Variability in the Basaltic Rocks Hosting Copper-Gold Porphyry Mineralization in the Quesnel Terrane, South-Central British Columbia (NTS 092, 093): Geochemistry, Stable Isotopes and Physical Properties

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Introduction

The Late Triassic–Early Jurassic Quesnel terrane is a volcano-sedimentary intraoceanic-arc sequence. The Upper Triassic Takla and Nicola groups (hereafter referred to as Nicola Group), which define the Quesnel terrane, are composed largely of alkalic and lesser calcalkalic basalts, derivative volcanic products and associated marginal-basin sedimentary strata (Preto, 1979; Nelson and Bellefontaine, 1996). Paleontological and paleomagnetic data show that this volcanic belt may have originated more than 1000 km south of its present location (Irving et al., 1980), and was accreted to the western margin of North America by the pre–Middle Jurassic (Monger et al., 1982).

The Quesnel terrane hosts the majority of the alkalic porphyry Cu-Au deposits in British Columbia (BC), including (from north to south) Lorraine, Mount Milligan, Mount Polley, Afton/Ajax and Copper Mountain (Figure 1). Much of the area underlain by the Quesnel terrane is densely vegetated and extensively covered by younger glacial and volcanic products, making mineral exploration challenging. The main objective of this project is to identify the relationships between alkalic porphyry mineralization and the basaltic hostrocks, with the aim of generating a regional map showing areas of prospective arc segments for porphyry exploration. This paper presents the results of whole-rock geochemical and magnetic susceptibility analysis of coherent basalts from arc segments with known deposits, and compares them to arc segments without known mineralization.

Keywords: *Quesnel terrane, alkalic porphyry, geochemistry, physical properties, stable isotopes, basalt*

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The entire volcanic sequence in the Quesnel terrane was affected by post-Triassic low-grade metamorphism, which is characterized by a calcite-chlorite-epidote assemblage, the same mineral assemblage associated with propylitic alteration haloes around porphyry bodies, thus further complicating exploration efforts. However, the presence of calcite allows for analysis of carbon and oxygen isotopes within the propylitic and/or metamorphic assemblage, which can be used to identify regional patterns in carbonate isotopic compositions and to identify district-scale patterns around a porphyry deposit. The results of a pilot study testing this technique on a regional scale are presented here.

Samples

Sampling for geochemistry, conducted in the summers of 2009 and 2010 (sample locations shown on Figure 1), focused on coherent volcanic rocks or large volcanic clasts in volcaniclastic breccias. Our first field season concentrated on sampling Nicola Group basalt from the following four regions, which form the study area for this paper:

- near Mount Polley, in an arc sequence hosting broadly coeval porphyry Cu-Au mineralization related to silica-undersaturated magmatism (Logan and Bath, 2005)
- near Mount Milligan, where Cu-Au mineralization is related to silica-saturated alkalic intrusions that are approximately 20 m.y. younger than the volcanic hostrocks (Nelson and Bellefontaine, 1996)
- northeast of Bridge Lake, in an apparently barren part of the arc
- near Lac la Hache, in reportedly significant porphyry Cu-Au mineralization that probably has a temporal relationship to volcanism similar to that observed at Mount Polley (Schiarizza et al., 2008; Figure 1)

Additional sampling in southern BC was carried out in 2010; however, full results are not yet available.

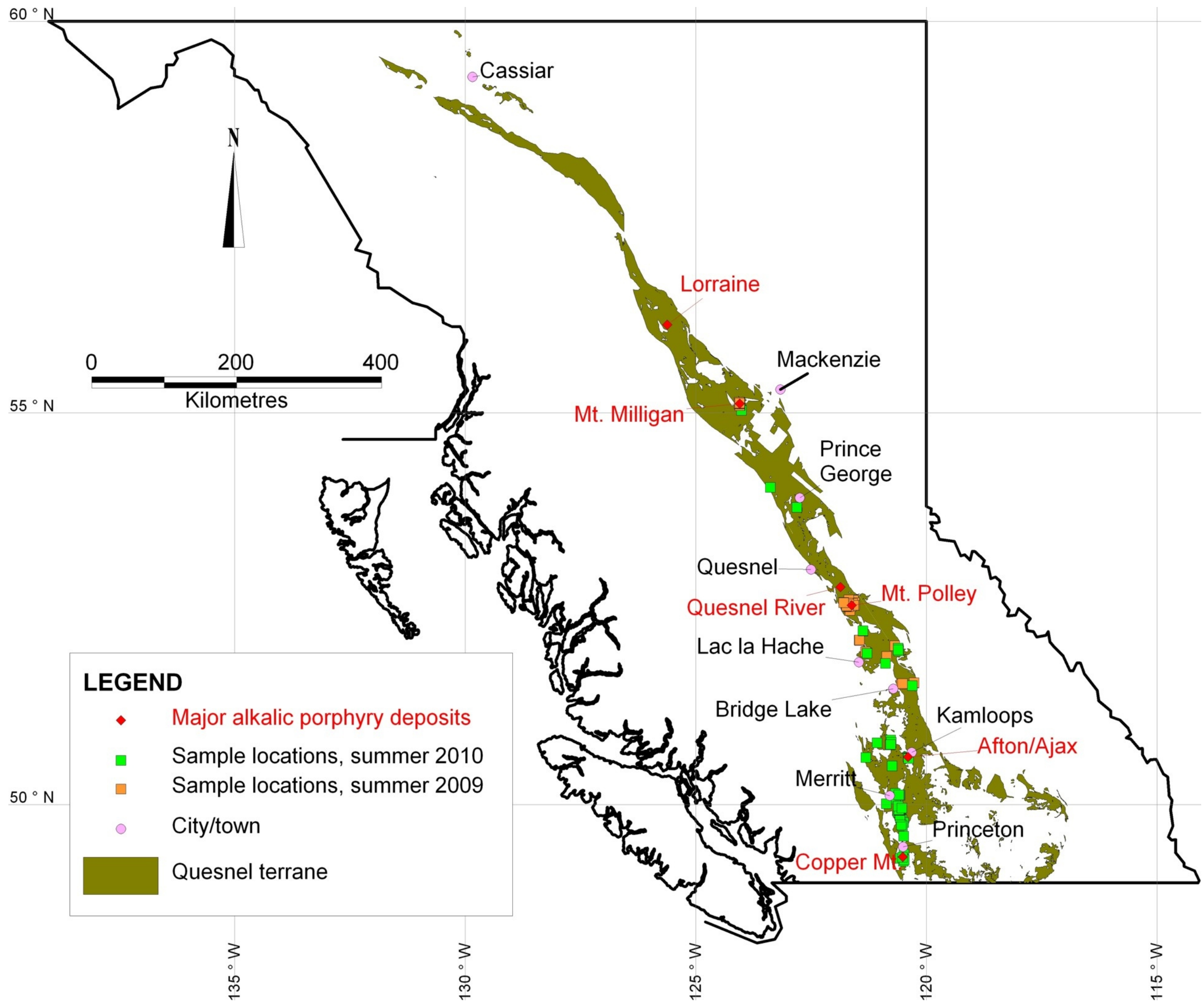


Figure 1. Major alkali porphyry Cu-Au deposits in the Quesnel terrane of Britiish Columbia, showing sample locations from 2009 and 2010 fieldwork.

Analytical Procedures

Magnetic susceptibility was measured in the field, using a KT-9 Kappameter handheld instrument. This device automatically displays the true measured susceptibility of the sample in dimensionless SI units, with a sensitivity of 1 10^{-5} SI units. The values reported are the average of 10 readings for the outcrop or sample (see also Bissig et al., 2010).

Forty-two Nicola Group basalt samples collected in 2009 were analyzed at the ALS Chemex laboratory, North Vancouver, BC by the major- and trace-element whole-rock package ME-MS81D, which uses a Li-borate fusion and inductively coupled plasma–mass spectrometry (ICP-MS) technique. Ferrous iron was measured in twenty-three selected samples by H_2SO_4-HF acid digestion and titrimetric finish (ALS Chemex, Fe-VOL05 package), to obtain Fe^{2+}/Fe^{3+} ratios.

A subset of twenty-five samples with calcite-chlorite-epidote alteration assemblages were analyzed for stable carbon and oxygen isotopes ($^{13}C_{PDB}$[1] [‰], $^{18}O_{SMOW}$[2] [‰]) using a modified Los Gatos Research (LGR) DLT-100 infrared spectroscopic analyzer at the University of British Columbia. This instrument analyzes CO_2 gas extracted from carbonates after rock powder has been exposed to 100% phosphoric acid at ambient temperatures.

Petrography and Geochemistry

Petrography of the basalts shows that the presence of opaque inclusions in pyroxene phenocrysts is not uniformly distributed across the study area. The Mount Polley and Lac la Hache areas have primary magnetite inclusions

[1] *normalized to Pee Dee belemnite*
[2] *normalized to Standard Mean Ocean Water*

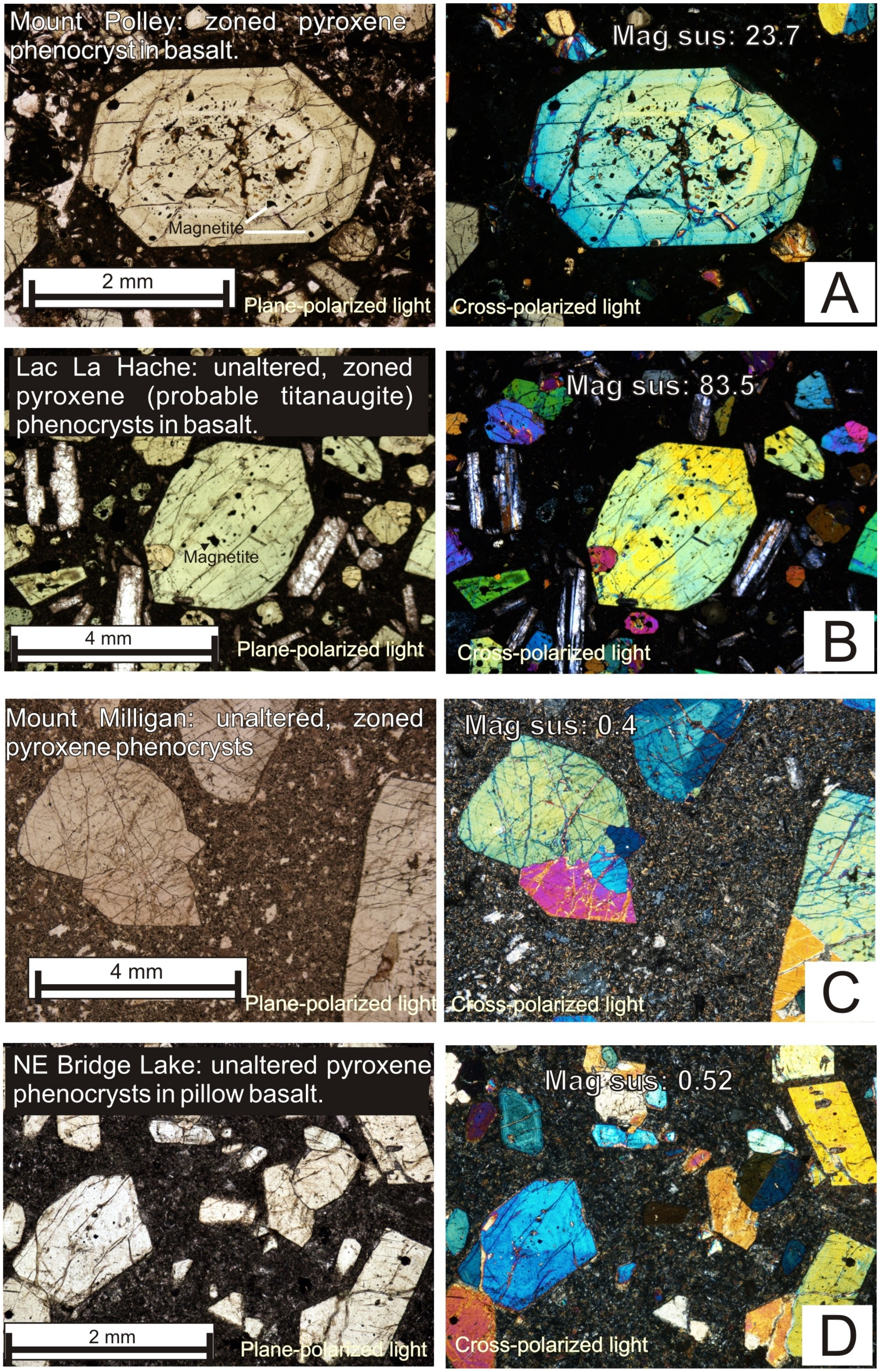


Figure 2. Unaltered zoned pyroxenes from the Nicola Group, south-central British Columbia; note that the Mount Polley **(A)** and Lac la Hache **(B)** areas contain opaque magnetite inclusions, whereas the Mount Milligan **(C)** and Bridge Lake **(D)** areas lack magnetite inclusions; magnetic susceptibility measurements for each suite are indicated.

in pyroxene (Figure 2A, B), whereas magnetite inclusions are normally absent in the Mount Milligan area and northeast of Bridge Lake (Figure 2C, D).

Basalts of the northern and central parts of the Quesnel terrane straddle the alkalic-calcalkalic boundary, with some samples plotting just into the subalkalic field in the bivariant diagram of Irvine and Baragar (1971; Figure 3A). All rocks fall within the arc-basalt field when using the ternary Zr-Th-Nb plot of Wood (1980; Figure 3B). The geochemical variations between the different areas are subtle, but basalts from the Mount Polley area are slightly more alkaline, generally having higher Na_2O concentrations at given SiO_2 contents compared to the other areas sampled (Figure 4). At a given SiO_2 content, rocks from Mount Polley and Lac la Hache also have higher Al_2O_3/MgO ratios and lower MgO content (Figure 4).

Overall, these rocks from the northern and central Quesnel terrane have an SiO_2 content of 45–55 wt. % (Figure 4) and exhibit less variation than those reported by Mortimer (1987) from the southern part of the belt, where volcanic rocks have ~47–70 wt% SiO_2. The basalts from near Lac la Hache and Mount Polley are also characterized by low Fe^{2+}/Fe^{3+} ratios (<1.5) and high magmatic susceptibilities of up to 110 10^{-3} SI (Figure 5), which is indicative of a relatively high oxidation state. This contrasts with the basalts from Bridge Lake and Mount Milligan, where Fe^{2+}/Fe^{3+} ratios are between 1.5 and 6.5, and magnetic susceptibility is generally <30 10^{-3} SI (Figure 5; see also Bissig et al., 2010).

The basalts can thus be subdivided into two groups. Group 1 includes the Bridge Lake and Mount Milligan areas and is characterized by relatively reduced basalts with moderate Na content. These basalts lack a close temporal relationship to known porphyry Cu-Au mineralization. Group 2, which includes the Mount Polley and Lac la Hache areas, is characterized by relatively oxidized basalts that have relatively low MgO (Figure 4D) but high Na_2O (Figure 4B). These are thought to have erupted immediately prior to a change to intrusive activity and porphyry mineralization, and are thus thought to be broadly coeval with the mineralizing magmatic-hydrothermal system (Logan and Bath, 2005; Schiarizza et al., 2008)

Stable Isotopes

Carbonate minerals in rock samples affected by a calcite-chlorite-epidote overprint were analyzed for stable carbon and oxygen isotopes ($^{13}C_{PDB}$ [‰], $^{18}O_{SMOW}$ [‰]) to identify regional patterns. The analyzed samples were collected at least 1 km away from known mineralization, but usually much farther.

Group 1 samples have ^{13}C values of –16 to –7‰, and ^{18}O generally varies between +8 and +16, with one value at +20‰ (Figure 6). Group 2 samples exhibit slightly less negative values of ^{13}C (–6 to +2‰) and overall slightly higher ^{18}O values (+12 to +22‰; Figure 6). For comparison, calcite from propylitically altered rocks at the Quesnel River alkalic intrusion–related Au deposit (Melling et al., 1990; Panteleyev et al., 1996; MINFILE 093A 121; BC Geological Survey, 2010), hosted in Nicola-equivalent Takla Group basaltic rocks, have ^{13}C values from –10 to –7‰ and ^{18}O varying from +10 to +14‰ (Melling, et al., 1990; Figure 6), and fall within the range of group 1.

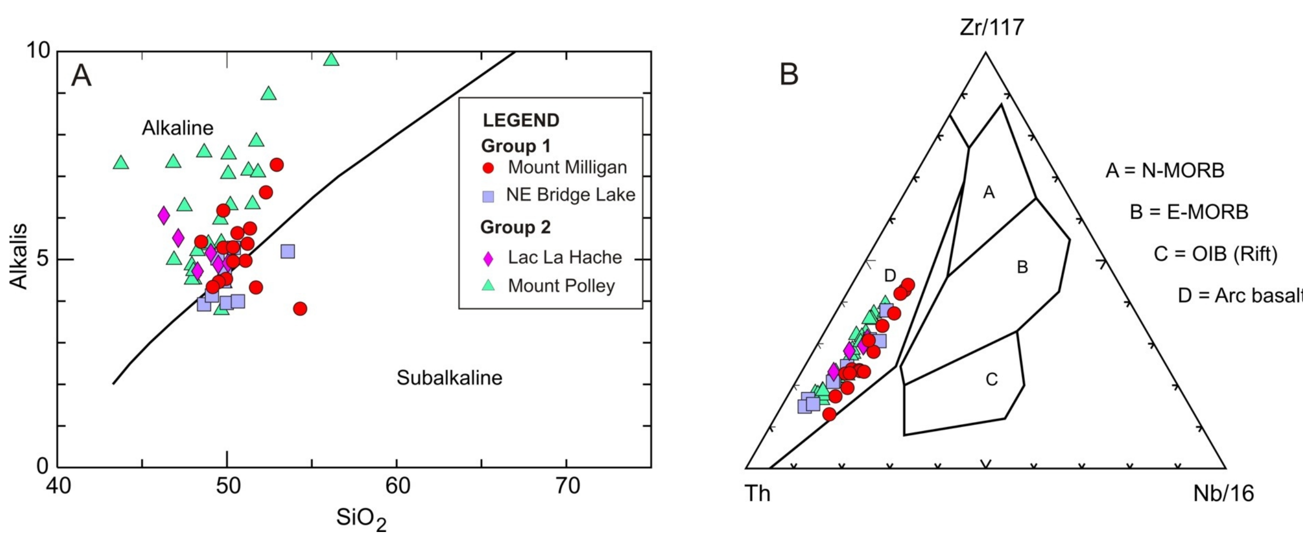


Figure 3. Classification of Nicola Group basalts: **A)** Plot of SiO_2 vs. Na_2O+K_2O (Irvine and Baragar, 1971), indicating the alkaline nature of the basalts of the Quesnel terrane; rocks from northeastern Bridge Lake and some from Mount Milligan have a subalkaline signature (Group 1), whereas basalts from Mount Polley and Lac la Hache are somewhat more alkaline (Group 2); **B)** Th–Zr/117–Nb/16 plot (Wood, 1980), indicating that all the rocks belong to a magmatic-arc tectonic setting.

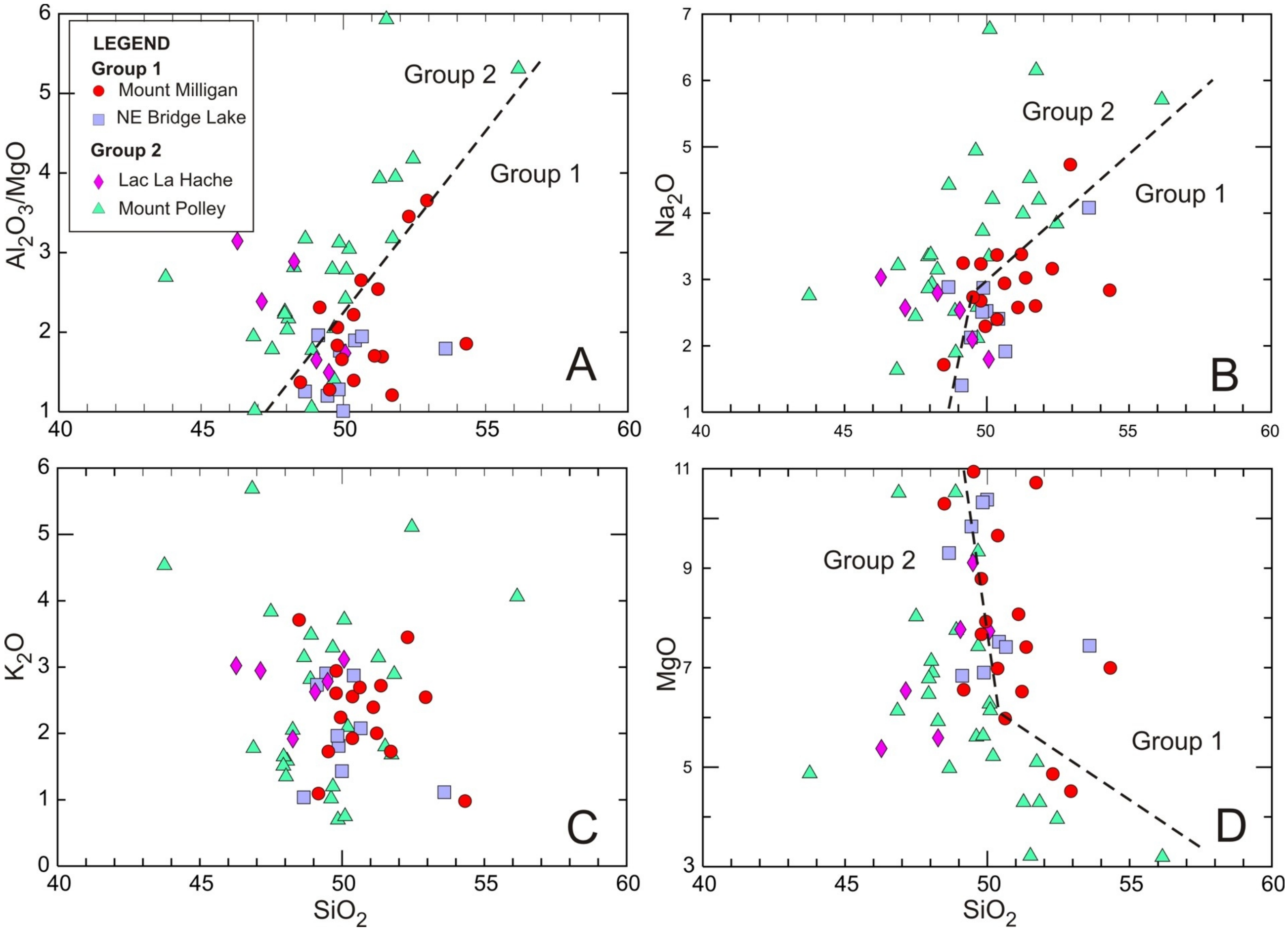


Figure 4. Harker-type diagrams for basalts from the Nicola Group. Two groups can be separated on the basis of Na and Mg content, as well as Al_2O_3/MgO ratios at given SiO_2: group 1 includes basalts from Mount Milligan and northeast of Bridge Lake; group 2 includes basalts from the Mount Polley and Lac la Hache areas.

Discussion

This project seeks to understand the geochemical and physical characteristics along and across the Late Triassic volcanic-arc components of the Quesnel terrane, which host porphyry Cu-Au mineralization.

The Nicola Group in southern BC consists of three major belts that show a west to east chemical variation (Mortimer, 1987). The western belt comprises augite- and plagioclase-phyric basalts and andesites with a calcalkalic affinity. Basalts from the central and eastern belts are petrographically similar to each other, consisting mainly of augite-phyric basalt, locally analcime bearing, and heterogeneous andesite and basalt. The central belt is characterized by variably tholeiitic to alkalic affinity, whereas the eastern belt is predominantly alkalic (shoshonitic). Paleontological data

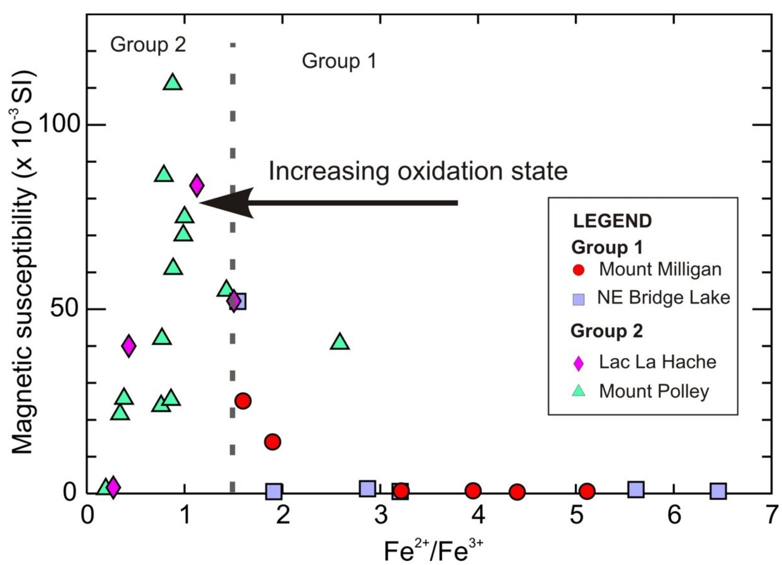


Figure 5. Plot of Fe^{2+}/Fe^{3+} versus magnetic susceptibility for weakly altered coherent basalts of the Quesnel terrane, showing the similarities between basalt samples from the Mount Milligan and northeastern Bridge Lake areas (Group 1) and the samples from the Mount Polley and Lac la Hache areas (Group 2), the latter with relatively high oxidation states and magnetic susceptibility measurements.

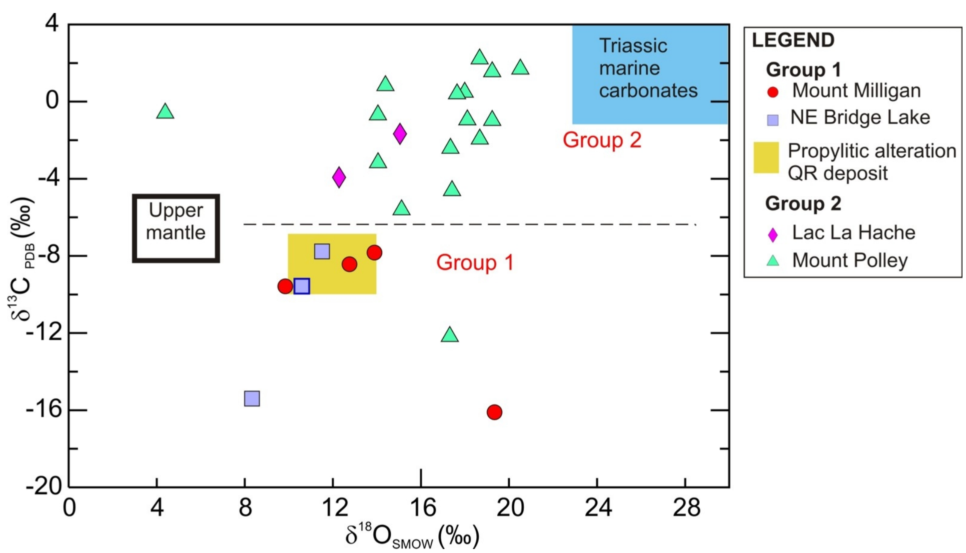


Figure 6. Plot showing the $^{18}O_{SMOW}$ (‰) and $^{13}C_{PDB}$ (‰) compositions of carbonate from basalts with propylitic alteration assemblages in the north-central part of the Quesnel terrane; fields for the Quesnel River Au deposit (Melling et al., 1990), Triassic marine carbonate rocks (Veizer et al., 1999) and upper mantle (Taylor et al., 1967) are shown for comparison.

suggest that the eastern belt is younger (Late Norian, ca. 204 Ma) than the western belt (Late Carnian–Early Norian, ca. 216 Ma; Carter et al., 1991).

North of latitude 51°N, these three belts have not been systematically documented or characterized geochemically prior to this study. The preliminary results presented above show that geochemical differences between volcanic rocks are subtle. However, variations in the magnetic susceptibility values and Fe^{2+}/Fe^{3+} ratios are distinctive and, combined with the regional interpreted aeromagnetic map (Logan et al., 2010), allow the separation of the volcanic arc into a more magnetic and presumably more oxidized western belt and a more reduced eastern belt (Figure 7). These belts are tentatively correlated with the central and eastern belts, respectively, described by Mortimer (1987) for the southern Nicola Group based on geochemistry (Figure 7).

Carbon isotope (^{13}C) values show a systematic variation according to magnetic susceptibility and oxidation state. Negative carbon isotope values coincide with relatively reduced segments of the arc and may suggest a greater contribution of organic carbon than in the more oxidized samples from around Mount Polley and Lac la Hache. The two groups cannot clearly be distinguished on the basis of the ^{18}O data, although group 2 samples may have higher ^{18}O values. The overall range between 8 and 22‰ falls between upper mantle and oceanic carbonate ^{18}O compositions (Figure 6). Although these preliminary isotopic data cannot be interpreted conclusively, they are consistent with a partly marine carbonate source for calcite in the group 2 basalts. This could suggest that the eruption of the Mount Polley and Lac la Hache basaltic rocks occurred in relatively shallow water, where marine carbonate was present.

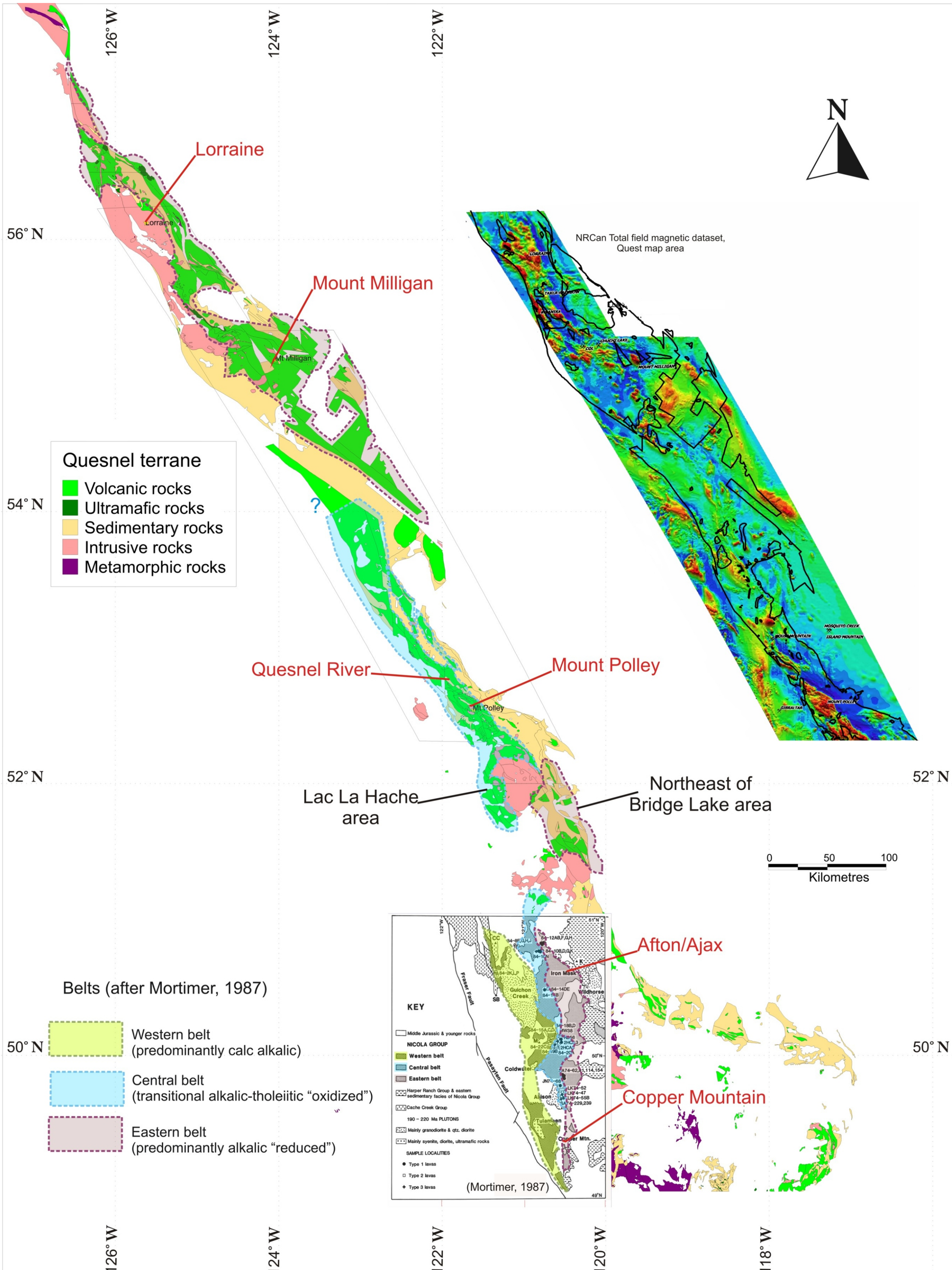
Low Fe^{2+}/Fe^{3+} ratios and high magnetic susceptibilities suggest an oxidized magmatic source for the group 2 basalts. A high oxidation state is characteristic of igneous rocks related to porphyry Cu-Au mineralization (e.g., Seedorff et al., 2005; Chamberlain et al., 2007). Mount Polley was emplaced into a relatively oxidized arc segment, which is consistent with the close temporal and genetic relationship between basalt and porphyry Cu-Au–related intrusive activity at Mount Polley (Logan and Bath, 2005).

Current and Future Work

Additional work on samples collected during the summer of 2010 will help us understand the spatial distribution of the different volcanic belts within the Quesnel terrane. Field observations will permit petrographic comparisons between the belts defined by Mortimer (1987) in southern BC and our interpreted belts in the north-central part of the province.

Analcime-bearing basalts have been identified in Mortimer's central belt, as well as in our interpreted central belt (Figure 8). At Mount Polley, such rocks are found within a few kilometres of Cu-Au mineralization, whereas no major mineralization is known to be spatially related to analcime-

Figure 7. Proposed arc segments within the Quesnel terrane. The belts of southern British Columbia have been interpolated to the north using the NRCan total-field airborne magnetic dataset (in Logan et al., 2010), geochemical and physical evidence, and field observation. The geological map is based on the digital data included in Goodfellow (2007).



126° W
124° W
122° W
120° W
118° W
56° N
54° N
52° N
50° N
N
Lorraine
Mount Milligan
Quesnel River
Mount Polley
Lac La Hache area
Northeast of Bridge Lake area
Afton/Ajax
Copper Mountain
NRCan Total field magnetic dataset, Quest map area
Quesnel terrane
Volcanic rocks
Ultramafic rocks
Sedimentary rocks
Intrusive rocks
Metamorphic rocks
0
50
100
Kilometres
Belts (after Mortimer, 1987)
Western belt
(predominantly calc alkalic)
Central belt
(transitional alkalic-tholeiitic "oxidized")
Eastern belt
(predominantly alkalic "reduced")
KEY
(Mortimer, 1987)

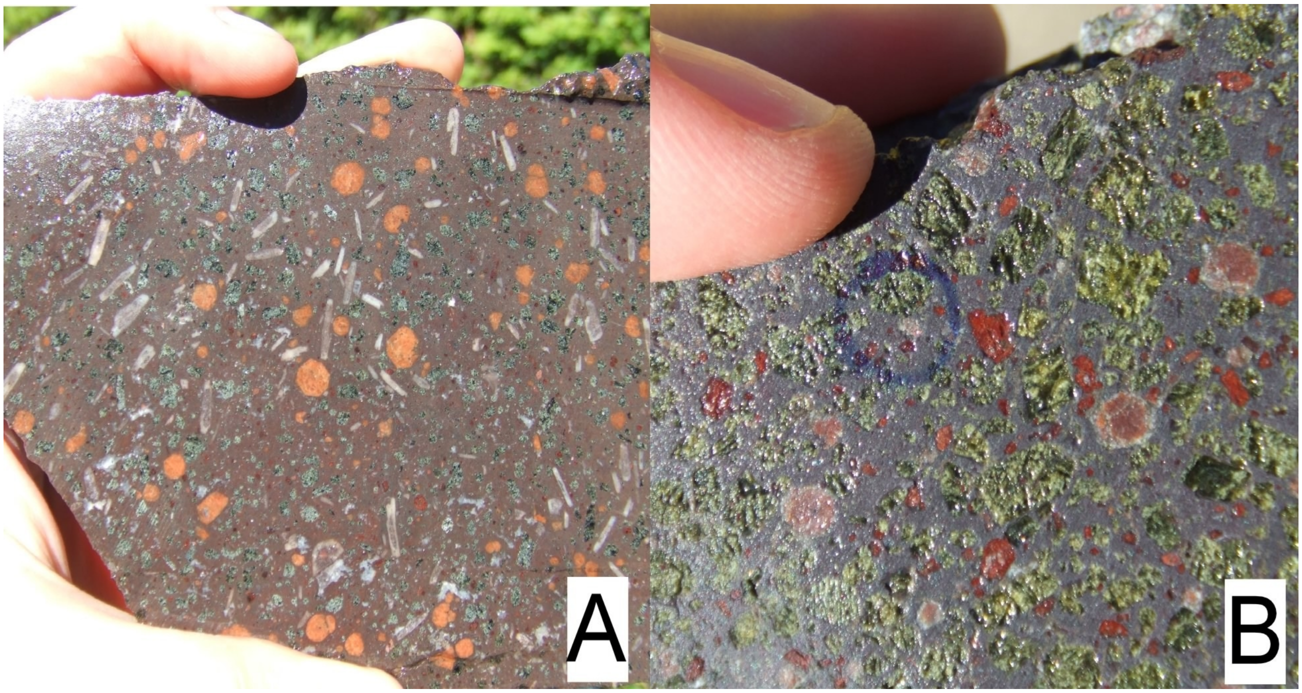


Figure 8. Analcime-bearing basalts, south-central British Columbia: **A)** reddish, pyroxene-plagioclase-analcime–phyric basalt in the Mount Polley area; **B)** pyroxene-analcime–phyric basalt of Mortimer's (1987) central belt, southern BC. The blue circle shows specks of native Cu within an analcime phenocryst.

bearing basalts in the south. Nevertheless, small specks of native copper were recognized within those basalts, indicating at least a spatial link between the basalts and high Cu content.

Research in the upcoming year will include further geochemical analyses of samples collected in 2010, as well as density measurements of the basalts. Petrographic work will include investigation of the textural relationship of the Cu contained in analcime-bearing basalts.

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