scale bar equals 1 cm.
Figure 3.31-Trachyte clast, carbonate and gypsum infill breccias; a; trachyte dyke cut by fluorite-carbonate infill breccia; b; carbonate-infill crackle breccia; c; carbonate infill breccia crosscutting equigranular monzonite/trachyte contact; d; carbonate-infill, trachyte-clast breccia crosscut by gypsum vein. Scale bar equals 1 cm.
In thin section, the trachyte dykes contain 70-80% fine-grained biotite (figure 3.32). They are considered the end-member of the hornblende- to hornblende- and biotite-bearing equigranular monzonite. This family of dykes shows a trend of increasing mafic content and increased hydrous mineral content over time.

**Figure 3.32-Photomicrographs of a trachyte microdyke.** The dominant groundmass mineral in the microdyke is biotite. A; margin of the microdyke; b; K-feldspar phenocryst in the microdyke; c; carbonate vein crossing the microdyke margin; d; euhedral and resorbed phenocrysts in the microdyke. Field of view 5 mm.

**Diorite and plagioclase porphyry**

Two distinct units in the Northeast zone compose the diorite group. The plagioclase porphyry observed in Section 29 consists of an aphanitic dark brown or green-brown groundmass crowded with 2-3 mm plagioclase phenocrysts which make up
>60% of the rock. The ‘dark monzonite’ is an equigranular fine-grained dark brown rock, also dominated by plagioclase, which forms larger bodies in section 18. The timing relationship between them is ambiguous, as the “dark monzonite” was only observed in Section 18 and the plagioclase microporphyry was only observed in Section 29 (figure 3.33).

Both units appear to post-date most alteration and all mineralization. They are cut only by the mafic dykes described below.

Figure 3.33a-Dark monzonite dykes on section 18.
Mafic dykes

Aphanitic, green-black mafic (alkali basalt) dykes are the most distinctive dykes in the Northeast zone (figure 3.34). The mafic dykes have complex intrusive margins against other units, showing distinct chilled margins. In many cases the dyke material infiltrates the breccia, forming intrusive cement breccias. In a few cases, these intrusive cement breccias show grading parallel to the dyke margins. (figure 3.35). The mafic dykes can be
subdivided into a three subtypes: augite-phyric, plagioclase-phyric, and olivine-phyric.

All three dyke types have fine-grained, plagioclase-dominated groundmasses with augite and/or olivine phenocrysts (figure 3.36). All three dyke types contain local carbonate and carbonate-silicate amygdules.

Figure 3.34-Mafic dykes on section 29.
Figure 3.35-Grading of clastic material parallel to mafic dyke margins. Scale bars both equal 1 cm.
Figure 3.36- Photomicrographs of a mafic dyke, including a carbonate amygdule (top right). Top; plane polars; bottom; crossed polars. Field of view 5 mm.
Augite-phyric mafic dykes are the most difficult to recognize in hand sample, as the <2 mm black augite phenocrysts blend into the aphanitic black groundmass of the dyke. The phenocrysts make up <5% of the rock, and are most visible where the rock has been partially altered to late sericite. The augite-phyric mafic dykes are cut by plagioclase-phyric mafic dykes (figure 3.37). The contacts between the plagioclase-phyric and augite-phyric mafic dykes are commonly indistinct, but the presence of 3-5% very fine, white, elongate plagioclase phenocrysts distinguish the former unit. The plagioclase phenocrysts are <2 mm long and <0.5 mm wide, and show flow alignment along the margins of the dykes (figure 3.38). The plagioclase-phyric mafic dykes are distinguished from the plagioclase porphyry by their finer grain, darker color, and less abundant phenocrysts.
Emplacement of the augite- and olivine-phyric mafic dyke with respect to the other mafic dykes is ambiguous due to the rarity of the olivine-bearing unit. Olivine forms 5-7% of the rock, as euhedral phenocrysts typically rimmed by bright red iddingsite (figure 3.39). Augite forms 2-3% of the rock as more subtle, blocky black phenocrysts in the dark groundmass of the dyke. The presence and preservation of olivine in these dykes suggests that the olivine-phyric dykes post-dated all hydrothermal activity except that responsible for the sericite-quartz-carbonate alteration assemblage (see Chapter 5).
Figure 3.39-Olivine-phyric mafic dykes. A; Variably-sized olivine phenocrysts; b; carbonate veins cutting olivine phenocrysts; c; olivine phenocrysts altered to dark red iddingsite; d; complex dyke margins.

Scale bar equals 1 cm.
Augite Porphyry

Unlike the mafic dykes described above the augite porphyry has a fine-grained, bright green groundmass with conspicuous, blocky, 2-3 mm black augite phenocrysts (figure 3.40). Direct cross-cutting relationships between the augite porphyry and aphanitic mafic dykes were not noted. The augite porphyry dykes have a notably different habit and distribution than the other dykes in the system; rather than being fairly planar or branching and steeply dipping, the augite porphyry dykes exploit or are exploited by fault surfaces (figure 3.41). They are irregular in width and orientation. Where observed in core, the dykes commonly display chilled margins on one edge, with gouge indicating reactivation of the other contact. On the basis of this unique habit, the augite porphyry dykes were assigned the latest timing in the igneous sequence.

Figure 3.40-Augite porphyry. Scale bar equals 1 cm.
In thin section, the augite porphyry consist of 60-70% fine-grained elongate plagioclase crystals, 25-35% large euhedral augite phenocrysts, and <5% small subhedral olivine phenocrysts (figure 3.42). The augite porphyry is distinctly coarser grained than the members of the mafic dyke family. Ross (2004a and b) noted that the augite porphyry is also chemically distinctive; this will be addressed in more detail below.
Figure 3.41b-Augite porphyry dykes on Section 29.
Figure 3.42-Photomicrographs of augite porphyry, showing polycrystalline augite phenocrysts in a dominantly plagioclase groundmass. A; monocry stalline and polycrystalline augite phenocrysts; note the two dominant orientations of the plagioclase grains in the groundmass. B; polycrystalline prismatic augite phenocryst, top right. Field of view 2.5 mm.

**Conclusions**

The intrusive rocks of the Northeast Zone appear to reflect a trend of increasing differentiation and increasing residence time culminating with the syn-breccia K-feldspar monzonite porphyry. Following brecciation and the intrusion of the syn-breccia K-feldspar monzonite porphyry, this trend is reversed, as the post-breccia dykes become increasingly mafic, hydrous, and fine-grained.
Chapter 4 - Characteristics of the Northeast Zone Breccia

Introduction

Magmatic-hydrothermal breccias

Hydrothermal and magmatic-hydrothermal breccias are common in porphyry copper deposits (Lowell and Guilbert, 1970; Gustafson and Hunt, 1975; Sillitoe, 1985; Laznicka, 1988; Corbett and Leach, 1996 and 1998). Depending on their timing relative to mineralization and the nature and genesis of the breccias, they can provide either preferential sites for mineralization and high-grade zones, or they can provide fluid barriers that retard movement of fluids, causing the ponding of mineralizing fluids adjacent to low-grade or barren zones (Burnham, 1979; Burnham, 1985; Sillitoe, 1985; Bushnell, 1988; Zweng and Clark, 1995; Serrano et al., 1996). Late breccia formation can dilute ore by mixing fragments of variably mineralized rock, or by erupting, venting potentially mineralizing fluids to the atmosphere and diluting the grade of the rock mass. Establishing those relations are important as breccia can have strong influences on distribution of metals and the economics of the deposit.

At Mount Polley, the relationship between breccia and economic mineralization is strong (Barr et al., 1976; Bailey, 1976; Fraser, 1993, 1994 a and b; Fraser et al., 1995; Read, 1997; Bailey, 2004a and b; Gillstrom, 2004; Rees et al., 2005 and 2006). Nearly all Cu-sulfide minerals are confined to breccia bodies, but not all areas within the breccia are mineralized (Fraser et al., 1995; Rees et al., 2005 and 2006). Understanding the interaction between brecciation and mineralization processes is important to distinguishing prospective from less prospective volumes of breccia, and to recognizing possible potential for economic mineralization in areas which may not show evidence for
Brecciation at present erosional levels (Burnham, 1979; Burnham, 1985; Sillitoe, 1985; Bushnell, 1988; Zweng and Clark, 1995; Serrano et al., 1996). Clarifying the origins and architecture of the breccia can also assist in structural reconstruction of the district as a whole, and to recognition of further mineral potential.

**"Classic" breccia-associated porphyry deposits**

Sillitoe (1985) estimates that 50-60% of porphyry orebodies are spatially related to breccias. These breccias take a variety of roles in the localization of ore. For example, pre- or syn-mineral breccia could have acted as a permeability control on fluid flow or a chemical trap, which caused deposition of ore and gangue minerals (e.g. the Maria breccia, La Cananea, Mexico (Bushnell, 1988)), or the formation of a breccia can drastically change the nature of the ore deposition environment (e.g. the collapse of the Louise Volcano at the Ladolam deposit, Lihir, Papua New Guinea (Mueller et al., 2002, Carman, 2003) and the Kelian deposit, Borneo (Davies, 2002; Davies and Cooke, 2000)). Conversely, a post-mineral breccia body could excise portions of the sulfide ore body system (e.g. the Braden pipe at the El Teniente deposit, Chile (Skewes et al., 2002, Cannell et al., 2005).

**Review of classification and processes**

Breccias are produced by a wide variety of geologic processes and combinations of processes (Laznicka, 1988). The formation of a breccia requires varying degrees of breakage, transport, comminution, and cementation (Jebrak, 1997). The processes involved can be sedimentary/diagenetic, volcanic, tectonic, magmatic, or hydrothermal (Davies, 2002). Even within the subset of hydrothermal, magmatic, and volcanic ore-associated breccias common in porphyry deposits, breccias have been defined and
classified via a wide variety of descriptive and genetic schemes (e.g. Bryner, 1961 and 1968; Sillitoe, 1985; Baker et al., 1986; Laznicka, 1988; McPhie et al., 1993; Taylor and Pollard, 1993; Corbett and Leach, 1998; Davies, 2002). Most schemes have been intended to discriminate between breccias formed by different genetic processes or combinations of processes. Some sources distinguish between processes of breakage, transport, and comminution, whereas others do not.

In order to comprehend the relationship between brecciation and mineralization, the process of “brecciation” is divided into four approximately sequential subprocesses (Jebrak, 1987):

I. Breakage
II. Transport
III. Comminution and sorting
IV. Cementation

In attempting to assign semi-quantitative parameters to these processes, conceptual work done by Burnham (1985) and Fournier (1999) on brecciation in calc-alkaline rocks was restated to consider the different physical, mechanical, and chemical properties of the silica-undersaturated rocks in which the Mount Polley breccias formed. Minimum prerequisites for brecciation are: 1) energy and 2) open space (Jebrak, 1997; Ross et al., 2001 a and b; Ross, 2002). Energy is consumed by fragmentation and creation of new surface area (fracture energy, or energy required to overcome the work strength of the rock), plasticity (friction) and elastic wave energy dispersion (Cummins and Given, 1973). Open space must be sufficient to accommodate the difference between the volume of the original rock mass and the volume of open packing of the fractured rock mass.
(Cummins and Given, 1973). This amount of open space probably never existed as single opening or in aggregate at any one point during breccia development. Instead the open space formed is filled via the bulking effect of rock mass fracturing nearly simultaneously (Locke, 1926).

**Descriptive classification**
Despite the abundance of literature on breccias and brecciation processes, no generally agreed upon descriptive terminology has emerged. For purposes of this study, the descriptive terminology advocated by Davies, (2002) has been slightly modified. Davies described breccias using five elements: alteration, internal organization, components, grain size, and body geometry. With minor changes, this convention will be followed here (Table 4.1).

The five elements can be further subdivided. Alteration includes pre-, syn-, and post-breccia alteration. Internal organization includes dilation, grading, and sorting. The components, which are most commonly described in breccia bodies, include clasts, clastic infill, chemical infill, and open space. Grain size involves both grain size and grain size range and size distribution. Body geometry describes both the shape of the overall breccia body and distribution of the other characteristic within that volume.
Table 4.1-Breccia Descriptive scheme

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<td>Grain size</td>
<td>Body Geometry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Body Geometry
   a. Geometry
      i. Pipe
      ii. Cone
      iii. Dyke
      iv. Irregular
      v. Tabular
   b. Orientation
      i. Strike and dip of principle axes
      ii. Strike and dip of irregular branches
   c. Contacts
      i. Sharp
      ii. Gradational
      iii. Irregular
      iv. Faulted
      v. Planar
   d. Contact relationships
      i. Concordant
      ii. Discordant

2. Grain size
   a. Mud (<1/16 mm)
   b. Sand (1/16 - 2 mm)
   c. Breccia / conglomerate
      i. Fine-grained (2 - 4 mm)
      ii. Medium-grained (4 - 64 mm)
      iii. Coarse-grained (64 - 256 mm)
      iv. Very coarse-grained (256 mm to 1 m)
      v. Megabreccia (>1 m)
   d. Grain size distribution
      i. Normal
      ii. Slightly bimodal
      iii. Extremely bimodal

3. Components
   a. Clasts
      i. Monomict or polymict
      ii. Lithology
      iii. Shape
         1. Angular, subangular, subrounded, rounded, tabular, faceted, equant
      b. Clastic infill
         i. Rock flour
         ii. Lithic fragments
         iii. Crystal fragments
         iv. Vein fragments
      c. Chemical infill
         i. Crystalline igneous rock
         ii. Chemical
            1. Mineralogy
            2. Paragenesis
            3. Texture
               a. massive
               b. layered
               c. drusy
               d. bladed
               e. cockade
      d. Open space or vugs

4. Internal Organization
   a. Dilation
      i. Crackle
      ii. Mosaic
      iii. Rotated
      iv. Transported

5. Alteration
   a. Clast alteration
   b. Matrix alteration
   c. Textural destruction
**Alteration**
Alteration in breccias may be pre-, syn-, or post-brecciation (Beane and Titley, 1981; Gustafson and Hunt, 1975; Lowell and Guilbert, 1970). Alteration may take different forms in clasts than in infill; it may form veins which either transverse or are truncated at clast margins (Davies, 2002). Alteration assemblages may rim clasts, or they may be confined to either clasts or infill, subject to differences in reactivity, surface area, and fluid residence time or reactivity (Gifkins et al., 2005). Also, as per normal in coherent rocks, alteration may be stable with respect to some mineral phases in a rock and destructive with respect to others (Gifkins et al., 2005; Barnes, 1997). Assigning a single alteration classification to a breccia may thus be inaccurate and uninformative. Alteration was not used as a major criterion for subdividing breccia units at Mount Polley; it is discussed as a separate characteristic of the rocks, as Chapter 5.

**Internal organization**
Davies (2002) defines the internal organization of the breccia as a number of subsidiary characteristics including clast abundance (clasts greater than or less than infill), clast distribution (in situ, rotated, or chaotic), graded or non-graded, and stratified or unstratified. At Mount Polley, mineralogy and alteration made clast/infill boundaries locally difficult to pinpoint, making clast abundance difficult to define. For this reason clast abundance was seldom quantified, but described qualitatively. Clast distribution, on the other hand, was found to merit more detailed subdivision. At Mount Polley a gradient was observed from intact ('coherent') country rock into chaotic, mixed and transported breccias (figure 4.1, Table 4.2). In order to capture this variability, breccias were described ranging from ‘crackle breccias’ (<1 mm infill between clasts,
jigsaw-fit, no visible rotation or transport), to 'mosaic breccias' (>1 mm infill between clasts, jigsaw fit clasts, no visible rotation or transport), rotated breccias (variable infill, visible rotation, but no mixing of clast types), chaotic breccias (variable infill, clasts cannot to be visually returned to their original positions, but all clasts represent a single rock type) and transported breccias (variable infill, clasts cannot be visually returned to their original positions and rock types are mixed) (Table 4.2).

These classifications are arbitrary, based on units which could be consistently defined from core-scale observations. Mixtures of clasts of the same rock type but different alteration types presents a problem. Differences in alteration between clasts may be related to variation in susceptibility to post-breccia alteration, or to the syn-breccia mixing of clasts from different zones of alteration. Grading and stratification are not observed at Mount Polley.

**Table 4.2-Breccia internal organization**

<table>
<thead>
<tr>
<th>BRECCA INTERNAL ORGANIZATION</th>
<th>Breccia type</th>
<th>%dilation</th>
<th>Infill</th>
<th>Alteration</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jigsaw</td>
<td>Crackle</td>
<td>&lt;5%</td>
<td>Chemical</td>
<td>Uniform</td>
<td>Monomict</td>
</tr>
<tr>
<td>Mosaic</td>
<td>5-10%</td>
<td>Chemical</td>
<td>Uniform</td>
<td>Monomict</td>
<td></td>
</tr>
<tr>
<td>Chaotic</td>
<td>Rotated</td>
<td>10-25%</td>
<td>Chemical or elastic</td>
<td>Uniform or mixed</td>
<td>Monomict</td>
</tr>
<tr>
<td>Transported</td>
<td>&gt;25%</td>
<td>Chemical or elastic</td>
<td>Mixed</td>
<td>Monomict or polymict</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.1-Breccia internal organization. A; crinkle breccia, b; mosaic breccia, c; rotated breccia, d; transported monolithic and e; transported polyolithic breccias. Scale bar =1 cm
Components
The components of the breccia are subdivided into clasts and infill. In the majority of breccia literature related to economic geology, infill is referred to as “matrix” without regard to its composition or origin (Bryner, 1961 and 1968; Sillitoe, 1985; Baker et al., 1986; Laznicka, 1988). Davies (2002) reserves the term “matrix” for clastic infill, and uses the term “cement” to denote chemically precipitated infill, in accordance with general practice in volcanology and sedimentology (McPhie et al., 1993). However, retention of a common term creates confusion. As such and to clarify the issue, infill is herein subdivided into open space, clastic infill, chemical infill, and igneous infill, avoiding the terms “matrix” and “cement” entirely. Open space preserved within breccias can be described on the basis of the size, percentage, and shape of voids or vugs. Clastic infill denotes material with a grain size of less than 2mm between clasts. This material is referred to elsewhere as rock flour matrix, milled matrix, hydrothermal sandstone, or ‘mud’ (Farmin, 1937; Emmons, 1938; Bryner, 1961 and 1968; Sillitoe, 1985; Baker et al., 1986; Laznicka, 1988; Kwak, 1990; McPhie et al., 1993; Taylor and Pollard, 1993; Serrano et al., 1996; Corbett and Leach, 1998; Davies, 2002; Jensen, 2003). The term ‘clastic infill’ is the most free of genetic connotation and potential confusion, especially in cases where there is no clear break between the grain size of the clasts and the grain size of the infill. Clastic infill also avoids confusion in situations where the material described includes lithic fragments, vein fragments, and crystal fragments. The texture of the clastic infill can also be described. Clastic infill can show laminated, graded, banded or draped textures (McPhie et al., 1993). It can be well or poorly graded, or massive (McPhie et al., 1993; Davies, 2002). At Mount Polley the great majority of clastic infill is massive. The grain size of the clastic infill is also an important characteristic, but this
becomes problematic when there is no clear size distinction between the clasts and the infill material. At Mount Polley, an arbitrary cutoff of 2 mm was selected. This decision will be discussed at more length below.

Chemical infill, also called cement, hydrothermal cement, or precipitate (Davies, 2002; Davies and Cooke, 2000; McPhie et al., 1993), involves any mineral that is precipitated by hydrothermal solutions in the spaces between settled clasts or onto the surfaces of clasts in suspension. In many cases, infill is an intimate mixture of clastic and chemical infill (figure 4.2). Chemical infill is described by mineralogy, paragenesis, grain size, habit (cockscomb, drusy, laminated, massive, etc.), just as it would be in a vein. At Mount Polley, where clastic and chemical infill are normally intermixed (figure 4.3) and where igneous infill is normally restricted to the margins of dykes cutting breccia, it was found to be useful to consider the three as end members of a ternary system (figure 4.4), thus separating igneous infill into its own category rather than including it within a broader ('cement') category.

Figure 4.2-Photomicrographs showing the intimate mixture of clastic and chemical infill. Field of view is 3.5 mm; a; reflected light, b; transmitted light with plane polars, and c; transmitted light with crossed polars. Note that the clastic infill includes both crystal and lithic fragments; the chemical infill is bornite.
Figure 4.3a-Breccia components, ranging from all clastic to all chemical infill. Scale bar is 1 cm.
Figure 4.3b-Breccia components, showing igneous infill and open space. Note the bladed textures of the silica (chalcedony?) infill in the lower sample. Scale bar equals 1 cm.

Figure 4.4-Ternary plot showing the relationship between clastic, chemical, and igneous infill. Shading indicates probable range observed in magmatic-hydrothermal settings. Samples shown in figure 4.3.
There is no consensus in the literature regarding methods for distinguishing silicate mineral infill from alteration (McPhie, et al., 1993; Barnes, 1997; Gifkins et al., 2005). Clastic infill can be modified by pre-, syn- or post-breccia alteration. Clasts and clastic infill can be modified by syn-breccia or post-breccia alteration, resulting in difficulty distinguishing clasts from infill, clastic infill from chemical infill, and pre- from syn- and post-breccia changes in mineralogy. Here, silicate infill, with a few exceptions clearly distinguishable as syn- and pre-breccia assemblages, is considered mostly under the heading of ‘alteration’. Modifications of clastic material, and chemical infill, which resulted from infiltration of fluids into the breccia after the breccia body had formed and settled, may be related to the same fluids that formed the breccia or to different ones, and thus should be considered alteration rather than primary breccia characteristics (Sillitoe, 1985; Barnes, 1997; Gifkins, 2005).

Description of the infill of the breccia lends crucial insight into the processes that formed the breccia, but description of the clast population is somewhat more ambiguous. Clast population reflects the original distribution of rock types in the body of rock disturbed by brecciation processes, the mixing or transport involved in those brecciation processes, and, for certain clast types, they can indicate the sources of energy or fluids, and in some cases the nature of fluid flow (Burnham, 1985; McCallum, 1985; Taylor and Pollard, 1993; Jebrak, 1997; Link et al., 2006; Mukherjee and Mishra, 2007). Clasts are described on the basis of range of lithology (monolithic vs. polyolithic), and clast lithology (rock types, vein fragment, breccia clasts, mineralized and altered clasts) (McPhie et al., 1993; Davies, 2002). Where the stratigraphy of the surrounding rock is well understood, the distribution of clast lithologies can be used to constrain the motion of clasts within the
breccia in striking precision (Bryant, 1968). Unusual clast types which are particularly
useful for genetic interpretation include accretionary lapilli, indicating high velocity gas
streaming, and juvenile magmatic clasts, identified by their globular, peperitic, or fluidal
clast shapes, which indicated juvenile magmatic input into the breccia (McPhie et al.,
1993; Davies, 2002). The morphology of the clasts can also be useful; it may be angular,
rounded, faceted, tabular or equant (Jebrak, 1997; Ross et al., 2001a and b; Ross, 2002).
The morphology of clasts may vary with rock type, due to the mixing of clasts which
have been transported different distances.

Grain size
The grain size of the breccia is an important, but problematic aspect of breccia
description. Average grain size is important, but grain size distribution and differences in
grain size between different lithologies also yield valuable information about brecciation
processes (figure 4.5). At Mount Polley, it was useful to identify if the distribution of
clast sizes was normal, meaning that there was no break in grain size distribution between
the smallest and largest clasts observed, or if it was bimodal, with two distinct clast size
populations. In some cases, the average clast size was different for some lithologies than
others. The presence of 'outlier' or 'outsize' clasts, or clasts substantially larger than the
average, was also noted. The distinction between clasts and clastic infill is ignored for
this descriptive tool, with clastic infill simply considered as a volume of < 2mm clasts.
Clast size distribution was determined by visual estimate, rather than by quantitative
means.
Figure 4.5-Normal (a), slightly bimodal (b), and extremely bimodal (c) grain size distributions. Scale bar equals 1 cm. All three samples have significantly smaller grain sizes than the average for the Northeast Zone breccia body.

**Geometry**

Davies (2002) emphasizes that understanding the geometry of a breccia body is very important to any determination of breccia genesis. Breccias can be pipelike, tabular, irregular, conical, vein-like or dyke-like (Sillitoe, 1985; Jebrak, 1997; Bryant, 1968; Bushnell, 1988; Ross, 2002). They can also be concordant or discordant. Where the top of a breccia is preserved it may be gradational or abrupt, domal, conical, convex, concave or planar (Sillitoe, 1985; Jacobsen et al., 1976; Norton and Cathles, 1968). Fluid escape structures may emanate from the tops of breccias in the form of veins, radial or concentric fracture networks, 'breccia dykes' or 'pebble dykes' (Farmin, 1934; Baker and Andrew, 1991; Gustafson and Hunt, 1975). A breccia can terminate downward into a
fault, a vein, or an intrusive body (Bushnell, 1988; Gustafson and Hunt, 1975; Norton and Cathles, 1973). The nature of the lateral contacts of the breccia is also informative. They may be gradational, abrupt, faulted, irregular, or planar.

General

Breccia geometry
The drill program at Mount Polley concentrated on the breccia body that hosts ore. Limited condemnation drilling was completed around the margins of the breccia body. From the data available, however, the breccia appears to be geometrically divisible into two segments (figure 4.6). The southern segment is fault-bounded, forming a discordant wedge defined by three major faults: the Green Giant Fault, the Brown Wall fault, and an inferred fault. The northern segment of the breccia appears to be conical, narrowing with depth and overprinted by post-breccia dykes. Whether or not this shape reflects the original geometry of the breccia body can not be confirmed.
Section 18 and Section 29 relative to the breccia body as a whole
The two cross-sections chosen for this project cut both segments of the breccia (figure 4.6, 4.7). Section 18 cuts the southern segment of the breccia at an azimuth of 120, intersecting both the Brown Wall fault and the Green Giant fault. Section 29 is parallel to section 18, cutting the northern segment of the breccia near its widest point.
Breccia types

Subunits within the breccia body were divided on the basis of clast populations, infill character, grain size, grain size distributions, clast shape, and internal organization. Clast populations were defined by ‘key clast types’ which are particular rock types concentrated within restricted volumes within the breccia body as a whole. Key clast
populations are the altered mafic clasts, and megacrystic porphyry clasts (see Chapter 2) (figure 4.8 and 4.9).

Figure 4.8-Distribution of altered mafic clasts on Section 29. No altered mafic clasts were observed on Section 18.
Infill character was divided into chemical infill only, chemical infill exceeding clastic infill, clastic infill exceeding chemical infill, and clastic infill only (figure 4.10). Chemical infill exceeding clastic infill dominated in section 29. Chemical infill only was most prevalent near the base of the preserved breccia body. Clastic infill and clastic infill greater than chemical infill dominated in the upper, western portion of the breccia.
Grain size and grain size distribution in the breccia is problematic, due to the fact that in much of the breccia, average clast size exceeds the diameter of the core. Thus, grain size estimates are approximate, and, in areas where grain size was considerably larger than core diameter, outsize clasts may significantly skew estimates. Alteration also complicates estimates of clast size. Where alteration was intense or texture destructive,
the margins of clasts are usually obscured. Excluding outsize clasts (clasts >2x core diameter), the average clast size is between 6 and 25 cm except in a discrete zone on the western side of Section 29 (figure 4.11).

Figure 4.11-<4 cm clast zone on Section 29.
Grain size distribution was normal, slightly bimodal, and extremely bimodal. In normal clast size distributions, there is no clear break in grain size between the largest and the smallest clastic fragments in the breccia. Bimodal clast size distributions are further subdivided into slightly versus extremely bimodal distributions. Slightly bimodal grain size distributions were those in which the two populations of grains were less than an order of magnitude different in mean grain diameter. For example, clasts averaging over 10 cm in diameter in clastic infill averaging less than 2 mm in diameter would be extremely bimodal, whereas a breccia with clasts averaging 4 cm in diameter in a clastic infill averaging 1 cm in diameter and grading smoothly down to <2mm would be classed as a slightly bimodal grain size distribution (figure 4.5). Extremely bimodal clast size distributions, with 6-25 cm clasts and <2mm matrix, dominated (figure 4.12), with a zone of normal clast size distribution in Section 29 and a transitional slightly bimodal zone between the two.
Clast shape was qualitatively assessed. Clasts were generally subrounded to subangular. Angular clasts were more common in the crackle and rotate breccia at the margins of the body, and rounded clasts more common in the fine grained portion of the body (figure 4.13).
The breccia was divided into crackle, mosaic, or rotated breccias, referred to collectively as non-transported breccias and transported breccias (figure 4.14). The majority of the breccia body is dominated by chaotic, polylithic breccias. The margins of the chaotic breccia were rotated with limited or absent transport, and the contact between the breccia and the coherent equigranular monzonite on its margins grades from mosaic to crackle.
breccia. Most mineralization originally described (Rees et al., 2005, 2006) as being hosted in monzonite is in fact hosted in the crackle breccia transitional between the chaotic breccia and the equigranular monzonite host rock.

Figure 4.14-Transported versus non-transported breccia units on section 29.
Margins and nature of margins of breccia body

Most margins of the breccia are truncated by faults or are intruded by post-breccia dykes. Where original breccia margins are preserved (drillholes WB-04-90 and WB-04-149), there is a gradation from coherent country rock to crackle breccia, mosaic breccia and into rotated, transported and chaotic breccias. The original breccia margins are poorly known overall, thus hindering a coherent view of the original volume and geometry of the body.

Breccia subunits

Based on the primary characteristics described above, the breccia body was divided into five major subunits (Figure 4.15, Table 4.3). The peripheral subfacies of the breccia consist of monolithic equigranular augite-bearing monzonite clasts, generally angular to subangular, with little infill. Clastic infill is far subordinate to chemical infill, clast size distribution is generally normal, and breccia internal organization ranges from crackle breccias to transported breccias. Clast size is varied.
Figure 4.15-Units within the Northeast zone breccia, Section 29.
### Table 4.3-Characteristics of breccia subunits.

<table>
<thead>
<tr>
<th>BRECCIA SUBUNITS</th>
<th>Unit</th>
<th>Internal organization</th>
<th>Clast size</th>
<th>Clast size distribution</th>
<th>Clast shape</th>
<th>Clast lithology</th>
<th>Infill</th>
<th>Contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic breccia</td>
<td>Jigsaw or rotated</td>
<td>2mm- &gt;1 m</td>
<td>Normal</td>
<td>Ang. to sub-ang.</td>
<td>Eq. Monz</td>
<td>Chemical</td>
<td>Grad.</td>
<td></td>
</tr>
<tr>
<td>Bilithic breccia</td>
<td>Transported</td>
<td>4-25 cm</td>
<td>Extremely bimodal</td>
<td>Sub-ang. to sub-rounded</td>
<td>Eq. Monz and mega. porphyry</td>
<td>Clastic to chemical</td>
<td>Grad.</td>
<td></td>
</tr>
<tr>
<td>Trilithic breccia</td>
<td>Transported</td>
<td>4-25 cm</td>
<td>Extremely bimodal</td>
<td>Sub-ang. to sub-rounded</td>
<td>Eq. Monz, mega. porphyry, and alt. mafic</td>
<td>Clastic to chemical</td>
<td>Grad.</td>
<td></td>
</tr>
<tr>
<td>Bimodal breccia</td>
<td>Transported</td>
<td>1-10 cm</td>
<td>Lith. dependent bimodal</td>
<td>Sub-ang. to sub-rounded</td>
<td>Eq. monz and mega. porphyry</td>
<td>Clastic&gt;chemical</td>
<td>Grad.</td>
<td></td>
</tr>
<tr>
<td>Fine grained breccia</td>
<td>Transported</td>
<td>1-4 cm</td>
<td>Normal</td>
<td>Sub-rounded to rounded</td>
<td>All lith.</td>
<td>Clastic</td>
<td>Grad.</td>
<td></td>
</tr>
<tr>
<td>Breccia units unrelated to the main breccia body</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vein breccia</td>
<td>Crackle to mosaic</td>
<td>&lt;2 cm</td>
<td>Normal</td>
<td>Ang.</td>
<td>All lith.</td>
<td>Chemical</td>
<td>Sharp</td>
<td></td>
</tr>
<tr>
<td>Fault breccia</td>
<td>Transported</td>
<td>&lt;1 cm</td>
<td>Normal</td>
<td>Ang.</td>
<td>All lith.</td>
<td>Clastic</td>
<td>Faulted</td>
<td></td>
</tr>
<tr>
<td>Igneous infill</td>
<td>Jigsaw to transported</td>
<td>&lt;1 cm</td>
<td>Normal</td>
<td>Ang. to round.</td>
<td>All lith.</td>
<td>F.g. igneous</td>
<td>Igneous</td>
<td></td>
</tr>
</tbody>
</table>

Lith=lithology, ang=angular, Eq. monz=equigranular monzonite, mega=megacrystic, f.g.=fine grained, grad=gradational

Inward from the monolithic breccias along the breccia margins, the bulk of the breccia body consists of polylithic chaotic breccia with subangular to subrounded clasts. This breccia contains at least 2-5% megacrystic monzonite clasts, locally grading into >90% megacrystic monzonite clasts. Clastic infill is subequal to or greater than chemical infill in Section 18, but chemical infill dominates over clastic infill in Section 29. Clast size distribution is extremely bimodal, with a clear gap in grain sizes between the <2 mm clastic infill and the 4-10 cm clasts. This breccia commonly contains outsize equigranular monzonite clasts.
The polylithic chaotic breccia with extremely bimodal clast size distribution grades into a polylithic chaotic breccia with a slightly bimodal clast size distribution, characterized by a normally distributed 4-20 cm megacrystic monzonite clast population in a normally distributed 2-20 mm polylithic clast population with up to 10% mafic clasts. This breccia subunit is observed only in section 29, where it is dominated by chemical infill.

The extremely bimodal breccia grades into a fine grained (clast sizes <2mm), polylithic chaotic breccia. Clast size distribution is normal, with no abrupt grain size change between clasts and clastic infill. The largest clasts in this breccia unit are smaller than the phenocrysts that define the megacrystic monzonite porphyry, but the presence of abundant broken K-feldspar crystals in the clastic infill suggests that megacrystic monzonite was present, but has been disaggregated beyond recognition. Mafic clasts form up to 15% of this breccia unit.

The fine-grained breccia unit appears to form a narrow, vertical sub-pipe within the overall breccia (J. Blackwell, pers.comm.), but the western margin of this body has not been drilled. Examination of Imperial Metals core logs indicates that the gradual nature of the fine-grained breccia to more 'normal' breccia transition observed in Section 29 is consistently observed around the body. This gradual transition suggests that the fine-grained breccia subunit is not a separate pipe cutting the main breccia body.
Infill
In addition to distinguishing between clastic and chemical infill, infill mineralogy and paragenesis also lend insight into the nature and origin of the breccia and the fluids which formed it and which pervaded it after formation. Infill mineralogy, however, straddles the space between primary brecciation features and the alteration features which modified the breccia after its development. Particularly where texturally destructive alteration modifies both clasts and clastic matrix, the original nature of the infill is impossible to determine.

Chemical infill types were distinguished on the basis of the most volumetrically significant mineral component. A broad overview of alteration mineralogy and distribution is provided here, as is relevant to the development of the breccia body; a more comprehensive description and analysis is provided by Pass et al. (2007).

Carbonate
White and pink carbonate (calcite, dolomite, and rhodocrosite) infill is a common late component of vein breccias (figure 4.16) overprinting the main breccia body and filling relict open space in the breccias. These late minerals commonly exhibit bladed textures. Carbonate infill was more pronounced in section 18 than in section 29. In thin section, carbonate was observed intimately mixed with gypsum. In a few cases, carbonate was observed as infill in the main-stage breccias, pre-dating or coeval with sulfides. Sulfides were observed on the contact between carbonate and gypsum infill (WB-04-32 212.23).
Chlorite
Chlorite is the most common infill mineral in the peripheral subunit of the breccia. It forms very fine-grained green to green-brown infill in crackle breccias. Chlorite infill is most common in the upper and peripheral portions of section 29 (figure 4.17). In thin section, chlorite is the most common product of the alteration of mafic minerals, particularly augite, and is also observed as rims on amygdales in coherent monzonite.
Figure 4.17-Chlorite infill on Section 29.

**Biotite**

The transition between chlorite and biotite infill in the breccias is subtle. The dark green color of the fine grained phyllosilicate infill becomes dark brown, and the overall color of the breccia becomes darker. Some caution must be exercised with the biotite infill, because in case where the breccia has been subject to K-feldspar flooding, clasts are commonly altered to biotite. Distinguishing biotite infill from biotite altered clasts, or
biotite altered rims on clasts, is locally difficult. Biotite infill occupies the bulk of section 29, and is coincident with the majority of sulfide mineralization (figure 4.18).

Figure 4.18-Biotite infill on section 29.
**Sulfide**

Sulfide is the most common infill mineral, especially in section 18. Sulfide assemblages can also be subdivided by sulfide mineralogy into chalcopyrite only, chalcopyrite-bornite, chalcopyrite-magnetite, and magnetite-pyrite assemblages (figure 4.19).

*Figure 4.19-Sulfide infill on section 29.*
Magnetite is the earliest mineral in the ‘sulfide’ paragenesis (figure 4.20a-d). It is commonly replaced by chalcopyrite (figure 4.20a), and less commonly by pyrite (4.20b-d). Where magnetite, pyrite, and chalcopyrite are present together, magnetite is replaced by pyrite and pyrite is replaced by chalcopyrite (figure 4.20c). Primary pyrite is less common (figure 4.20e). Bornite is not observed directly replacing magnetite. Where bornite and chalcopyrite co-exist, cusp-and-caries textures show chalcopyrite replacing bornite (figure 4.20g) and exsolution textures (figure 4.20f) indicating that the two minerals are co-eval. In rare cases, especially associated with sericite-carbonate alteration as described below, both chalcopyrite (figure 4.21h) and bornite (figure 4.21i) are replaced by chalcocite. Chalcocite is not abundant enough to contribute to the grade of the orebody, but their presence indicates remobilization of Cu or a late increase in the sulfidation state of mineralizing fluid.

Paragenesis of the sulfide minerals and magnetite is discussed in the context of alteration, brecciation, and intrusion events in Chapter 5.
Figure 4.20—Photomicrographs of magnetite and silicate infill. A; Two generations of magnetite (euhedral and as anhedral overgrowths; overgrown and surrounded by chalcopyrite. B; magnetite and pyrite overgrown by chalcopyrite. C; magnetite replaced by pyrite replaced by chalcopyrite. D; magnetite fractured and infilled with pyrite, replaced by chalcopyrite E; primary pyrite fractured and infilled with chalcopyrite; sketch at right shows textural relationship. F; Exsolution textures in chalcopyrite and bornite. G; cusp-and caries textures showing chalcopyrite replaced by bornite. Mt= magnetite, cp=chalcopyrite, py=pyrite, bn=bornite, sil=silicate. Except as noted, field of view is 2.5 mm.
Magnetite
Locally within the breccia, magnetite is the dominant or the only infill mineral (figure 4.19). In contrast with the physically separate magnetite breccia described by Fraser (1995), the magnetite breccias in the Northeast zone form an infill-based subfacies of the main body, with no distinctive differences in clast type or geometry. In thin section, magnetite infill, as distinct from magnetite-constructive alteration, is observed rimming clasts and intimately mixed with clastic infill (figure 4.22).
Figure 4.22. Photomicrographs of magnetite infill in transmitted light with plane polars (left) and reflected light (right). Note the complex clast boundaries. Field of view 2.5 mm.

**Silicate infill**

Three distinct infill types may reflect primary hydrothermal infill or post-breccia modification of infill by alteration processes. These assemblages are albite-actinolite, albite-epidote, and K-feldspar. Albite-actinolite infill is restricted to a narrow zone within the fine-grained breccia in Section 29 and to areas in Section 18 on the west side of the Green Giant fault. Albite-epidote assemblages are observed deep in Section 29, and K-feldspar infill forms a tabular zone between biotite and albite-epidote assemblages in Section 18 and a restricted zone in the center of Section 18, coinciding with the zone of highest megacrystic clast concentration (figure 4.23).
Discussion of breccia features

The fairly uniform clast lithologies and gradational contacts between breccia subunits suggest that the Northeast Zone breccia body at Mount Polley reflects a single brecciation event (Rees et al., 2005 and 2006; Logan and Bath, 2006; McPhie et al., 1993). The lack of variation in clast lithologies between breccia subunits, and the lack of clasts of breccia in breccia or mineralized clasts, reinforces this hypothesis. Given that
the breccia represents a single event, variation in sulfide mineralization within the breccia body suggests a secondary control on mineralization. The highest grades are present in zones:

I. Where chemical infill exceeds clastic infill
II. Where clast transport was significant (mixing of lithologies)
III. Close to the highest concentration of megacrystic porphyry clasts
IV. Close to the transition between biotite and K-feldspar infill assemblages

The first and second controls are explained by permeability; mineralization occurred in the most permeable zones within the breccia body (Emmons, 1906; Davies, 2002). The third control suggests that the megacrystic porphyry was the originator of the mineralizing fluids as well as the initiator of brecciation (McPhie et al., 1993; Tosdal et al., 2008). The last control is chemical and thermal, based on the evolution of the mineralizing fluid as it infiltrated the breccia body (Gifkins et al., 2005; Barnes, 1997).

If the mineralization is both syn-breccia and controlled by permeability established by the internal structure of the breccia, then the actual process of brecciation must be examined in more detail. Brecciation cannot be dealt with as a single, instantaneous event, but as a series of sequential processes separated in space and time (Burnham, 1985; Fournier, 1999; McCallum, 1985; Zweng and Clark, 1995; Yang et al., 2007). The first prerequisite for brecciation is hydraulic or hydrothermal fracturing (Fournier, 1999; Burnham, 1985; Gonnerman and Manga, 2003; Bonafede and Danesi, 1997, Engvik et al., 2003 and 2005).

Hydrothermal fracturing occurs when a volume of rock is subjected to fluid pressure in excess of the lithostatic load and the tensile strength of the rock (Li, et al.,
2002, Lockner, 1995; Krech, 1973). Fluid overpressure can develop in a variety of ways (table 4.4), including continuous input of fluid within the rigid carapace of a cooling intrusion (Burnham, 1985), or onset of hydraulic conductivity between deeper and shallower lens-like fluid pockets of reservoirs (Fournier, 1999). Rapid spikes in fluid pressure can occur as the result of tectonic processes (Husen et al., 2004; Manga and Brodsky, 2006). Overpressure can also be induced by sudden evolution of volatiles from a melt, induced by disequilibrium degassing (Mangan and Sisson, 2000) or by injection of mafic material into a felsic magma chamber (Sparks et al., 1977 and 1993; Eichelberger, 1980; Pallister, 1992; Murphy et al., 2000; Gerbi et al., 2004; Keith et al., 1998).
### Table 4.4-Mechanisms for triggering a hydraulic overpressure

<table>
<thead>
<tr>
<th>Source of overpressure</th>
<th>Locality</th>
<th>Result</th>
<th>Reference</th>
<th>Deposit type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloading via mass wasting</td>
<td>Ladolam</td>
<td>Transition from porphyry to epithermal</td>
<td>Carman, 1994; Gemmell et al., 2004; Moyle et al., 1990</td>
<td>Alkalic Cu-Au porphyry/epithermal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mount St. Helens</td>
<td></td>
<td>Eruption</td>
<td>Dzurisin et al., 1983</td>
<td>Stratovolcano</td>
</tr>
<tr>
<td>Injection of mafic material into felsic magma</td>
<td>Mt. Pinatubo, Montserrat</td>
<td>Eruption</td>
<td>Pallister, 1992; Murphy et al., 2000; Eichelberger, 1980; Gerbi et al., 2004; Keith et al., 1998</td>
<td>Stratovolcano</td>
</tr>
<tr>
<td>chamber</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seismicity triggered by distant earthquake</td>
<td>Yellowstone, Long Valley</td>
<td>Fluid overpressure in a meta-stable hydrothermal system.</td>
<td>Manga and Brodsky, 2006; Husen et al., 2004; Roeloffs et al., 2003</td>
<td>Active geothermal system</td>
</tr>
<tr>
<td>connectivity of fluid lenses</td>
<td>Theoretical</td>
<td>Stockwork and breccia formation</td>
<td>Fournier, 1999; Cline and Bodnar, 1994; Bagdassarov, 1994</td>
<td>Many</td>
</tr>
<tr>
<td>Accumulation of fluid within a cooled carapace</td>
<td>Penasquiera</td>
<td>Lens shaped accumulations of hydrothermal minerals</td>
<td>Kelly and Rye, 1979; Lange, 1994</td>
<td>Sn-W granitoid</td>
</tr>
<tr>
<td>Collapse of fluid-supported arch</td>
<td>Questa</td>
<td>Tabular-clast breccia</td>
<td>Ross, 2001 a and b, 2002; Cline and Bodnar, 1994</td>
<td>Porphyry Mo</td>
</tr>
<tr>
<td>Magma withdrawal</td>
<td>Questa</td>
<td>Tabular-clast breccia</td>
<td>Ross, 2001 a and b, 2002; Cline and Bodnar, 1994</td>
<td>Porphyry Mo</td>
</tr>
<tr>
<td>Mineral self-sealing</td>
<td>Many</td>
<td>Mineral deposition</td>
<td>Fournier, 1983; Beane and Titley, 1981</td>
<td>Many</td>
</tr>
</tbody>
</table>
Fracturing occurs when the overpressure exceeds the sum of the lithostatic load and the tensile strength of the rock mass (Fournier, 1999; Li et al., 2002; Pollard, 1998). The potential energy of the overpressure is expended via the creation of new surface area, friction (plasticity) and elastic wave energy dispersion (Li et al. 2002; Atkinson, 1987; Krech, 1973). Fracture network development, especially to the point of hydraulic conductivity, is much easier in already jointed rock (Gillou-Frottier and Burov, 2003; Janssen et al., 2001; Broek, 1982; Broberg, 1999; Boone, 1986; Pollard, 1979; Cloos, 1955).

Where these fractures become hydraulically contiguous, a fluid flux can be established, with fluid flow driven by thermal buoyancy, tectonic or hydraulic pumping, and fluid expansion via first and second boiling (Burnham, 1979; Brodsky et al., 2003). When hydrothermal fracturing is accompanied by loss of volume (via hydrothermal dissolution or magma withdrawal) or the presence of available free space (i.e. breach to the surface, regional extension, or doming), rotation of fragments becomes possible (Davies, 2002; Burnham, 1985; Segall, 1984; Pollard et al., 1983; Sillitoe and Sawkins, 1971). At this point in the development of a system of hydraulically contiguous fractures, the system can form a hydrothermal breccia (Sillitoe, 1985; Burnham, 1985; Beane and Titley, 1981).

The point at which a hydrothermal stockwork becomes a hydrothermal breccia is poorly defined in the literature. The establishment of hydraulic conductivity between fractures may be the most appropriate stage to which to assign the onset of brecciation, but for practical purposes of field identification, rotation or transport of fragments may be easier to establish (Davies, 2002; Taylor and Pollard, 1993; Bryant, 1968).
Where void space exceeds 25.4% (depending on fragment geometry), the fractured rock mass can flow (Bryant, 1968). In the case of a hydrothermal breccia, which is inferred to be a relatively closed system with respect to clasts, but an open system with respect to fluids, ‘flow’ refers to the ability of clasts to move relative to each other, and to mix or segregate in accordance with three-phase fluid dynamics (Yang et al., 2008; Mukherjee and Mishra, 2007; Link et al., 2006; Wolfe, 1980). When flow is established, the solid mass mimics the behavior of a fluid and enabling the transport and mixing of fragments (Bryant, 1968). When the upward fluid flux exceeds the settling rate of the fragments, as a function of the fluid viscosity, fragment shape and density, and the presence and bubble size of a gas phase, fluidization can occur (Yang et al., 2008; Mukherjee and Mishra, 2007; McCallum, 1985). Fluidization enables the sorting of fragments by size (fines segregation), spouting and channeling within the fluidized pipe (Link, et al., 2007; Mukherjee and Mishra, 2007; McCallum, 1985). Fluidization, especially in a gaseous or low-viscosity medium, facilitates impact and abrasion between fragments (Link et al., 2007; Kennedy et al., 2005). The upward motion of the fluid medium, results in plucking of grains from the fragment rims, also resulting in rounding, attrition and comminution of fragments. This process is enhanced if the fluid medium is corrosive (Gonnerman and Manga, 2003; Carlson and Sawkins, 1980; Emmons, 1906).

Fragment size reduction is also aided by mutual impact between particles. Due to decreased drag forces on particles, mutual impact is a more effective mechanism for fragment size decrease when the fluid is gaseous rather than liquid (Yang et al., 2007; Alidibirov and Dingwell, 1996a and b; Anderson, 1991). Attrition and comminution create a positive feedback loop with fluidization; fluidization is dependent on fragment
size and on the viscosity of the fluid medium (Yang et al., 2008). Attrition and comminution both decrease fragment size and increase effective fluid viscosity by the addition of fines; the fluid becomes slurry as opposed to a simple fluid (Mukherje and Mishra, 2007). Accretionary lapilli may form in hydrothermal pipes, as a result of accretion of fines in a fluidized state (Davies, 2002, Gofton, 2007; McPhie et al., 1993).

Upward fluid flux also results in the sorting and mixing of clasts. Mixing and segregation are dependent on clast size, clast density, and the velocity of fluid flux (Mukherjee and Mishra, 2007); both mixing and segregation can occur in the same particle bed dependent on fluid flux velocity (Mukherjee and Mishra, 2007).

After the upward fluid flux velocity declines and particles settle back through the fluidization threshold, the sorting of particles becomes ‘locked’ (Yang et al., 2008). The zones in which fines were concentrated became zones of decreased permeability, ‘choked’, with all potential open space between the larger clasts occupied by fine grained clastic infill. In zones where the fines are depleted, ‘stripped out’, abundant open space between larger clasts will be available for the subsequent mineral deposition (Davies, 2002).

Aside from the availability of open space for sulfide deposition, the major prerequisite for the deposition of porphyry mineralization in the breccia is the failure of the breccia to breach directly the surface (Holliday and Cooke, 2007; Skewes et al., 2002; Cannell et al., 2005; Sillitoe, 1985). The breach of the breccia to the surface creates a diatreme, venting mineralizing fluids directly to the atmosphere without allowing adequate residence time in the fractured mass for sulfides to precipitate (Cannell et al., 2005; Emmons, 1938).
Mineralization in close proximity and directly above the highest concentration of megacrystic clasts indicates a direct relationship between mineralizing fluids and to disaggregated megacrystic dykes. The juvenile nature of the megacrystic clasts indicates that the megacrystic dykes were the breccia initiator, and relationship between the megacrystic clasts and the mineralization indicates that the megacrystic dykes were the source of the mineralizing fluids. However, the permeability control of breccia subunits on sulfide deposition suggests that sulfide deposition did not occur, or did not occur in quantity, until after the fluidized breccia mass had settled. The fluid evolution which makes the deposition of breccia cement from the same fluid responsible for fracturing the rock mass is discussed in Chapter 6.
Chapter 5-Alteration

Introduction

Primary breccia features record the energetics of the hydrothermal flux responsible for fracturing and rearranging the rock mass (Laznicka, 1988). Alteration, and especially the timing of alteration relative to the stages of breccia development, records the chemical evolution of the hydrothermal fluid before, during, and after brecciation (Gifkins et al., 2005; Barnes, 1997; Lowell and Guilbert, 1970; Meyer and Hemley, 1967). The single episode of brecciation at Mount Polley, and the genetic link between brecciation and mineralization, results in relatively simple alteration zoning.

Alteration in the Northeast zone can be divided into pre-, syn-, and post-breccia types (figure 5.1). Pre-breccia alteration is recognized by the uniform alteration of clasts, veins and vein selvages which are truncated at clast margins, and by clasts of different alteration types juxtaposed in the breccia. Syn-breccia alteration is recognized by altered rims on clasts, veins which originate in the breccia chemical infill but penetrate clasts, and alteration which modifies clastic infill but not the clasts themselves. Post-breccia infill alters clasts and clastic infill uniformly and may be breccia-texture destructive. Post-breccia alteration also modifies post-breccia dykes, and the timing of these events is constrained by the dykes (Fraser et al., 1994 a and b; Fraser, 1995).
Figure 5.1 - Timing of alteration versus brecciation. No scale is presented; these structures are fractal. Pre-breccia alteration: a- Veins truncated by clast margins, b-Clasts of mixed alteration types, c-Broken altered clast rims. Syn-breccia alteration: d-Altered clast rims, e-Hydrothermal minerals armoring clasts, and syn-breccia veins, f-Hydrothermal mineral infill. Post-breccia alteration: g-Veins cross-cutting breccia textures, h-Hydrothermal minerals occupying re-opened breccia, i-Clasts of breccia in breccia, or vein fragments in breccia.

The relationship between infill, as described above, and alteration can be ambiguous, as can the relationship between syn- and post-brecciation processes. The ambiguity and complexity of this relationship is discussed in Chapter 4. For purposes of breccia description here, the ‘syn-breccia’ period is defined as the period from the development of a hydraulically contiguous fracture network through clast movement and potentially fluidization, until the mass has settled and been cemented with the first generation of chemical infill. This description is predicated on the assumption that there was no extended period of quiescence with unfilled permeability or open space within the
breccia between the settling of the mixed bed and mineralization, and places the end of the syn-breccia period at the point at which the breccia begins to behave as a rheological unit, rather than as a particle bed.

**Pre-breccia Alteration**

Pre-breccia alteration is widespread and pervasive in the Mount Polley system. Due to the lack of drilling information outside the mineralized system, the lateral and vertical extent of pre-breccia alteration is unknown. Pre-breccia alteration can be pervasive or restricted to veins and vein haloes, but the pre-breccia nature of the alteration can be determined by alteration restricted to breccia clasts or truncated by clast margins.

**Altered mafic clasts**

As discussed in Chapter 2, the most distinctive pre-breccia alteration is the alteration of the 'altered mafic clasts'. These clasts have been subject to texturally destructive albite- and actinolite-forming alteration of the groundmass, cut by magnetite veins with pink feldspar haloes. This overprint renders the clast protolith indistinct. The alteration style is not observed in coherent rocks, making it difficult to place the clasts in stratigraphic context, although the clustering of the clasts within the breccia suggests that the unit may have had an originally tabular geometry, somewhat disrupted by subsequent brecciation. The most distinctive feature of these rocks is the presence of magnetite and K-feldspar veins in a mottled, dark grey-green grundmass. These veins are truncated by clast margins (figure 5.2).
Figure 5.2-Altered mafic clast within the breccia; some magnetite has been replaced by chalcopyrite after the inclusion of the clast in the breccia. The magnetite vein is truncated by the clast margin, showing that the vein pre-dated fragmentation.

**Hematite-carbonate**

The most widespread pre-breccia alteration was a K-feldspar-stable hematite-carbonate alteration. Nearly all clasts in the breccia and much of the surrounding coherent monzonite was subject to this alteration, which resulted in a ‘dusting’ of hematite, lending the rock a pink to red-orange coloration. Wherever this red coloration was observed, the rock is also pervaded by small (<1 mm) clots and blebs of calcite (figure 5.3a and b).
Figure 5.3a-Hematite staining on pre-breccia monzonite. Hole WB-04-32, 111 m; Scale bar equals 1 cm. Veins are calcite (left) and chalcopyrite (right).

Figure 5.3b-Photomicrographs of “equigranular” monzonite. Note the hematite deposited along grain boundaries and interstitial calcite. The veins cutting all four samples are also calcite. A; note the replacement of mafic minerals by chlorite and opaque minerals. B; Carlsbad-twinned K-feldspar phenocryst rimmed with hematite (center), and partially hematite stained K-feldspar phenocryst (lower left). C; less intense hematite-staining. D; hematite staining on phenocryst rims and preferentially replacing domains within phenocrysts. Each FOV=5mm.

Hematite-carbonate alteration is also observed in the equigranular augite-monzonite, K-feldspar and K-feldspar-plagioclase porphyry dykes that cut the breccia. It
is observed less strongly in the hornblende-bearing monzonite dykes, and is absent in the plagioclase microporphyry or mafic dykes. In the K-feldspar porphyry dykes, the margins of the dykes are in some cases strongly reddened by hematite-carbonate alteration while the interiors of the dykes are not (figure 5.4). This suggests that the hematite dusting and carbonate is a secondary, fluid-related modification of the igneous rocks, rather than related to magma characteristics. The hematite-carbonate alteration is most evident modifying the feldspar site in the affected rocks. Mafic minerals in rocks affected by hematite-carbonate alteration are generally replaced by chlorite.

Figure 5.4-Grey interior (a) and red exterior (b) of the same crowded K-feldspar porphyry dyke. Scale bar equals 1 cm.

In most cases where the rock is modified by syn- and post-breccia alteration, some sign of relict hematite-carbonate mineralization remains, suggesting that the alteration was uniform throughout the Northeast zone prior to brecciation.
**Biotite-magnetite**

Biotite-magnetite alteration, as described here, applies mostly to the mafic xenoliths incorporated into the pre-breccia equigranular monzonite. Some of this alteration may be the product of reaction between the mafic xenoliths and the magma into which they were incorporated, as evidenced by the rimmed xenoliths (see figure 3.4). The xenoliths, which were probably originally dominated by pyroxene, are replaced by a texturally destructive combination of biotite and magnetite (figure 5.5).

![Figure 5.5-Biotite-magnetite alteration of a pre-monzonite xenolith. Plane and crossed polars. FOV=1 cm](image)

**Chlorite**

The mafic sites in rocks modified by pre-breccia hematite-carbonate alteration were generally replaced by polycrystalline chlorite. Mafic minerals are still recognizable based on the shapes of the mineral sites. Chlorite completely pseudomorphs blocky, square mineral sites (originally augite), and elongate mineral sites (originally hornblende). Rare secondary biotite is also present. The euhedral nature of the pseudomorphs suggests that the mafic minerals were directly altered to chlorite, rather than being altered to secondary biotite, then to chlorite, which would result in more diffuse, irregular pseudomorphs.
**Syn-breccia Alteration**

Syn-breccia alteration is widespread in the Northeast zone, but is more difficult to recognize than the pre-breccia alteration.

**Chlorite**

Syn-breccia chlorite alteration and chlorite chemical infill are difficult to distinguish. Chlorite chemical infill is distinguished by fine, inward-pointing chlorite crystals nucleated along clear, well-defined clast margins (figure 5.6). Chlorite infill is frequently the only infill in crackle breccias, and usually completely surrounds clasts even where they are in direct contact with other clasts. Chlorite alteration, on the other hand, forms very thin rims or rinds on clasts, resulting in indistinct clast margins where the outer 1 mm edge of the clast has been replaced by chlorite (figure 5.7). Chlorite alteration is mostly observed in the shallow and peripheral parts of the breccia (figure 5.8).

![Figure 5.6-Chlorite infill followed by chalcopyrite infill; WB-03-14-88m; Scale bar equals 1 cm.](image)
Figure 5.7-Chlorite-altered clast margin (green, top left) against K-feldspar altered infill (brown, bottom right); crosscut by late calcite vein (white, center). WB-04-32, 125.5 m FOV 2.5 mm.
Biotite

Syn-breccia biotite alteration occupies the bulk of the breccia in the Northeast zone (figure 5.9), where it overprints the pre-breccia hematite-carbonate alteration, giving the rock a dark brown cast. Unlike chlorite alteration, biotite alteration forms distinct 1-2 cm rims on clasts and occasionally overprints clasts entirely. Biotite alteration predated K-feldspar flooding (see below) as biotite-altered ‘ghost’ clasts survive within pervasive, texturally destructive K-feldspar alteration (figure 5.10). Biotite alteration is directly
spatially associated with sulfide mineralization, but chalcopyrite-bearing veins with K-feldspar haloes crosscut biotite-altered clasts (figure 5.11)
Figure 5.10-Biotite altered relict clasts in pervasive K-feldspar flooding. Scale bar equals 1 cm.

Figure 5.11-Chalcopyrite veins with K-feldspar haloes crosscutting biotite-altered clasts. WB-04-133, 310.4m. Scale bar equals 1 cm.
Sulfide replacement

In local regions of the breccia, the combination of a high percentage of mafic clasts and the presence of mineralizing fluids resulted in the replacement of mafic clasts by chalcopyrite (figure 5.12). This local relationship is the only evidence of chemical control on ore distribution at Mount Polley by wall-rock reactivity. Areas of replacement of mafic clasts are commonly high grade, but they are small and restricted such that they contribute little to the overall grade and tonnage of the mineralized body.

![Figure 5.12-Mafic clasts replaced by chalcopyrite. Scale bar equals 1 cm.](image)

K-feldspar

The origin and timing of the texturally destructive K-feldspar "flooding" observed in both section 18 and 29 is somewhat obscure. K-feldspar flooding post-dates biotite alteration related to sulfide deposition in most cases, but in other cases sulfide deposition appears to post-date K-feldspar. The K-feldspar flooding forms a ‘blanket’ at depth in section 29, and a ‘bulb’ in the heart of section 18 (figure 5.13). In rocks affected by this alteration, the infill of the breccia is completely or almost completely replaced by a uniform, monomineralic zone of salmon-pink K-feldspar. This alteration post-dates the biotite alteration as surviving clasts replaced by biotite are visible within the K-feldspar alteration. In megacrystic monzonite porphyry clasts, the K-feldspar phenocrysts survive within diffuse biotite aggregates largely destroyed by subsequent K-feldspar flooding.
(figure 5.14). The K-feldspar flooding pre-dates and is overprinted by albite-epidote alteration at depth (figure 5.15). All of these textures might indicate that K-feldspar flooding was post-breccia, but the presence of K-feldspar rims on some clasts (figure 5.16) suggests a syn- to late-breccia timing. Likewise, the spatial relationship between K-feldspar flooding and ore (the highest grades in section 29 coincide with the upper 1/3 of the K-feldspar alteration), suggests a syn- to late-breccia provenance. Bornite mineralization appears to post-date K-feldspar deposition. In some areas, anhydrite is also present within and immediately above the K-feldspar flooded zone.
Figure 5.13—Silicate alteration on Section 29. Note the relationship between K-feldspar alteration and bornite mineralization.
Figure 5.14 - Biotite-altered relict clasts in pervasively K-feldspar altered infill. Scale bar equals 1 cm.

Figure 5.15 - Albite-epidote alteration (grey) overprinting K-feldspar alteration (orange) overprinting biotite alteration (brown). Scale bar equals 1 cm.

Figure 5.16 - K-feldspar rims on biotite-altered clasts. Scale bar equals 1 cm.
Magnetite

Magnetite alteration forms a blanket at depth in Section 29, with a distinct upward extension coinciding with the central portion of the fine-grained breccia subunit (figure 5.17). Magnetite alteration pre-dates sulfide deposition; magnetite is paragenetically early and replaced by chalcopyrite where they occur together (figure 5.18). Magnetite and bornite seldom coexist, and where they do, magnetite is extremely corroded; thin laths of what appear to be specular hematite do occur with bornite (figure 5.19). Magnetite alteration is overprinted by both K-feldspar and albite-epidote alteration. Where it is overprinted by albite-epidote alteration, magnetite is replaced by pyrite (figure 5.20). The nature and timing of magnetite alteration with respect to post-breccia albite-actinolite alteration (described below) is unknown as the two alteration assemblages have yet to be seen in contact. As both alteration styles are early and reflect high-temperature processes, they are assumed to be relatively coeval.
Figure 5.17-Magnetite and sulfide infill on Section 29.
Figure 5.18-Magnetite replaced by chalcopyrite. WB-04-14 99 m; scale bar equals 1 cm.

Figure 5.19-Hematite lath (center) occurring with bornite and chalcopyrite. WB-04-29 117.8 m. Field of view 1 mm.
Albite-actinolite

Albite-actinolite alteration is, at least as far as it is preserved, the least volumetrically significant of the syn-breccia alteration assemblages (figure 5.13). Albite-actinolite alteration is best preserved in the fine-grained breccia. This is unusual in that none of the other syn-breccia alteration types are well developed in the fine-grained breccia. Actinolite alteration is commonly developed as actinolite rims on clasts, with albite replacement of K-feldspar on clast rims and sometimes in the interior of clasts. Clastic infill is commonly completely replaced by albite and actinolite (figure 5.20). In some cases, actinolite alteration coincides with extremely high Cu-Au grades at the bases of the breccia (figure 5.21).

To the west of Section 18, an area of albite and actinolite alteration is interpreted as being related to the structurally deeper and temperature ‘Leak Zone’ area of low-grade mineralization, juxtaposed with the shallower Northeast zone by the Green Giant Fault (figure 5.22). Much of the albite-actinolite alteration related to this zone forms psuedobreccia textures, but some of it may be a texturally destructive overprint on a true breccia, with relict K-feldspar altered clasts (figure 5.23). Unlike the albite-actinolite alteration in the Northeast zone, which is associated with high-grade mineralization or with barren zones, the albite-actinolite mineralization in this zone contains small amounts of chalcopyrite, nowhere exceeding 1% of the rock.
Figure 5.20-Albite-actinolite alteration overprinting K-feldspar alteration (WB-04-73, 14.4 m) Scale bar equals 1 cm.

Figure 5.21-Biotite-altered clasts with K-feldspar rims and albite-actinolite altered clastic infill associated with bornite and chalcopyrite chemical infill, WB-04-189, 315 m. Scale bar equals 1 cm.
Figure 5.22-The Northeast Zone. The Leak Zone is located south and west of Section 18; Leak-zone style alteration was encountered in hole WB-04-73, WB-04-26 and WB-04-27.

Figure 5.23-Albite-actinolite alteration overprinting K-feldspar altered clasts. WB-04-28 38.2 m. Scale bar equals 1 cm.
**Post-breccia alteration**

**Sulfide replacement in coherent rocks**
In some coherent rocks intruding the breccia, sulfides are present as blebs occupying former mafic sites within the rock (figure 5.24). The blebs are commonly associated with <1 mm white albite veins. Chalcopyrite is most common. Pyrite is commonly disseminated in the K-feldspar and K-feldspar and plagioclase phyr: monzonite porphyry dykes, but it appears to be magmatic, not a replacement of mafic minerals.

![Image](image-url)

**Figure 5.24: Chalcopyrite replacing mafic site in coherent post-breccia monzonite. Scale bar equals 1 cm.**

**Sulfide veins**
Sulfide veins crosscut the breccia and the contacts between breccia and immediately-post-breccia equigranular monzonite and trachyte dykes (figure 5.25). These dykes show no macroscopic gangue or accessory minerals, except for chalcopyrite. Post-breccia chalcopyrite is minor and does not appear to have contributed significantly to the overall grade of the system, at least in the Northeast zone. It was not widespread or consistent enough to be reliably tied to any particular dyke generation.
Albite-epidote

Albite-epidote is common and texturally destructive in the deepest portions of Section 29 (figure 5.26). It was not observed in Section 18. Albite is more prevalent than epidote in Section 29. This proportion appears to be consistent throughout the zone. Pyrite is associated with albite-epidote alteration, and replaces both Cu-sulfides and magnetite (figure 5.27). Albite-epidote alteration post-dates the post-breccia hornblende-bearing equigranular monzonite dykes (figure 5.28). Mafic dykes cut albite-epidote alteration.

Figure 5.25-Chalcopyrite veins crosscutting breccia textures. The chalcopyrite vein has been exploited by a later gypsum vein. Hole WB-04-106, 380.4 m
Figure 5.26-Albite-epidote alteration on section 29.
Sericite-quartz-carbonate

Sericite-quartz-carbonate alteration is restricted to the immediate vicinity of veins, fractures, and small faults in the Northeast Zone (figure 5.29). The alteration assemblage is texturally destructive, usually resulting in a featureless, amber-colored rock. The hardness of the rock varies greatly, from quite soft where sericite and carbonate dominate, to quite hard where disseminated quartz is dominant. Generally the rock is hardest closest to the central vein or fracture around which the alteration is developed. The center of each sericite-quartz-carbonate zone is marked by a multi-generation vein of
white, visually opaque quartz (figure 5.30). The best developed of these veins form vein breccias, with breccia clasts formed of banded vein fragments containing carbonate and quartz, sometimes with euhedral, terminated quartz crystals forming cockade clusters at the vein margins (figure 5.31). This is the only quartz observed in the Northeast Zone.

![Diagram](image.png)

**Figure 5.29-** Quartz-sericite carbonate alteration on Section 29.
Figure 5.30-Multi-generation quartz vein associated with quartz-sericite carbonate alteration. To the right of the image, chalcopyrite is replaced by chalcocite.
Although small quantities of pyrite are commonly present in the sericite-quartz-carbonate alteration as fine, disseminated grains, the alteration does not seem to destroy Cu-sulfides (figure 5.32). Chalcocite and covellite postdating chalcopyrite and bornite are only associated with this alteration assemblage, and are locally abundant (>50% of sulfides) (figure 5.33). Sericite-quartz-carbonate alteration overprints all generations and types of dykes, including the latest augite porphyry dykes (figure 5.34).

Figure 5.31-Quartz-infilled vein breccias with vein fragments as clasts. A; the cockade textures in the clasts; b; cockade textures in infill.
Figure 5.32-Chalcocite replacing chalcopyrite in a zone of sericite alteration (hand sample).

Figure 5.33-Chalcopyrite (lavender) replacing chalcopyrite (yellow) in a zone of sericite alteration (reflected light photomicrograph). FOV equals 2.5 mm.
Carbonate-gypsum-(clinozoisite-zeolite)

In Section 18, all rock types are overprinted with a network of carbonate-gypsum veins. Veins are ubiquitous in Section 18 but scarce in Section 29. Veins are composed of white calcite, gypsum, pale pink carbonate, cryptocrystalline grey clinozoisite, and salmon-pink zeolite (figure 5.35) (Ross, 2004). These minerals form vein breccias, mosaic and rotated breccias with carbonate infill around clasts of other rocks types, including sulfides (figure 5.36). Carbonate veins commonly have bladed textures indicative of boiling (figure 5.37). The bladed carbonate veins are exclusively post-sulfide.
Figure 5.36-Chalcopyrite clast in a late carbonate-gypsum zeolite vein. WB-04-29, 198 m; Scale bar equals 1 cm.

Figure 5.37-Bladed textures in post-sulfide chalcedony. WB-04-29, 33m. Scale bar equals 1 cm.
**Sequence of alteration, brecciation, and intrusion**

Alteration, brecciation, and intrusion establish a sequence of events recording both the physical and chemical evolution of the Northeast Zone hydrothermal system (figure 5.38). Hematite-carbonate alteration pervasively altered the monzonite before the intrusion of the megacrystic monzonite porphyry. The alteration may be related to the first pulse of fluid coming off the mineralizing intrusion. The hematite dusting and the carbonate blebs suggest that this fluid was oxidizing, near-neutral, and possibly CO$_2$-rich.

![Figure 5.38-Paragenesis of mineralization and alteration relative to brecciation and intrusion in the Northeast zone at Mount Polley.](image)

The alteration that followed, during and immediately after fragmentation, was more complex, involving a temperature-dependent zonal arrangement of chlorite, biotite,
actinolite-albite, and magnetite alteration. Chlorite alteration was the most distal alteration assemblage, forming high and peripheral within the system. Biotite alteration formed at slightly deeper depths and higher temperatures. Magnetite alteration formed at higher temperatures still, deeper in the system and proximal to the zone of highest fluid flux. This area of highest fluid flux also controlled the location of the actinolite breccia. The relationship between the magnetite alteration and the zone of fine-grained breccia are two expressions of the same phenomenon, a local area in which the most direct corridor was available between high and low hydraulic potential, between the origin and the destination of hydrothermal fluids. Due to the high fluid flux through this area, this particular pipe-within-the-pipe had a direct corridor to magmatic temperatures, hence the high temperature alteration assemblages localized along this zone.

As this initial fluid flux waned, the grain size segregation developed during breccia fluidization established permeability contrast within the breccia. Later fluids infiltrating this quiescent bed deposited K-feldspar which overlapped with the last stages of fluidization. This timing explains the existence of both K-feldspar rimmed clasts and of K-feldspar as breccia infill and overprinting the breccia. Concentration of sulfide minerals immediately above the K-feldspar flooding suggests that the two may be tied to the same evolving fluid, and that after K-feldspar had been deposited, the resulting fluids were oversaturated with respect to sulfides. Sulfides were deposited in the available open space within the most permeable breccias. Permeability control on sulfide deposition suggests that the breccia was not well consolidated at the time of mineralization. The sulfide mineralization is thus late, but still syn-breccia.
The relationship between sulfides and the gangue minerals associated with them is unclear. Anhydrite seems to be related to the zone between the K-feldspar flooding and biotite alteration, and may be related to the actual mineralizing fluids. Apatite and possibly garnet appear to be syn-sulfide. Other gangue minerals associated with the sulfide, notably magnetite, which appears to be pre-sulfide, and carbonate, which is post-sulfide, are not related to the sulfide depositing fluids.

Sealing of the system by sulfide deposition apparently resulted in, to a limited extent at least, repressurization of the system. Thus, the last of the sulfide mineralization achieved enough pressure to exceed the lithostatic pressure and form veins rather simply exploiting pre-existing open space. These veins post-date and cut the first generation of breccia-cutting dykes.

At sometime after this last generation of copper sulfides, the system experienced a lower temperature, ‘retrograde’ alteration event, which resulted in the Cu-sulfide destructive, deep albite-epidote overprint at the base of Section 29. This alteration assemblage shows all the hallmarks of a deep propylitic overprint on a waning system (Guilbert and Park, 1980), possibly related to the influx of meteoric fluids as the hydrothermal system waned and fluid flow collapsed back in on itself. Albite, epidote, and pyrite replaced K-feldspar, Fe- and Mg-bearing minerals, magnetite, and chalcopyrite.

The sericite-quartz-carbonate alteration is the product of conversion of K-feldspar to sericite and silica in response to acidic solutions (Barnes, 1997). The high neutralization capacity of the monzonite host rocks restricted the visible effects of alteration by acidic fluids to areas immediately adjacent to faults.
The alteration assemblages and zoning observed at Mount Polley are similar to those observed in other alkalic porphyry systems (Holliday and Cooke, 2007; Cooke et al., 2006; Deyell and Tosdal, 2005; Frei, 1995; Heithersay and Walshe, 1995; Lang et al., 1995a and b). The presence of sericite alteration suggests that the Northeast zone may represent a comparatively shallow portion of the hydrothermal system.
Chapter 6-Evolution of the Northeast Zone Breccia

Discussion

The genesis of the Mount Polley deposit, for purposes of this study, began with the intrusion of the Mount Polley Intrusive complex into the rocks of Nicola Volcanic Group. The Mount Polley intrusive complex does not differ greatly from trends expressed in the igneous evolution of the host volcanic arc. Instead, the Mount Polley Intrusive complex represents a further development in the overall evolution of the volcanic sequence into which it intruded (Logan and Bath, 2006). Logan and Bath (2006) and Logan et al. (2007) suggest that the Mount Polley intrusive complex may have formed quite high within or subjacent to a volcanic edifice. The similarities between the intrusive and extrusive rocks may support this hypothesis, although a simpler explanation may be that the intrusive and extrusive systems simply tapped the same crustal magmatic reservoirs.

In the Northeast zone, magmatic evolution continued with the intrusion of the megacrystic monzonite porphyry. The megacrystic monzonite porphyry represents a deviation in the physical, though not the chemical, evolution of the igneous system. Rather than fine-grained, relative equigranular textures indicative of relatively short super-solidus residence time, the extreme grain size contrast between phenocrysts and groundmass indicate extended storage at supersolidus temperatures (McLeod and Tait, 1999; Blake, 1984; Higgins, 1999; Cabane et al., 2001; Eberl, 2002; Higgins and Roberge, 2003).

The extended super-solidus residence time of the megacrystic magma resulted directly in the accumulation of fluids in the magma chamber presumably subjacent to the
dykes (Lickfold, 2002; Dilles and Einaudi, 1992; Burnham, 1985; Manning and Prichavant, 1984; Marsh, 1982 and 2000). The megacrystic dykes are inferred to represent the uppermost apophyses of a larger plutonic body at depth (Marsh, 1082, 1996, and 2000; McLeod and Tait, 1999). If the cores of the dykes were held as plastic, permeable crystal mush, they provide a favorable conduit for collecting or focusing fluids evolving off the underlying body by second boiling (Michioka and Sumita, 2005; Lange, 1994). The multi-stage intrusive complex preceding the intrusion of the megacrystic dykes probably aided in preheating and rheologically homogenizing the rockmass into which the dykes intruded (Belcher and Kisters, 2006).

This accumulation of fluids probably had a positive feedback relationship with the supersolidus cores of the dykes. Fluids were able to infiltrate because the crystal mush was plastic and permeable, and the presence of abundant fluid, and of direct hydraulic conductivity to the higher temperatures at depth, kept the interiors of dykes as crystal mush (Marsh, 1996; Eggleton, 1979). As fluid accumulated into the fluid-saturated zone under the chilled margin of the dyke, it formed horizontal lenses within the plastic interior of the dyke (Fournier, 1999; Marsh, 1996). These lenses propagated until they extended from the interior rheological limit of the dyke, the limit of where the material was rigid enough to sustain a fracture at the strain rate controlled by the rate of fluid influx, to the exterior limit where the dyke was too rigid to be fractured under the available overpressure (Hubbert and Willis, 1957).

The limits of the fluid lenses were controlled by a combination of crystal mush physical properties, fluid overpressure, and strain rate (Bertram and Kalthoff, 2003; Fournier, 1999; Brisbin, 1986). The vertical expansion of the fluid lenses is limited by the
same factors, but once the horizontal expansion limits of the fluid lens is reached, overpressure resulting from continued fluid input is released through the development of fractures (Li et al., 2002; Carrington, 1998; Clemens and Mawer, 1992). These fractures would link fluid-filled lenses at different topographic levels within the intrusion, possibly over a vertical extent of a kilometer or more (Gustafson and Hunt, 1975; Dilles and Einaudi, 1992; Lickfold, 2002; Sillitoe, 1973). This would result in significant hydraulic pressure in the upper reaches of the system. Alternatively, the fluid lenses could be linked or overpressured as the result of a tectonic event (Husen et al., 2006; Roman, 2005; Linde et al., 1994; Rubin, 1993 and 1995; Segall, 1984 a and b).

Through whatever process, fluids accumulated within the carapace of the megacrystic monzonite dykes until an overpressure was developed. This overpressure exceeded both the lithostatic pressure exerted by the overlying rock and the tensile strength of the dyke carapace (Li et al., 2002). The fluid overpressure at the apex of the dyke complex resulted in a cone of fracture that propagated upward from its original base and downward from its original apex, in a manner analogous to the development of diatremes (Skewes et al., 2002; Cannell et al., 2005; Lorenz, 1986, 2003 a and b; Lorenz and Kurszlaukis, S. 2006; Yakovlev, 1980).

Where overpressure exceeds the sum of the lithostatic load and the tensile strength of the rock, fractures can form and propagate (Passchier and Trouw, 2005; Li, et al., 2002). Energy is expended in the creation of new surface area (fracture propagation) (Cummins and Given, 1973; Hubbert and Willis, 1957). If these fractures are sufficiently closely spaced and accompanied by volume loss in the system, they come to define breccia clasts (Laznicka, 1988). In order for the breccia body to propagate upward,
continued energy input at least equal to the energy expended in surface area creation and transport of fragments is required to continue upward propagation of the breccia body (Vyazmensky et al., 2008; Laubscher, 2000; Suppe, 1995).

**Mathematical model for breccia propagation**

In constructing a simple mathematical model for breccia propagation, certain base assumptions must be made. The stress regime at the point of breccia initiation is treated here as axial. This assumption is reasonable for hydrothermal breccias formed in the shallow crust within fairly isotropic country rocks (Belcher and Kisters, 2006; Richards, 2003; Bergantz, 1991). Given these assumptions, the growing breccia can be modeled as a cone, with its axis normal to $\sigma^3$ and its apex at the point of initial rupture (figure 6.1a).

![Figure 6.1-Geometric model for breccia propagation. a: Cone-in-cone damage cone (green) and shatter cone (red) geometry. b: Triangular damage zone and shatter zone cross-section.](image-url)
The model breccia body is composed of two nested cones with coplanar bases and a common apex; the central cone is arbitrarily defined as the zone within which fracture density is great enough for rotation and movement of clasts (the shattered zone), and the outer cone is defined by the outward extent of fracture propagation (the fracture cone).

The cones can be modeled as two right triangles rotated around a common side (h); the angle between the height of the breccia cone (h) and the hypotenuse of the triangle is expressed as $\theta_1$ for the inner cone and $\theta_2$ for the outer cone. The radius of the base of the cone is expressed as $r_1$ for the inner cone, and $r_2$ for the outer cone (figure 6.1b).

The total volume of the breccia body for a given height can be expressed as the volume of the outer cone:

$$V = \frac{1}{3} \pi ((\tan \theta_2)h)^2 * h$$

The volume of the shattered area within the breccia body for a given height can be expressed as the volume of the inner cone:

$$V_1 = \frac{1}{3} \pi ((\tan \theta_1)h)^2 * h$$

The volume of the fractured but not shattered area can be expressed as:

$$V_2 = \frac{1}{3} \pi ((\tan \theta_2)h)^2 * h - \frac{1}{3} \pi ((\tan \theta_1)h)^2 * h$$
Thus the incremental increase in volume of the breccia body for an incremental increase in height increases with the increasing height of the breccia (figure 6.2).

Figure 6.2-Breccia volume as a function of breccia core height. The graph is unitless due to the fractal nature of the processes involved.

This can be considered as the derivative of the above functions (figure 6.3):

\[ V_1' = \pi (\tan \theta_1) h^2 \]

\[ V_2' = \pi (\tan \theta_2) h^2 - \pi (\tan \theta_1) h^2 \]

\[ V_3' = \pi (\tan \theta_2) h^2 \]
The energy required to increase the height of the breccia is proportional to the volume of rock that must be broken for each incremental increase in height, so the energy required in order to continue upward growth of the breccia ($E_n$) can be expressed as:

$$E_n = (E_1 - E_2)(\pi \tan \theta_1 2h^2) + (E_2)(\pi \tan \theta_2 2h^2)$$

Where $E_1$ is the energy input needed to shatter the country rock and $E_2$ is the energy input needed to fracture the rock. This equation assumes that fracturing precedes shattering. If the growth of the breccia is assumed to be constant at some rate $g$ ($\Delta h/t$), then the energy input over time required to continue breccia growth can be expressed as:

$$E_n = (E_1 - E_2)(\pi \tan \theta_1 2g^2t^2) + (E_2)(\pi \tan \theta_2 2g^2t^2)$$
Energy input into the breccia system comes from a variety of sources: continuing upward fluid flux from the parent intrusion (Burnham, 1985), expansion of the fluid with decreasing pressure (Li et al., 2002), fluid phase changes such as exsolution of CO$_2$ or boiling (Wiebe, 1996; Burnham, 1985; Burnham, 1979b; White et al., 1971), gravity (Vyazmensky et al., 2007; Ross, 2002; Laznicka, 1988), or tectonic rupture (Manga and Brodsky, 2006; Linde et al., 1994). Energy is consumed by the creation of new surface area (fracturing and shattering) (Swanson, 1984; Cummins and Given, 1973; Hubbert and Willis, 1957), friction between fragments (Yang et al., 2007), between fluids and fragments, and between fluids, fragments, and the country rock, heat loss via conduction and convection, fluid escape into the host rocks, and fluid contraction with decreasing temperature (Secor, 1965). The energy inputs into the system are difficult to quantify, but finite; for purposes of this exercise they can be approximated by the arbitrary expression:

\[ E_a = -4t^2 + 20t + 50 \]

$E_a$ is the total energy available to fracture rock; where $E_a < E_m$, the energy available to fracture the rock is no longer sufficient to maintain the same rate of growth in breccia volume. As $\sigma^3$ is assumed to be far less than $\sigma^2$ or $\sigma^1$, and $\sigma^2$ and $\sigma^1$ are assumed to be approximately equal, then growth of the breccia radius will decrease while growth in breccia height remains the same, producing a decrease in the radius of the breccia body with height (figure 6.4), or a decrease in fracture density until the fractured rock mass is no longer a breccia (Norton and Cathles, 1973; Sillitoe, 1985; Ensign Bushnell, 1988). In
either case, where the tops of hydrothermal-magmatic breccias are undisturbed, they are commonly domal (Sillitoe, 1985; Norman and Sawkins, 1985; Wenrich, 1985).

![Diagram showing decreasing breccia radius with increasing height.](image)

Figure 6.4-Decreasing breccia radius with increasing height.

$E_n$ as expressed above is graphed against $E_m$, with $g=1$, $E_1=2$, $E_2=1$, $\theta_1=10$, and $\theta_2=25$ (figure 6.5). Values for $g$, $E_1$, and $E_2$ were chosen in order to simplify the mathematics of the system; $\theta_1$ and $\theta_2$ were based on observational evidence from breccia bodies (Sillitoe, 1985; Norton and Cathles, 1973; Bushnell, 1988) and analogous processes related to block-cave mining (Vyazmensky et al., 2007; Gilbride et al., 2005;
Laubscher, 2000; Cummins and Given, 1973). If $g$ is equal to 1, then the ordinate axis of the graph (figure 6.5) is valid as both time and height of the breccia from point of origin.

Volumetric growth of the breccia is based on the assumption that energy input is proportional to increase in breccia volume. At the intersection of $E_a$ and $E_n$, the radius of the breccia is at its maximum and begins to decrease. Because the instantaneous energy required to form breccia volume is a function of the derivative of breccia volume, it is proportionate to breccia radius; the rate of decrease of breccia radius is proportional to the derivative of function $E_a$:

$$E_a' = -8t + 20 \text{ or }$$

$$E_a' = 8h + 20$$
If \( h_{\text{max}} \) is the height of the breccia at the time when \( E_a = E_n \), then maximum radius of the breccia would be:

\[
R_1 = \tan \theta_1 \times h_{\text{max}} \\
R_2 = \tan \theta_2 \times h_{\text{max}}
\]

Because \( E_a \) expresses the total amount of energy available to fracture the rock, and the amount of energy required to fracture a given volume of rock is less than that necessary to shatter the same volume of rock, \( R_1 \) and \( R_2 \) will not decrease at the same rate after the breccia has reached \( h_{\text{max}} \). Instead, \( R_1 \) will be greater than 0 only as long as \( E_a \) is greater than \( E_2; E_{a1} \), or the energy available to shatter the rock, is equal to \( E_a - E_2 \). If \( E_{a1} < 0 \), and \( E_a > 0 \), the fractured zone will continue to propagate upward, but without the central shattered zone. This would produce a fractured zone (Norton and Cathles, 1973) or even a single fluid escape structure such as those observed at the Cananea deposit (Bushnell, 1988).

The radius of the breccia body is actually one possible expression of decreasing \( E_a \). \( E_a \) is the energy available to fracture the rock, and this energy is dominantly expended via the formation of new surface area (Cummins and Given, 1973). The decreasing availability of energy to create new surface can be manifested either as the creation of new surfaces at the same fracture density over a decreasing volume of rock, or as more widely spaced fractures (larger clast sizes). Identifying wider fracture spacing at the original top of the breccia body can be complicated by post-fracturing processes. If sufficient volume increase occurs that the breccia mass can flow, large clasts originally at the top of the mass could fall through the smaller clasts below, reversing the original
grading of the body (Mukherjee and Mishra, 2007; Bryant, 1968). In the absence of reliable stratigraphy, as at Mount Polley, this would be difficult recognize, but the abundant outsize clasts recognized at depth in Section 29 may reflect this process.

The decrease in available energy can come from a variety of sources. Upward fluid flux from the magma chamber at depth can diminish (Burham, 1985), volume loss via thermal loss from the fluid to the surrounding rock can exceed volume gain via depressurization, or a short-lived pulse of upward fluid movement from a seismic event can be exhausted (Manga and Brodsky, 2006). Fluid flux from the magma chamber is dependent on the cooling rate of the pluton (Candela, 1989; Burnham, 1979), and also on the availability of a conduit to focus that fluid into the base of the breccia (Lorenz, 2006). Spot depressurization at the point of origin of the breccia can result in a decompression quench of melt, effectively “corking” the breccia from below (Lorenz, 2006; Sillitoe, 1985). Note that the upward fluid flux into the breccia need not stop or even decrease in order to no longer propagate the breccia “cone”; $E_a$ must simply stop increasing as rapidly as $E_n$. The presence of hydrothermal minerals as cement in breccias is ample evidence that fluid flux continues after the movement of clasts within the breccia has ceased (Davies, 2002; Hedenquist and Henley, 1985).

Rheological anisotropy in the host rock to the breccia also causes changes in $E_n$ (Vyazmensky et al., 2007; Belcher and Kisters, 2006). If the growing breccia cone intercepts a body of rock of significantly higher tensile strength than the general country rock, the net effect on the breccia propagation would be equal to the effect of a proportionate decrease in $E_a$. If the zone of high tensile strength rock is limited, for example by a sill or a sedimentary rock unit, the breccia may pinch at that point and swell.
above it, with the radius of the breccia decreasing proportionately to the $E_n$ required to fracture the high strength rock unit (Sillitoe, 1985; Bryant, 1968). This constriction would induce changes in the fluid flow past that point, increasing fluid velocity while decreasing fluid pressure (Lamb, 1953); this in turn would affect fluid flow, clast transport, and mixing above and below the constriction (Lamb, 1953; McCallum, 1985; Yang et al., 2007; Mukherjee and Mishra, 2006).

**Fluid flux and breccia formation**

Within the pervasively fractured rock mass, some anisotropy is expected (Vyazmensky, et al., 2007). Pre-breccia joints and fractures result in zones of increased fracture density. Even though the breccia body may no longer grow, the fluid influx may not decline, let alone cease (Sillitoe, 1985). The kinetic energy of the fluid flux is simply no longer expended through the creation of new surface area (Norton and Cathles, 1973).

If the upward fluid flux exceeds the settling velocity of the 'clasts', and sufficient void space is available for clasts to move around each other, a fluidized bed state may be achieved (Mukherjee and Mishra, 2007). The most compelling evidence for the development of a fluidized bed state in the Northeast zone breccia is the thorough mixing of the megacrystic monzonite porphyry clasts with country rock monzonite in the breccia. The fine-grained breccia body is also a likely result of channelized fluidization adjacent to the zone of highest fluid flux (as indicated by the presence of actinolite and magnetite in the center of the fine-grained zone) (McCallum, 1985; Yang et al., 2007; Link et al., 2006). An alternative explanation for the fine grained breccia might be the presence of a pre-breccia zone of increased fracturing and jointing which was fractured more densely by brecciation processes than the surrounding rock mass (Sillitoe, 1985). Fluid flux
would vary across the diameter of the pipe (Gonnermann and Manga, 2003; Lamb, 1953). The perimeter facies of fractured to minimally rotated country rock on the Northeast zone breccia body reflect the lowest fluid velocity portions of the conduit (Kennedy et al., 2005; Boone et al., 1986).

At any given point within the breccia pipe, fluid flux would vary over time (figure 6.6) (Sillitoe, 1985). The time axis shown here is deliberately parameterless, given the uncertainty of the lifespan of the magmatic-hydrothermal systems (Schardt et al., 2005; Paterson and Tobisch, 1992; Titley and Beane, 1981). The highest fluid flux would occur early in the development of the breccia body, but the majority of the fluid volume would be introduced later (Sillitoe, 1985). Time zero represents the point in time at which hydrostatic pressure exceeds lithostatic pressure (Li et al., 2002). At time one, fractures have propagated to the point where they are hydraulically contiguous and a fluid flux is established (Sillitoe, 1985; Atkinson, 1987; Anderson, 1991; Li et al., 2002; Bertram and Kalthoff, 2003). As fluid flux continues to rise and the three dimensional fracture array continues to develop, fragments within the fractured rock mass become discretized (Whittles et al., 2006; Boone et al., 1986). At some point, the fluid velocity of the rising fluid flux exceeds the settling velocity of these particles (Richardson and Zaki, 1954; McCallum, 1985; Mukherjee and Mishra, 2007). Time two represents the point at which fluid flow ceases to be controlled by fractures, and particle movement begins to be dominated by fluid movement, entering a fluidized bed state.
Figure 6.6-Fluid flux at a given point within the breccia pipe over time. Time 0: Initiaition of fracture. Time 1: fractures become hydraulically contiguous. Time 2; Upward fluid flux exceeds particle settling velocity. Time 3; Particle settling velocity exceeds upward fluid flux. Time 4; Fluid flux continues through settled particle bed. Between time 0 and time 1 no fluid through-flow is possible; between time 1 and time 2, clasts control the movement of fluids. Between time 2 and time 3, fluids control the movement of clasts, and after time 3 clasts again control the movement of fluids.

The existence of a fluidized bed state in the Northeast Zone is indicated by the mixing of megacrystic and country rock clasts in the bulk of the breccia body. This fluidized bed state was most likely short-lived (Paterson and Tobisch, 1992; McCallum, 1985). Time three represents the point at which the diminishing fluid flux falls back through the settling velocity of the particle bed (Swanson, 1999 and 1989). This fluidization threshold drops during the fluidized bed state for two reasons. First, mutual impact and abrasion between clasts reduce average clast size, which decreases clast settling velocity (Scala et al., 1997; Lamb, 1953). Second, the material removed from the
clasts in the course of clast size reduction becomes part of the fluid phase (He and Forssberg, 2007a and b; Scala et al., 1997). This increases the density of the fluid phase, also decreasing particle settling velocity (He and Forssberg, 2007a and b). The presence of clastic infill and rounded clasts in the Northeast zone supports this hypothesis. The fine-grained, clastic-infill dominated portion of the breccia body probably represents the zone of highest fluid flux, and thus highest comminution (Yang et al., 2007; He and Forssberg, 2007b; McCallum, 1985). Fines generated by comminution in other portions of breccia may also have been stripped out and concentrated in the zone of highest fluid flux, explaining why in most portions of the Northeast Zone breccia, not enough fines are present to account for the rounding of the clasts (Powell and Morrison, 2007; Eisenmann, 2001; Heiskanen, 1993).

The dependence of fluidization state on clast size would lend itself to the stripping and concentration of fines. Fines would stay in suspension at lower fluid fluxes than coarser clasts, moving upward and inward within the breccia pipe (Mukherjee and Mishra, 2007; Rasul et al., 2000).

**Fluid Flux and Fluid Chemistry**

The fluid flux would peak, and then decline over an extended period of time as the underlying plutonic body cools and crystallizes (White, 1981). As the fluid flux wanes, the fluid chemistry would change as well (Barnes, 1997). Because the initial and peak fluid flux was not saturated with respect to any mineral, the fluid is not preserved as fluid or melt inclusions (Hedenquist and Lowenstern, 1994). In terms of alteration, it may have been the fluid responsible for the hematite-carbonate alteration. Post-peak fluid flux, during the declining period of the fluidized bed state, was responsible for the syn-breccia
biotite, chlorite, and magnetite alteration; the syn-breccia alteration which was not controlled by the permeability regimes established during post-fluidization settling.

Post-settling, ongoing fluid flux was responsible for K-feldspar flooding, the deposition of sulfides, and the destruction of magnetite by sulfide-stable fluids. This transition indicates the increase in K+ fugacity, S fugacity, and metals, and decrease in iron fugacity (Guilbert and Park, 1980).

Bornite is present in proximity to the highest concentration of megacrystic clasts and to the contact between biotite and K-feldspar alteration. These two areas reflect zones of high temperature, and zones of proximity to the dykes which initiated brecciation and focused fluid flow from the pluton beneath. Gold and silver are concentrated with bornite, reflecting the solubility of these metals in bornite (Simon et al., 2000; Makovicky et al., 1995). Sulfide mineralization, reflecting its post-settling deposition, exploited the most permeable zones within the breccia.

After the deposition of the sulfides, albite, epidote, and pyrite indicate a lower temperature, retro-grade propylilitic alteration phase (Barnes, 1997; Guilbert and Park, 1980).

**Vectors to ore**
Two main primary (pre-sulfide) controls on ore depositions were observed at Mount Polley. First, ore grade was higher in the vicinity of the highest concentration of megacrystic porphyry clasts. Within and above zones containing over 50% megacrystic clasts, bornite was most abundant, and Cu, Au, and Ag grades were higher than in adjacent, physically similar zones of breccia. The second primary control on
mineralization was the variation in permeability established within the breccia by fluidization processes. Where the breccia was most permeable, ore grade was highest.

Secondary controls on ore grade include the intrusion of post-ore dykes and the effects of post-ore Cu-sulfide destructive alteration. Post-ore dykes substantially diluted the overall grade of the rock volume, especially in Section 29. The deep albite-epidote alteration event also diluted or destroyed grade at depth in Section 29.

Although attempting a structural reconstruction of the Northeast Zone is outside the scope of this work, the original mineralized volume of the Northeast zone is disrupted by at least three major faults (figure 6.7). Reconstructing the relative movements of these faults could indicate the locations of displaced portions of the breccia body at depth.
The fine-grained breccia unit presents some intriguing possibilities for further mineralization around the Northeast zone. If the fine-grained breccia body represents an originally central zone of spouting or channeling within the fluidized breccia body (Link et al., 2007), additional mineralization may be preserved, with favorable fault movement, to the northwest or west of the currently known body. Alternatively, the fine-grained breccia subunit may reflect more complex processes such as bubble trails within a three-

Figure 6.7- The Northeast Zone breccia and the faults that truncate it, the Green Giant, the Brown wall, and the inferred fault.
phase fluidized bed (Yang et al., 2007). In this case, the fine-grained unit may be considerably more irregular and off-center than would be expected as a result of two-phase fluidization (Yang et al., 2007). In any case, a better understanding of the nature and orientation of faulting related to the post-ore Northeast Zone structures might lead to recognizing additional volumes of mineralized breccia which originally surrounded the fine-grained breccia body. Additional volumes of mineralized breccia may also survive to the east and southeast, offset by the Brown Wall fault.

**Sequence of Events**
The sequence of events which resulted in the Mount Polley orebody as observed today began with the development of the Nicola volcanic arc sequence (figure 6.10a). The oldest rocks in this sequence were the most geochemically primitive, and younger units became progressively more differentiated. The Mount Polley intrusive complex intruded this sequence (figure 6.10b), beginning with the augite and K-feldspar bearing diorite units, and dominated by the undifferentiated monzonite units. These successive intrusions were increasingly differentiated, continuing the same trend observed in the volcanic sequence. A hydrothermal system may have developed following the intrusion of the K-feldspar bearing diorite and pre-dating the intrusion of the monzonite, as evidenced by veining observed in diorite xenoliths within monzonite. A hydrothermal system was definitely in existence pre-dating the intrusion of the megacrystic K-feldspar monzonite porphyry, as evidenced by pre-breccia vein networks in altered mafic clasts. The altered mafic clasts may reflect a pre-megacrystic monzonite porphyry sill which intruded the monzonite, a roof pendant, or a massive xenolith of pre-MPIC volcanic rock (figure 6.10c). The intrusion of the megacrystic K-feldspar porphyry post-dated the alteration of
this body; the small megacrystic dykes and bodies observed today are almost certainly the apophyses of a larger, deeper body which contributed the volume of fluid necessary for deposit-scale alteration (Burnham, 1985) (figure 10d).

Figure 6.8-Sequences of events in the formation of the Northeast Zone at Mount Polley; a, deposition of the Nicola Group volcanic rocks. b; intrusion of the MPIC. C; intrusion (?) of the 'altered mafic' clast forming unit. d; intrusion of the K-feldspar megacrystic monzonite porphyry
Figure 6. 9-Sequence of events in the formation of the Northeast Zone at Mount Polley; a; Accumulation of fluids within and around the K-feldspar megacrystic porphyry dykes; b; overpressure of the fluid resulting in rupture and the initiation of brecciation; c; formation of a particle bed; d; fluidization within the particle bed and magnetite deposition.
During and after the intrusion of the megacrystic K-feldspar monzonite porphyry, fluids accumulated within and around the still-plastic porphyry magma (figure 6.11a). These fluids became overpressured with respect to the lithostatic load, initiating brecciation (figure 6.11b). Brecciation proceeded upwards until the amount of energy available no longer exceeded the amount of energy necessary to continue growth of the body. The breccia body probably did not breach the surface, or even the top of the pluton (figure 6.11c). Mixing of clast types indicates that at least parts of the breccia passed through a fluidized bed state, allowing juxtaposition of clasts, stripping and concentration of fines, and rounding of clasts. Magnetite deposition occurred in the central portions of the breccia, adjacent to the highest temperature fluid ‘jet’ (figure 6.11d).

Limited biotite and k-feldspar alteration, illustrated by K-feldspar rims on biotite-altered clasts, occurred during the fluidized bed state (figure 6.12a-c) After the fluidized bed state had collapsed (figure 6.12d) and fluid flow within the breccia was once again controlled by particle bed permeability, biotite, K-feldspar, and sulfide deposition occurred (figure 6.13). Permeability control on sulfide deposition is demonstrated by the presence of sulfides as chemical infill in polymictic breccia zones with moderate rounding of clasts and comparatively sparse fines (figure 6.14a). Equigranular augite monzonite dykes cutting breccia textures indicate that the breccia behaves as a coherent mass at the time of intrusion, rather than as a particle bed (figure 6.14b). For purposes of this study, this transition, from a particle bed to a coherent mass, differentiates the syn-breccia from the post-breccia period.
Figure 6.10- Alteration and infill of the breccia. a; mixed, rounded clasts in a fluidized bed state, after stripping of the fines; b; biotite alteration of the clasts in the fluidized bed state; c; k-feldspar alteration of clast rims; d; settling of the fluidized bed.
Post-breccia sulfide mineralization cuts both the breccia textures and the equigranular augite monzonite (figure 6.14c). These post-breccia veins do not cut the post-breccia K-feldspar porphyry dykes (figure 6.14d). These dykes represent at least four generations, established by crosscutting relationships (figure 6.15). These generations evolve from crowded, blocky phenocrysts to elongate, sparse phenocrysts over time. This evolution probably represents decreasing magma residence time at near-solidus temperatures, with the more crowded, blockier phenocrysts representing a more advanced state of Ostwald

Figure 6.11-Breccia infill, schematic and actual.
ripening (Higgins, 1999; Cabane et al., 2001; Higgins and Roberge, 2003). These dykes are not significantly different in chemistry from the megacrystic dykes that triggered both brecciation and mineralization, suggesting that long-term storage at near-solidus temperatures may have made the megacrystic dykes most able to segregate or store fluids (Fournier, 1999; Burnham, 1985).

Figure 6.12-Post-breccia settling. A; breccia infill; b; intrusion of equigranular dykes; c; post-breccia chalcopyrite veining; d; intrusion of post-breccia monzonite dykes.
Figure 6.13-Progressive changes in dyke texture over time. A; Megacrystic K-feldspar phytic monzonite porphyry, b; crowded K-feldspar phytic monzonite porphyry, c; moderate K-feldspar phytic monzonite porphyry, d; sparse K-feldspar phytic monzonite porphyry, e; trachyte porphyry. Scale bar equals 1 cm.
Subsequent dyke generations reflect decreasing magma residence time and increasingly hydrous and increasingly mafic character. Increasing plagioclase is observed from K-feldspar and plagioclase phryic through plagioclase-only porphyries (monzonite to diorite). In the monzonite dykes, augite-bearing dykes are cut by augite and hornblende-bearing dykes, then hornblende only, hornblende and biotite, and finally biotite-only dyke phases. Albite-epidote alteration observed deep in Section 29 post-dates the biotite-bearing dyke phases and pre-date the mafic dyke phases (figure 6.16).

![Figure 6.14-Mineral paragenesis and alteration timing.](image)

The mafic dykes continue the evolution observed in the other dyke groups, from plagioclase phryic to augite and finally olivine-phryic fine grained mafic porphyries
(figure 6.17). The mafic dykes pre-date major faulting, which is then exploited by the latest dyke generation, the augite porphyry. The augite porphyry, based on this unique behavior and its distinctive geochemistry (most notably in Ni and Cr) may not be a direct part of the magmatic evolution which produced the other dykes.

![Figure 6.15](image)

**Figure 6.15-Evolution of the pre- and post-mineral intrusive rocks of the Northeast Zone.**
The augite porphyry dykes are cut by the last phases of hydrothermal activity, including quartz-sericite alteration and carbonate-gypsum-zeolite veins and vein breccias (figure 6.16).

Figure 6.16-Complete cross-section of Section 18.
Although the relationship between the Northeast Zone breccia and sulfide mineralization was recognized early in the exploration of the deposit, the complexity of the dykes and intrusive history (figure 6.18 and 6.19) obscured the strong control of internal breccia architecture over mineralization (figure 6.20). Alteration assemblages reflect the
evolution of fluids before, during and after mineralization, and are in accordance with those observed at many porphyry systems (figure 6.21).

Figure 6.18-Breccia sub-units and sulfide mineralization, Section 29.
Figure 6.19 - Alteration cross-section of Section 29.
**Avenues for further research**

Many questions regarding the origin and nature of the Mount Polley mineralizing system remain unanswered. On a deposit scale, the alteration zonation of the Northeast Zone is still poorly constrained. The absence of good mineralologic candidates for fluid inclusion analysis means that the temperatures and pressures under which mineralization occurred are not well understood.

Part of the challenge in reconstructing the Mount Polley orebody is due to the complexity of the post-mineralization faulting and folding. Reconstructing the property-scale structure would yield insights into the original geometry of the orebody, and into the relationships between the ore zones. Structural reconstruction would also clarify the relationship between the mineralizing system and the volcanic stratigraphy, including the position of the mineralizing system within the volcanic edifice (if any; Logan et al., 2007; Breitsprecher et al., 2007).

Beyond the Mount Polley property, the relationship between the Mount Polley mineralizing system and near-by areas of mineralization and alkalic magmatism (i.e. the Bootjack stock, the Bullion stock, the Spanish Mountain deposit and others) may lend insight into the evolution of alkalic porphyry systems, and into the differences between high- and low-grade systems. On a still larger level, the differences between silica-saturated and silica-undersaturated alkalic centers in the Quesnel terrain in terms of their mineralization potential has yet to be fully explored. Lang et al., 1995, initiated this area of inquiry, but many questions are left unanswered and the advances of technology since that time have opened many new avenues of research.
On a tectonic level, the origins of alkaline magmas, especially silica-undersaturated alkaline magmas, are not well understood (Riishuus et al., 2008; Mueller et al., 1994). The Quesnel terrane presents many opportunities for better understanding the evolution of alkaline magmatism and volcanism (Breitsprecher et al., 2007). The relationship between the Quesnel and Stikine terranes also remains ambiguous. Similarities in the age and nature of magmatism and volcanism between the two terranes have been noted (Lang et al., 1995; Breitsprecher et al., 2007; Johnston and Borel, 2007), but as yet not fully explained.

Globally, alkaline porphyry and epithermal deposits occur in many different tectonic settings. Arc-related, rift-related and intra-cratonic alkaline mineralizing systems have all been described (Sillitoe, 2002; Jensen and Barton, 2002; Mutschler et al., 1998; McLemore et al., 1996; Holliday and Cooke, 2007). The similarities and differences between alkaline-related mineralizing systems in different tectonic settings may lend insight into the origins of alkaline magmas and into the ultimate sources of alkaline mineralization. The links between alkaline porphyry and epithermal mineralizing systems have still not been well described. Although spatial and in some cases, potential genetic links (Allard stock, Jensen and Barton, 2002) have been established, a systematic relationship with application to exploration has not been published.
Mount Polley in the larger context
The Northeast Zone at Mount Polley is a small, high-grade ore zone representing a small part of a larger mineralizing system, itself an aspect of a silica-undersaturated alkalic intrusive center. Mount Polley has the potential to reflect the shallowest depths of an alkalic porphyry system, but as of the date of writing, this has yet to be established. Perhaps the most significant aspect of the Northeast Zone is its high grade. The breccia development and the breccia architecture of Mount Polley may lend insight into mechanisms for focusing fluid flow and identifying areas of high grade in other systems.
References


Bloodgood, M.A. (1985), Structure and stratigraphy of the Eureka Peak area, Cariboo Mtns., British Columbia; Geological Society of America Abstracts with programs, vol. 17, no. 6, pp. 343

Bloodgood, M.A. (1987a), Structural transitions within the Quesnel terrane, Eureka Peak area, Central British Columbia; Geological Society of America Abstracts with programs, vol. 19, no. 6, pp. 359


Cummins, A.B., and Given, I.A., eds. (1973); SME Mining Engineering Handbook; vols. 1 and 2; The American Institute of Mining, Metallurgical, and Petroleum Engineers, Baltimore, MD

Darwin C. 1840. On the connexion of certain volcanic phenomena in South America; and on the formation of mountain chains and volcanoes, as the effect of the same power by which continents are elevated. Trans. Geol. Soc. Lond. 5:601–31

Davies, A.G.S., 2002, Geology and genesis of the Keliang gold deposit, east Kalimantan, Indonesia; Doctoral dissertation, University of Tasmania, Hobart, Tasmania, Australia

Davies, A.G.S., and Cooke, D.R., 2000, Hybrid phreatomagmatic and phreatic breccias at the Keliang gold deposit, east Kalimantan, Indonesia; triggering mechanisms and implications for ore genesis in magmatic-hydrothermal systems; Abstracts with programs, Geological Society of America, vol. 32, no. 7, p. 222


Emmons, S.F., (1906): Los Pilares Mine, Nacozari, Mexico; Economic Geology, volume 1, pp. 629-643


He, M., and Forssberg, E., (2007)b; Rheological behaviors in wet ultrafine grinding of limestone, Minerals & Metallurgical Processing, Vol.24 No.1,


Imperial Metals Corporation (2007)b, Imperial Metals Annual Information Form; Imperial Metals Corporation, 47 p.

Jacobsen, J.B.E., McCarthy, T.S., and Laing, G.J. (1976); The Copper-bearing breccia pipes of the Messina District, South Africa; Mineralium Deposita, Volume 11, pp. 33-45


Kennedy, B, Spieler, O., Scheu, B., Kueppers, U., Taddeucci, J., and Dingwell, D.B; (2005); Conduit implosion during Vulcanian eruptions; Geology; vol. 33, pp. 581-584


Kelly, K.D., and Ludington, S., (2002): Cripple Creek and other alkaline-related gold deposits of the Southern Rocky Mountains, USA: influence of regional tectonics; Mineralium Deposita, volume 37, pp. 38-60


Lamb, H., (1953); Hydrodynamics, 6th ed.; Cambridge: Cambridge Univ. Press.


Mankosa, M.J., (1990), Scale-Up of Column Flotation, Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.


Maughan, D.T., (2001): Mafic to intermediate alkali rocks of the Bingham District, Utah; MSc thesis, Brigham Young University, Provo, Utah


McCallum, M.E., (1985); Experimental Evidence for Fluidization Processes in Breccia Pipe Formation: Economic Geology, volume 80, pp. 1523-1543


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Meinert, L.D., (1982), Skarn, Manto, and Breccia Pipe Formation in Sedimentary Rocks of the Cananea Mining District, Sonora, Mexico; Economic Geology, volume 77, pp. 919-949


Murphy, M.D., Sparks, R.S.J., Barclay, J., Carroll, M.R., and Brewer, T.S., 2000, Remobilisation origin for andesite magma by intrusion of mafic magma at the Soufriere Hills Volcano, Montserrat, West Indies: Journal of Petrology, v. 41, p. 21–42.


Rees, C.J., (1987), The Intermontane-Omineca Belt boundary in the Quesnel Lake area, east-central british Columbia; tectonic implications based on geology, structure, and paleomagnetism; doctoral dissertation, Carleton University, Ottawa, ON, Canada.


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Scala, F., Cammarota, A., Chirone, R., and Salatino, P.,(1997); Comminution of limestone during batch fluidized-bed calcination and sulfation; AIChE journal vol. 43, n°2, pp. 363-373

Schardt, C; Yang, J., and Large, R.; (2005); Numerical Heat and Fluid-flow modeling of the Panorama Volcanic-Hosted Massive Sulfide District, Western Australia; Economic Geology, vol. 100; pp. 547-566


Sillitoe, R.H., (1973): The Tops and Bottoms of Porphyry Copper Deposits; Economic Geology, volume 68, pp. 799-815

Sillitoe, R.H., (1985): Ore-Related Breccias in Volcanoplutonic Arcs; Economic Geology, volume 80, pp. 1467-1514

Sillitoe, R.H., (2002): Some metallogenic features of gold and copper deposits related to alkaline rocks and consequences for exploration; Mineralium Deposita, volume 37, pp. 4–13

Sillitoe, R.H., and Bonham, H.F. (1984); Volcanic Topography and ore deposits; Economic Geology, vol. 79, pp. 1286-1298


Utikar, R.P., and Ranade, V.V.; (2007); Single jet fluidized beds: Experiments and CFD simulations with glass and polypropylene particles; Chemical Engineering Science, vol. 62; pp. 167-183


Wenrich, K., 1985, Mineralization of breccia pipes in Northern Arizona, Economic Geology, volume 80, pp. 1722-1735


Whittles, D.N., Kingman, S., Lownes, I., and Jackson, K.; (2006); Laboratory and numerical investigation into the characteristics of rock fragmentation, Minerals Engineering, Vol.19, No.14, pp. 1418-1429


Wolfe, J.A., 1980, Fluidization versus phreatomagmatic explosions in breccia pipes; Economic Geology, volume 75, pp. 1105-1111


