Continued Investigations of Physical Property–Geology Relationships in Porphyry-Deposit Settings in the QUEST and QUEST-West Project Areas, Central British Columbia (NTS 093E, K, L, M, N)

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Introduction

In 2007 and 2008, Geoscience BC supported regional-scale airborne electromagnetic and magnetic surveys over central and west-central British Columbia with the intent to improve geological understanding in Quaternary sediment–covered areas, and thus to encourage mineral exploration in these underexplored regions. As part of the QUEST and QUEST-West geophysical programs, six known porphyry deposits were also surveyed on a more detailed scale (Figure 1). Physical rock property studies based on sample suites from these deposits attempt to define relationships between porphyry deposit geology and geophysics. The results of these studies presented herein are of interest not only for interpretation of the recently collected geophysical datasets, but for application to geophysical exploration programs in similar geological settings throughout central BC.

Magnetic susceptibility data from the Mount Milligan (MINFILE 093N 194; BC Geological Survey, 2010), Endako (MINFILE 093K 006) and Huckleberry (MINFILE 093E 037) porphyry deposits were previously reported in Mitchinson and Bissig (2010a). Mount Milligan downhole and outcrop susceptibility measurements have also been used to generate constrained inversions of magnetic data collected over this deposit (Mitchinson and Bissig, 2010b). This paper summarizes the results of continued physical property studies on the Mount Milligan, Endako and Huckleberry deposits and provides an initial assessment of magnetic susceptibility data from three additional porphyry deposits from Geoscience BC's QUEST-West Project area: the Morrison

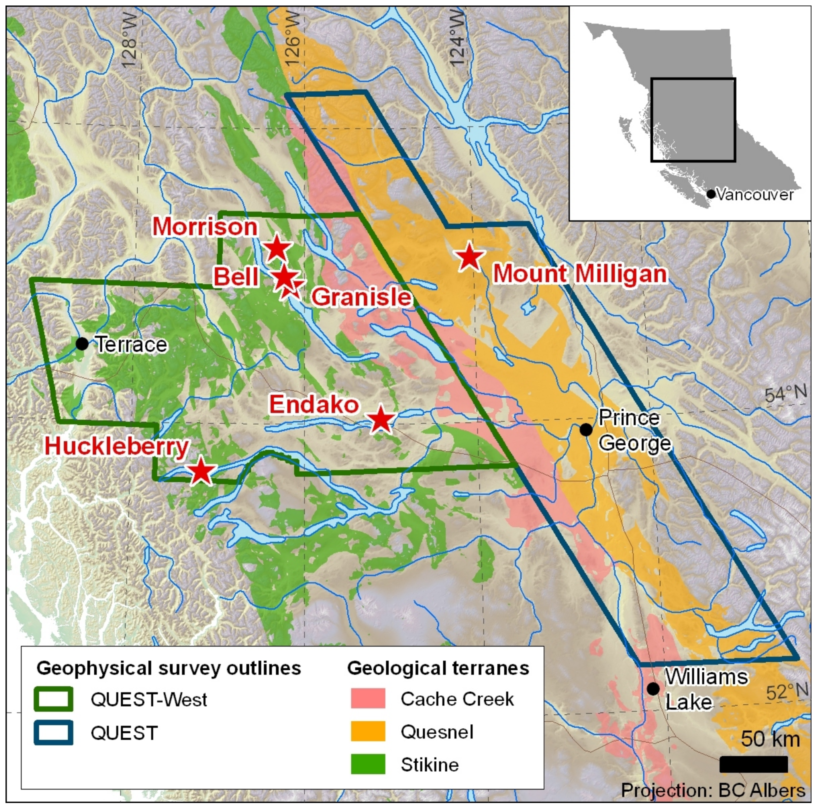

Figure 1. Areas covered by the Geoscience BC QUEST and QUEST-West airborne electromagnetic (EM) and magnetic geophysical surveys of central British Columbia. Locations of infill surveys completed over six known porphyry deposits (the Mount Milligan, Endako, Huckleberry, Granisle, Bell and Morrison deposits [BC Geological Survey, 2010]) are indicated. Base map data are from Natural Resources Canada (2004, 2010). The digital elevation model was prepared by K. Shimamura (Geological Survey of Canada). Geology and deposit locations are from Massey et al. (2005) and MINFILE, respectively.

Keywords: *porphyry deposit, physical properties, density, conductivity, magnetic susceptibility, QUEST, QUEST-West, Mount Milligan, Endako, Huckleberry, Granisle, Bell, Morrison*

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deposit (MINFILE 093M 007), a developed Cu (±Au±Mo) porphyry prospect, and the Bell (MINFILE 093M 001) and Granisle (MINFILE 093L 146) deposits, both past-producing Cu (±Au±Ag±Mo) porphyry deposits.

Background

The porphyry deposits examined in this study belong to two subtypes and represent four magmatic episodes. The Mount Milligan deposit is an alkalic porphyry Cu-Au deposit. Mineralization at Mount Milligan is spatially related to alkalic (silica-saturated) monzonitic plugs of the Early Jurassic, hosted within Takla Group volcanic rocks of the Quesnel terrane. The Endako, Huckleberry, Morrison, Bell and Granisle porphyry deposits all have a calcalkalic affinity and occur within the Jurassic to Cretaceous volcanic and sedimentary stratigraphy of the Stikine terrane. Endako is linked to Late Jurassic magmatism, Huckleberry to Cretaceous magmatic events, and Granisle, Bell and Morrison to Eocene intrusive rocks.

Initial physical property work has shown that the magmatic affinities of porphyry intrusions and related hydrothermal alteration, as well as the hostrock setting, play important roles in controlling the magnetic susceptibility signatures of the Mount Milligan, Endako and Huckleberry deposits. Proximal potassic alteration associated with alkalic porphyry deposits is commonly associated with magnetite formation. This relationship is evident in magnetic susceptibility data from Mount Milligan (Mitchinson and Bissig, 2010a). One of the key differences between calcalkalic and alkalic porphyry systems is the presence of extensive phyllic and argillic alteration zones in the former, contrasting with the latter, where phyllic and argillic alteration is restricted (Jensen and Barton, 2000). Magnetite is usually a less significant component of potassic zones in calcalkalic systems, but it may be that early magnetite-bearing potassic alteration assemblages are overprinted by later, lower-temperature magnetite destructive hydrothermal fluids. At Huckleberry and Endako, susceptibility data showed that phyllic and argillic alteration at these sites caused the destruction of magnetite (within host granite at Endako and within a magnetite-rich hornfelsed volcanic tuff at Huckleberry), reducing susceptibility in proximity to mineralized zones. Ongoing studies continue to highlight the influence of magmatic affinity and alteration zonation on physical property trends associated with BC porphyry deposits.

Density, Conductivity and Porosity Data from Mount Milligan, Endako and Huckleberry Deposits

Methods

Density, conductivity and porosity were measured at the Geological Survey of Canada–Pacific in Sidney under the supervision of the second author. Physical property measurements are made on 2.2 cm long cylindrical cores 2.5 cm in diameter, drilled from larger core samples or from hand samples. Skeletal density is measured for all samples using the hydrostatic method (Muller, 1967). Skeletal density accounts for only the mineral volume and not the connected pore space. Bulk density is measured on the core using geometric methods, and this paper reports on these measurements. The porosity can be calculated by determining the difference between the skeletal and bulk density, and normalizing the difference by the skeletal density. Samples with low apparent porosities (nearing zero) generally have higher associated errors with precisions of approximately ±2%. Resistivity data are derived from complex electrical impedance frequency spectra as per the method described in Enkin et al. (2011). Conductivity, the inverse of resistivity, is used interchangeably with resistivity in this paper. Sample population, mean and standard deviations related to data for the significant lithological and alteration groups are shown with each of the density and conductivity histogram plots.

Mineralogical composition, mineral abundance and mineral distribution, especially of sulphides and oxides, strongly influence the physical properties of a rock. To begin exploring the mineralogical controls on magnetic susceptibility, density and conductivity, a representative suite of 32 samples from Mount Milligan were analyzed using X-ray diffraction (XRD) Rietveld refinement methods described by Raudsepp and Pani (2003). The analysis was conducted by E. Pani at The University of British Columbia.

Density and Conductivity Studies

A brief introduction is given in the respective sections for geological setting, alteration zonation and mineralization related to the Mount Milligan, Endako and Huckleberry deposits. For more detailed descriptions of deposit geology and results of magnetic susceptibility analyses, see Mitchinson and Bissig (2010a).

Mount Milligan

Copper-gold mineralization at Mount Milligan is spatially related to several alkalic monzonite plugs that have intruded into basaltic volcanic and volcaniclastic rocks of the Takla Group of the north-central Quesnel terrane. Potassic alteration coincides with the mineralized core of the system. The potassic alteration grades outward into a sodic-calcic alteration zone, and finally into a propylitic alteration zone.

Mineralogy appears to best explain the variations in density seen in the Mount Milligan samples. The sample group with the highest average density (3.06 g/cm^3) is the propylitically altered basalt suite (Figure 2). These samples have the greatest abundance of mafic minerals, such as clinopyroxene (augite) and actinolite (3.31 and 3.07 g/cm^3, respectively; Ralph and Chau, 2010a, b). Basaltic rocks prox-

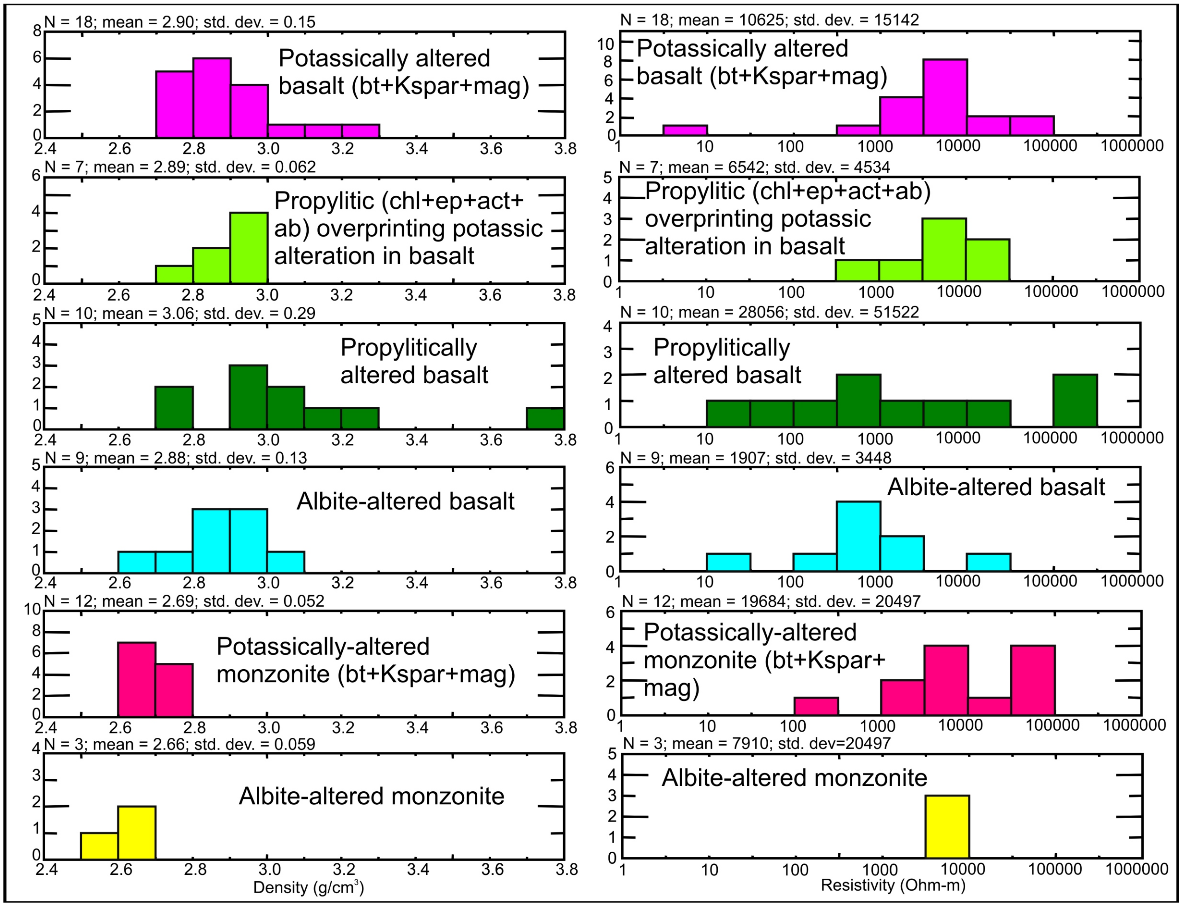

Figure 2. Density (left) and resistivity (right) data for basalt and monzonite samples taken from drillcore at the Mount Milligan deposit, central British Columbia. Abbreviations: ab, albite; act, actinolite; bt, biotite; chl, chlorite; ep, epidote; Kspar, K-feldspar; mag, magnetite; N, number of samples; std. dev., standard deviation.

imal to mineralization are altered to mineral assemblages increasingly dominated by felsic minerals; consequently, their density is lower. The lowest density samples are monzonitic (<2.66 g/cm^3). Monzonite is dominated by the low-density felsic minerals, albite and microcline (2.62 and 2.56 g/cm^3, respectively; Ralph and Chau, 2010c, d).

Propylitic and albitic (sodic-calcic)–altered basalt from Mount Milligan have lower average resistivities (higher conductivities) than potassically altered basalt (Figure 2). Propylitic and sodic-calcic alteration zones are correlative with high abundances of sulphides, specifically pyrite (Jago, 2008), and the presence of these metallic minerals potentially reduce the basalt's resistivity. X-ray diffraction mineral abundance data confirm that there is a positive correlation between sulphide abundance and conductivity (Figure 3). Monzonite intrusive rocks at Mount Milligan are generally resistive.

It is important to consider the scale of measurement when interpreting resistivity/conductivity data. Hand sample or drillcore measurements likely will not reflect measurements made at larger scales (over outcrops or larger areas), where district-scale structural fabrics or fractures and the presence of groundwater will influence measurements. The control on conductivity by larger-scale structural features may be seen in geophysical inversions of DC resistivity data from Mount Milligan (Oldenburg et al., 1997). The conductivity anomalies appear spatially correlated with known local faults (Figure 4). Since these faults coincide in part with the distribution of albite-rich and propylitic alteration assemblages, anomalies can potentially be attributed to the combined presence of sulphides and faulting.

Based on physical property assessments at Mount Milligan, with consideration of previous compilation of susceptibility data (Mitchinson and Bissig, 2010a), a prospective geophysical target at the deposit scale in the Mount Milligan area would comprise a high-susceptibility zone reflecting potassic alteration, coupled with low densities representing either monzonite intrusive rocks or altered rocks. Resistivities would be high at the core of the system, coinciding with altered volcanic rocks and monzonite, but would be lower in association with albitic and propylitic alteration shells.

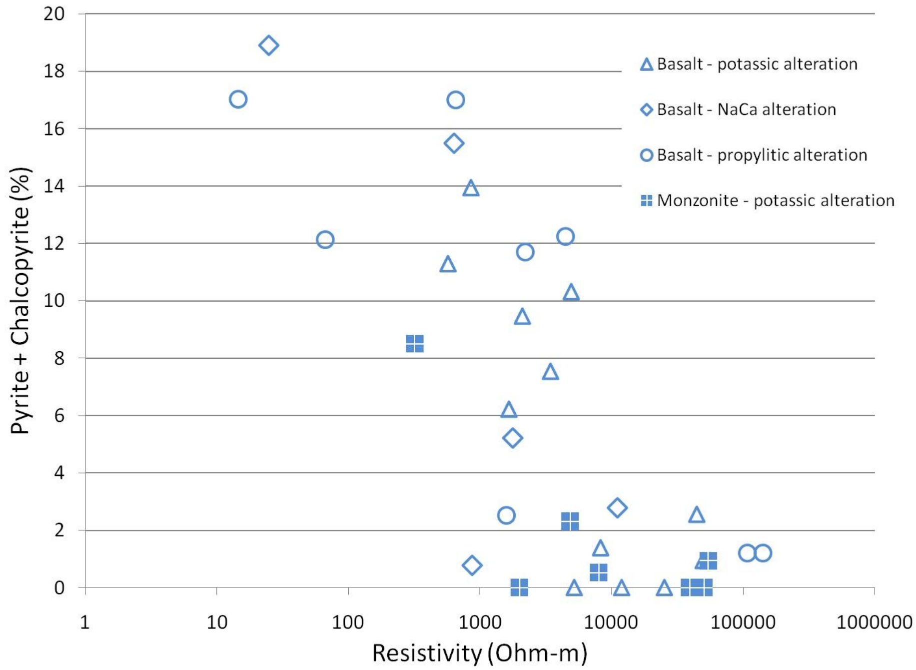

Figure 3. Percent total sulphides (pyrite+chalcopyrite) from X-ray diffraction (XRD) mineral abundance analyses versus resistivity data for Mount Milligan samples, central British Columbia. A negative correlation exists between the two variables, indicating that at Mount Milligan, increased sulphide content increases rock conductivities at the hand-sample scale.

Endako

The Endako Mo deposit occurs near the boundary between the Cache Creek and Stikine terranes, within the Endako quartz monzonite of the François Lake intrusive suite. The nearby Casey granite is temporally and potentially genetically related to the Endako deposit. Ore-related mineralization consists of an early pervasive potassic alteration, followed by later quartz-sericite-pyrite and clay (kaolinite) alteration.

It is difficult to discriminate between least-altered and altered Endako quartz monzonite (EQM) samples in the Endako deposit area based on density, due to the overlap in ranges of density data (Figure 5). From histograms, alteration has no apparent effect on this physical property. Casey granite samples are of similar density. Postmineral basalt dikes have average values only marginally higher than monzonite and granite densities. Their low densities could be due to their plagioclase-rich compositions.

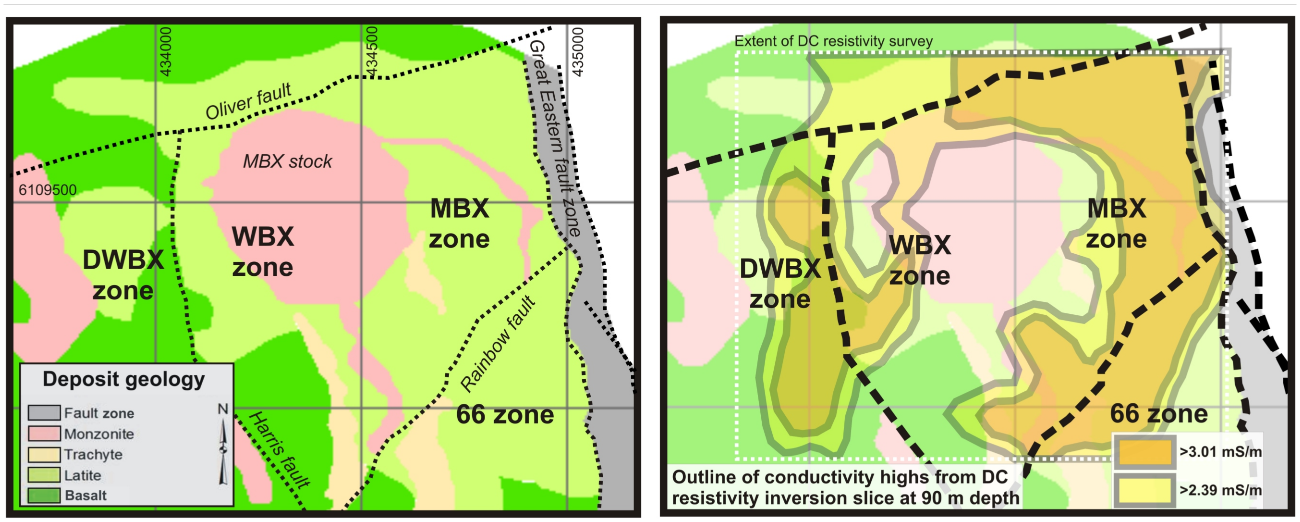

Figure 4. Plan-view geology of the Mount Milligan deposit, central British Columbia (left) and the same image overlain by conductivity anomalies associated with the Mount Milligan deposit, from DC resistivity inversions (right: Oldenburg et al., 1997). The four main mineralized zones related to the MBX stock at Mount Milligan are indicated. Outlines of high-conductivity zones are from a horizontal slice through the inversion result at 80 m depth. Mount Milligan base map files were provided by Terrane Metals Corp.

Least-altered EQM is relatively resistive (Figure 5). Least-altered samples having low resistivities correlate with low-susceptibility, 'least-altered' samples from Mitchinson and Bissig (2010a), and could indicate that these samples are actually weakly altered. As was previously indicated by Mitchinson and Bissig (2010a), even comparatively weak alteration can cause magnetite destruction and bring about a significant decrease in susceptibility. Resistivity drops with alteration, most noticeably in samples characterized by quartz-sericite-pyrite and clay (kaolinite)-dominated alteration. Their low resistivities (high conductivities) may be related to either pyrite in samples altered to quartz-sericite-pyrite assemblages, or to the higher porosities of the fissile clay-altered rocks. Two least-altered Casey granite samples have high resistivities, while it is unclear as to why a similar third sample is relatively conductive as there are apparently no sulphides and alteration is very weak. Postmineral basalt dikes are relatively resistive.

From this physical property assessment, an appropriate exploration strategy in the Endako area would target low susceptibilities caused by magnetite-destructive, ore-proximal alteration, combined with low density and low-resistivity zones indicative of strong sericite and clay alteration of granite.

Huckleberry

The Huckleberry deposit is a Cu-Mo porphyry deposit occurring in association with granodioritic plugs that intrude Hazelton Group andesitic rocks in the western Stikine terrane. Host andesite has been affected by hornfelsing related to intrusive activity. Biotite-quartz–dominated potassic alteration is coincident with mineralization. Granodiorite is overprinted additionally by sericite-clay alteration.

Histograms displaying density data for Huckleberry samples (Figure 6) show that hornfelsed and potassically al-

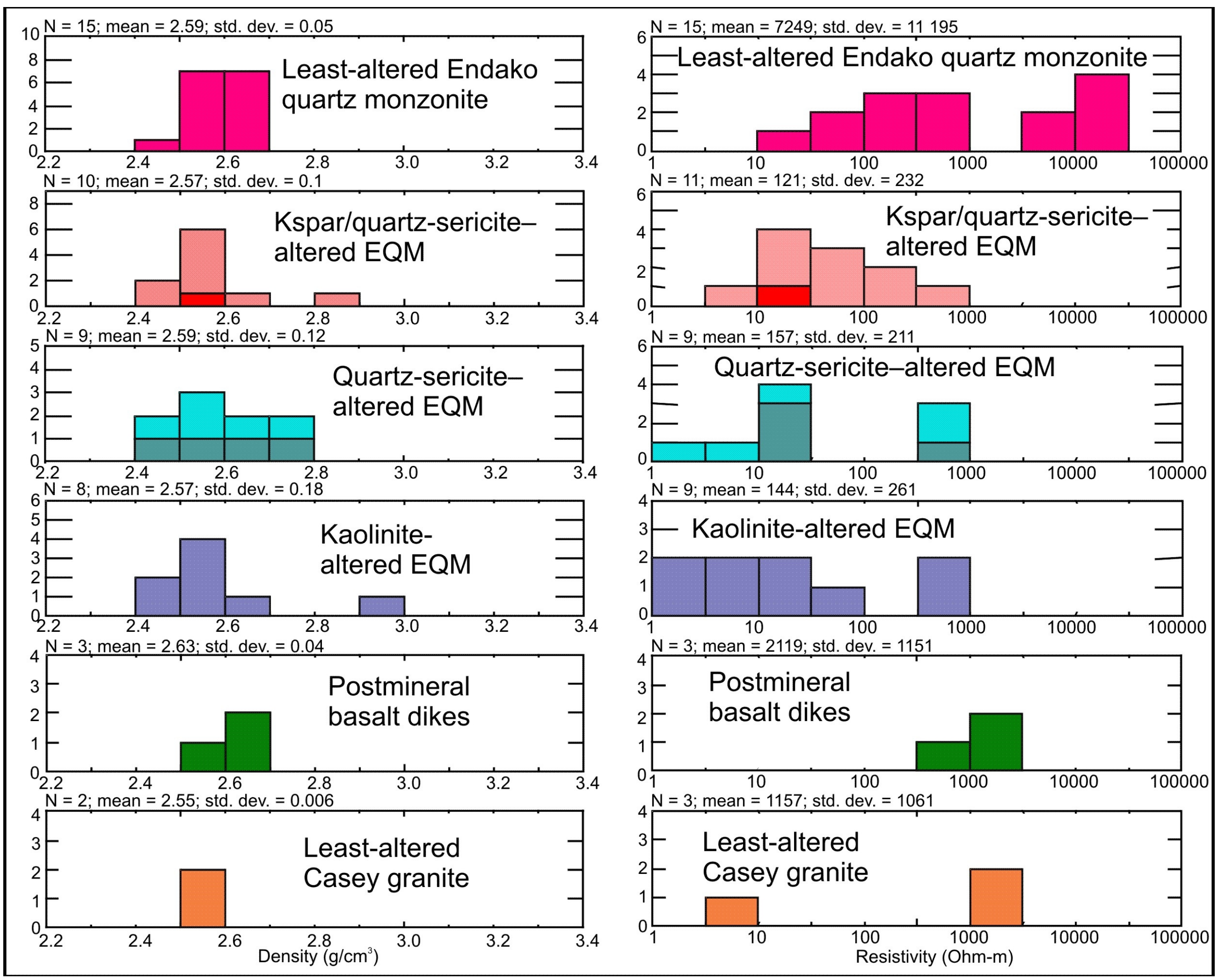

Figure 5. Density (left) and resistivity (right) data for samples taken from the Endako pit and from drillcore, central British Columbia. Abbreviations: EQM, Endako quartz monzonite; Kspar, K-feldspar; N, number of samples; std. dev., standard deviation.

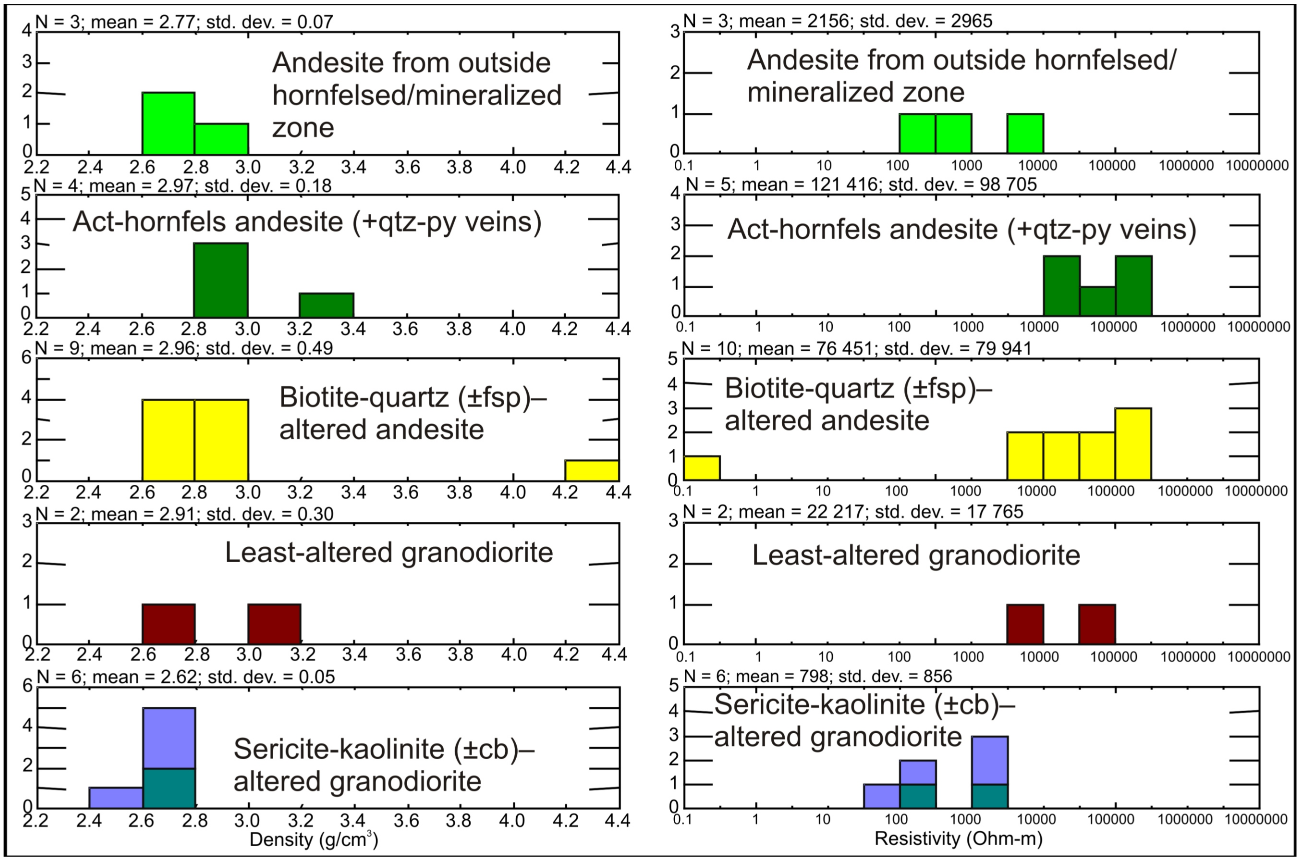

Figure 6. Density (left) and resistivity (right) data for andesite and granodiorite samples taken from the Huckleberry pit and from drillcore, central British Columbia. Abbreviations: act, actinolite; cb, carbonate; fsp, feldspar; N, number of samples; py, pyrite; qtz, quartz; std. dev., standard deviation.

tered (biotite-quartz) andesites have the highest average densities (2.97 and 2.96 g/cm^3, respectively), whereas background andesitic tuff samples from outside the zone affected by hornfelsing are the least dense of the andesite suite, which might reflect a slightly higher porosity. A slight decrease in density averages from andesite samples to granodiorite samples is apparent. As for Mount Milligan samples, this reflects an increase in felsic mineral content. The clay-altered granodiorite sample suite has the lowest average density; however, there are only two least-altered samples to compare with. One anomalously high-density biotite (potassically)–altered sample was collected from the ore zone and contains abundant sulphides (chalcopyrite and pyrite).

Altered andesitic rocks and least-altered granodiorite have resistivity ranges that generally overlap (Figure 6). Clay-altered granodiorite samples have the lowest resistivities (highest conductivities), a potential result of increased porosities in these more friable rocks. The anomalously low-resistivity biotite-quartz–altered andesite sample is the same sample as that described above, characterized by abundant sulphides and high density.

A geophysical exploration strategy in the Huckleberry area might target local susceptibility lows within areas characterized by high susceptibilities (representing magnetite-rich hornfels), and local density and resistivity lows reflecting clay-rich alteration of granodiorite, which contrasts the hornfelsed andesite.

Porosity Influence on Density and Conductivity

Rock density and conductivity are known to be influenced by rock porosity. The relative importance of mineralogy versus rock texture can be explored by considering the additional physical property.

Density and Porosity

In a plot of density versus porosity for all Mount Milligan, Endako and Huckleberry rock samples, a general trend of increasing density with decreasing porosity is evident (Figure 7a). The trend is especially apparent for Endako samples. In general, Endako samples are the most porous of the entire suite, likely because the extent of phyllic (quartz-sericite-pyrite) and argillic alteration was the greatest in Endako compared to the two other porphyry sites. An increase in mica and clay can cause the rock to become more friable and porous, thus decreasing the density of the rock. Correlations between density and porosity at Huckleberry and Mount Milligan are less clear cut. The lower density of intrusive rocks (open symbols) compared to volcanic rocks (closed symbols) is seen. Some Huckleberry granodiorite rocks altered to sericite and kaolinite have slightly higher porosities. Phyllic and argillic alteration at Huckleberry is apparently not developed to the same degree as at Endako. The Mount Milligan samples exhibit the weakest correlation. Some of the lower-density basalt samples (open symbols) have high porosities, which may in part be associated with brecciation, but there are no apparent trends between the two rock properties that can be related to alteration.

Conductivity and Porosity

When all samples are plotted, a negative correlation between resistivity and porosity is apparent (Figure 7b). With decreasing porosity, resistivity increases. Again, the correlation is best characterized by the Endako samples, which roughly trend from the high-resistivity (low-conductivity), low-porosity least-altered granite to the low-resistivity (high-conductivity), high-porosity K-feldspar–, sericite- and clay-altered granite. A similar trend, albeit slightly less evident, is obscured in the Huckleberry data; clay-sericite–altered granodiorite is less resistive than the least-altered granodiorite sample and the andesitic rocks. Alteration-related increases in porosity will allow water to permeate the rock, and through Archie's law, electrical conductivity increases with water content (Telford et al., 1990). Mount Milligan samples exhibit essentially no correlation between porosity and resistivity/conductivity and sulphide abundance remains the most important control on conductivity at this site (Figure 3).

Density versus Conductivity

When density and resistivity/conductivity are compared, the influence of alteration on rock texture and in turn, on physical properties, is further emphasized. Intrusive rocks (closed symbols) from all three porphyry deposits lie along a single trend of decreasing resistivity with decreasing density (Figure 7c). Those samples altered to clay±sericite have the lowest resistivities and the lowest densities. Mount Milligan monzonite intrusive rocks are the most resistive. Huckleberry volcanic rocks appear to follow this same trend. Mount Milligan volcanic rocks form a separate

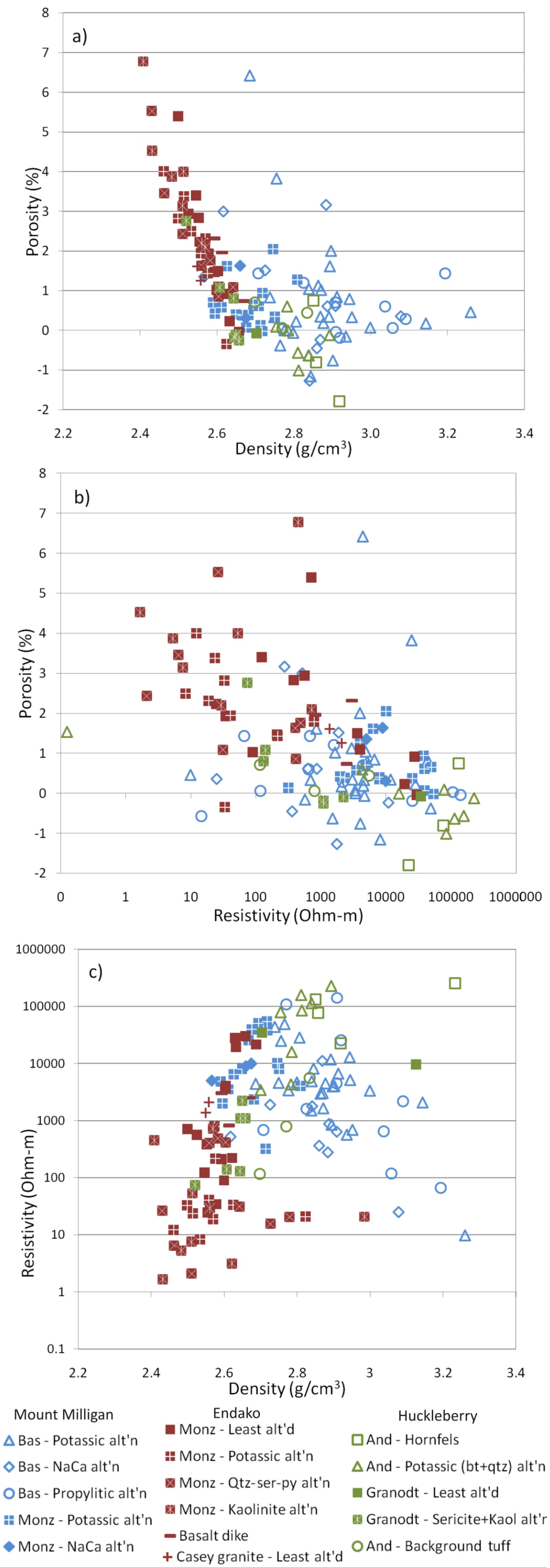

Figure 7. Plots showing relationships between rock type, alteration and porosity, and the influence of porosity on density and conductivity, central British Columbia: **a)** Relationship between density and porosity; **b)** relationship between conductivity and density and **c)** relationship between density and conductivity. Blue samples are from Mount Milligan, red are from Endako and green are from Huckleberry. Filled symbols represent important intrusive rocks and open symbols represent volcanic rocks. Abbreviations: alt'n, alteration; alt'd, altered; And, andesite; Bas, basalt; bt, biotite; Granodt, granodiorite; kaol, kaolinite; Monz., monzonite; py, pyrite; qtz, quartz; ser, sericite.

and contrary trend, as there is a decrease in resistivity (increase in conductivity) with an increase in density. This trend is related to the correlation of sulphides with marginal, higher-density, propylitic alteration assemblages.

Magnetic Susceptibility Data for the Morrison, Bell and Granisle Deposits

The Morrison, Bell and Granisle Cu (±Au±Ag±Mo) deposits belong to a region located within the western Stikine terrane referred to as the Babine porphyry copper district. The three porphyry deposits surveyed are similar in that mineralization is focused on a central Eocene biotite-feldspar–phyric intrusion (BFP), and alteration assemblages reflect 'classic' alteration patterns documented for calcalkalic porphyry deposits (e.g., Lowell and Guilbert, 1970). The deposits are aligned with the northwest-trending Morrison fault and the associated Newman fault. Biotite-feldspar porphyry plugs are interpreted to have intruded into dilational zones within graben structures adjacent to these faults during a period of Late Cretaceous to Early Tertiary extension (Dirom et al., 1995).

Despite similarities in associated intrusive rocks and alteration sequences, the three deposits are each hosted at different levels within the Jurassic to Cretaceous volcanic and sedimentary stratigraphy. The Granisle deposit sits within Early Jurassic Hazelton Group mafic volcanic rocks, the Morrison deposit is hosted in slightly younger Middle to Late Jurassic Bowser Lake Group sedimentary rocks and the Bell deposit is hosted in Early Cretaceous Skeena Group sedimentary rocks. Both the Granisle and Bell deposits are past-producing mines, while Morrison is a developed prospect.

The following results represent preliminary interpretations for the Morrison, Bell and Granisle sample suites for which samples have yet to be petrographically examined.

Magnetic susceptibility measurements were made at the Geological Survey of Canada–Pacific laboratory using a GF Instruments, SM-20 pocket magnetic susceptibility meter. Results are given in a series of histograms for better visual comparison of population distributions, but are also summarized in Table 1.

Granisle

Deposit Geology

The Granisle deposit is in the lowest stratigraphic position of the three deposits sampled. Mineralization is spatially related to two Eocene porphyritic intrusive units, a quartz-diorite microporphyry and a biotite-feldspar–phyric intrusive body, which were emplaced into Early Jurassic Hazelton Group volcanic and volcaniclastic rocks (Figure 8, left). The two intrusive units are interpreted to be cen-

Table 1. Statistical summary of magnetic susceptibility measurements for the Granisle, Bell and Morrison deposits, central British Columbia.

Deposit	Rock type	Alteration	No.	Min.	Max.	Mean	Median	Comments
Granisle	BFP	Biotite-magnetite	4	1.57	61.8	39.17	46.65	
	BFP	Ser (±cb, qtz, py)	2	0.1	0.24	0.17	0.17	
	BFP extrusive equivalent	Least altered	2	17.7	25.9	21.8	21.8	From west side of Newman Peninsula and from Bear Is.
	Granodiorite	Biotite-magnetite	3	22.3	45.3	35.7	39.5	
	Granodiorite	Qtz-ser-clay-py	1			0.03		
	Andesite tuff	Biotite-magnetite	1			42.7		
	Andesite tuff	Qtz-ser (±py)	4	0.08	20.8	5.3	0.17	
Bell	BFP	Biotite-magnetite	8	0.95	46	20.42	19.15	
	BFP	Qtz-ser (±py)	12	0	15.1	1.38	0.085	
	BFP extrusive equivalent	Weak qtz-ser	2	0.4	1.02	0.71	0.71	From Newman Is.—within Bell alteration halo
	Sedimentary	Biotite-magnetite	4	0.11	50.2	15.06	4.97	
	Sedimentary	Qtz-ser (±py)	6	0.01	0.42	0.22	0.2	
	Sedimentary	Ser-chl	1			0.13		
Morrison	BFP	Biotite-magnetite	8	0.45	63.8	18.51	11.27	
	BFP	Potassic, overprinted by qtz-ser-py	8	0.24	14.1	5.6	4.56	
	BFP	Qtz-ser-py	6	0.081	0.52	0.23	0.15	
	BFP	Clay	7	0.027	0.38	0.18	0.17	
	Sedimentary	Qtz-ser-py	11	0.035	9.86	1.62	0.17	

Magnetic susceptibility units are $\times 10^{-3}$ SI units. Abbreviations: BFP = biotite-feldspar porphyry; cb = carbonate; chl = chlorite; hem = hematite; py = pyrite; qtz = quartz; ser = sericite.

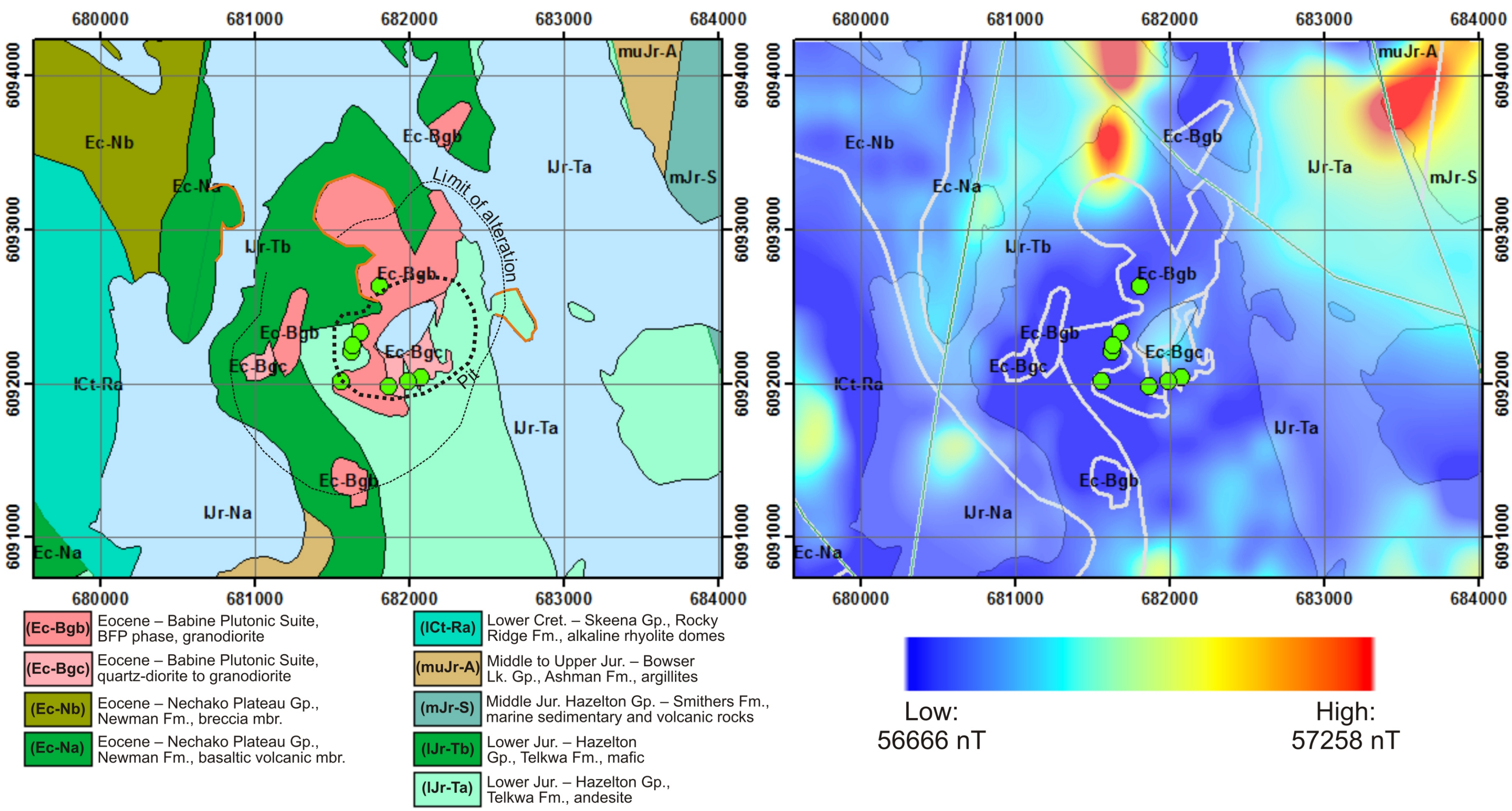

Figure 8. Map of Granisle deposit area geology, central British Columbia (left), showing pit outline, limit of alteration and location of hand samples collected from the perimeter of the open pit (green circles). Base map from Geoscience BC QUEST geology compilation (Williams and Ma, 2010). Pit outline and alteration limits from Dirom et al. (1995). Magnetic data (right) from Granisle deposit airborne variable time-domain electromagnetic (VTEM)/magnetic infill survey, Aeroquest Limited (2009).

tred on a zone of dilation occurring between two transverse faults (Dirom et al., 1995). Potassic biotite-magnetite alteration occurs in the core of the porphyry system. The majority of Cu ore is hosted in potassically altered quartz-diorite and BFP intrusive rocks. A later carbonate-sericite-quartz-pyrite alteration overprint occurs at the fringes of the deposit and most of the volcanic and intrusive rocks sampled from the upper walls of the pit for this study are extensively altered to this assemblage. This alteration assemblage is associated with low Cu grades and the affected rocks were considered waste for the mining operations (Dirom et al., 1995).

Regional aeromagnetic data from the Geological Survey of Canada and aeromagnetic data collected over the Granisle deposit as part of Geoscience BC VTEM (variable time-domain electromagnetic) infill surveying (Figure 8, right) indicate that the local Hazelton Group volcanic rocks are moderately to strongly magnetic. In the immediate vicinity of the Granisle deposit, however, background volcanic rocks and intrusive rocks are poorly magnetic. The exception is a small magnetic anomaly centred over the core of the Granisle pit, at the contact between the quartz diorite and the BFP intrusion.

Magnetic Susceptibility

Of the three Babine Lake area deposits, the Granisle sample suite contains the fewest number of samples. Although there was drillcore at the past-producing minesite, the core storage racks were partially collapsed, much of the core was unlabeled or depth markers were missing, and time spent at the site was limited. For this study, five samples were collected from the perimeter of the Granisle pit and were measured for magnetic susceptibility. Some outcrop measurements from the pit were used in addition to samples to enhance the dataset. Eight drillcore samples were collected, three of which have no location information.

Figure 9 compiles susceptibility data for intrusive (upper histogram) and volcanic rock (lower histogram, mainly Hazelton andesitic tuff) samples. Two samples collected from west of the Granisle deposit, outside the influence of alteration (not shown on map), are considered to represent Eocene extrusive equivalents of biotite-feldspar porphyry. These samples have moderate susceptibilities with an average of 21.8×10^{-3} SI units and are suspected to contain primary magnetite. Potassically altered BFP and granodiorite samples fall into a slightly higher susceptibility range (combined BFP and granodiorite samples average 37.68×10^{-3} SI units) with formation of secondary hydrothermal magnetite (possibly superimposed on primary magnetite). Carbonate-sericite-quartz-pyrite–altered BFP and granodiorite intrusive rocks have lower susceptibilities ranging from 0.03 to 0.17×10^{-3} SI units. Volcanic rocks show the same trends. A biotite-magnetite–altered tuff has a relatively high susceptibility of 42.7×10^{-3} SI units, whereas three carbonate-sericite-quartz-pyrite–altered volcanic rocks are associated with lower susceptibility ranges. A fourth carbonate-sericite-quartz-pyrite–altered andesite sample with a higher documented susceptibility may have been previously potassically altered and might contain relict secondary magnetite.

Based on susceptibility measurements collected from drillholes from the core of the mineralized system, the local magnetic anomaly over the Granisle pit (Figure 8) is likely related to the potassic alteration of the intrusive rocks. The magnetic anomaly might have once been more extensive prior to mining. At the time of the mine closing, the bulk of the mineralized, and likely the potassically altered, rock was thought to be almost completely mined out (Dirom et al., 1995). The magnetically weak zone surrounding the deposit might be attributed to strong overprinting carbonate-sericite-quartz-pyrite alteration that potentially caused destruction of primary and/or secondary magnetite within peripheral volcanic and intrusive rocks.

Bell

Deposit Geology

The Bell deposit was formed in association with BFP intrusive rocks that were emplaced into argillite and rhyolite domes of the Early Cretaceous Skeena Group (Figure 10).

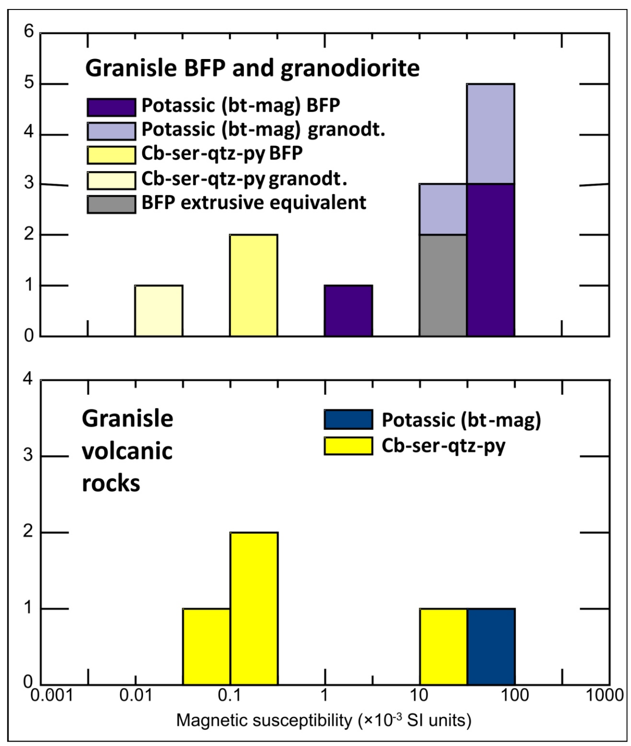

Figure 9. Histograms showing magnetic susceptibility data for variably altered intrusive (top) and volcanic (bottom) rock samples from the Granisle deposit, central British Columbia. Abbreviations: BFP, biotite-feldspar porphyry; bt, biotite; cb, carbonate; chl, chlorite; granodt., granodiorite; mag, magnetite; py, pyrite; qtz, quartz; ser, sericite.

Thus, this deposit sits higher in the Jurassic to Cretaceous volcanic and sedimentary package underlying the Babine Lake area than the Granisle deposit, which occurs in Jurassic volcanic rocks. The location of the deposit is controlled by the intersection of the northwest-trending Newman fault and a second east-northeast-trending fault (Dirom et al., 1995). Alteration is similar to that at Granisle, consisting of a potassic biotite-magnetite core surrounded by a distal propylitic alteration. Later sericite-carbonate alteration and a quartz-sericite-pyrite stockwork overprints earlier potassic alteration. Quartz-sericite-pyrite stockwork fringes the BFP intrusive and comprises an important alteration phase because it is associated with high Cu grades, which tend to decrease toward the biotite-magnetite–altered core of the intrusion. Results from isotope studies at Bell suggest the potential leaching and redepositing of Cu in association with later fluid boiling and modification by mixing with meteoric waters (Dirom et al., 1995). The Bell deposit is associated with an extensive, greater than 1100 m wide pyrite halo, which may in part be enhanced by pyrite-bearing Cretaceous argillite units. Airborne magnetic data indicate Skeena Group sedimentary rocks and rhyolite domes are nonmagnetic, contrasting with magnetic Cretaceous volcanic rocks in fault contact to the east. Eocene BFP intrusive rocks form clear positive magnetic anomalies within the only weakly magnetic sedimentary package (Figure 10).

Magnetic Susceptibility

Several magnetic susceptibility measurements were made on outcrop and hand samples from near the Bell site. Twenty-eight samples were collected from an archived drillcore library onsite. Drillcore from 25 core boxes representing 25 drillholes from a 1989–1990 drill program were measured for magnetic susceptibility. These downhole data will be presented in a future Geoscience BC paper.

Magnetic susceptibility data from BFP intrusive rocks at Bell show distinct bimodality (Figure 11). Potassically altered BFP dominates the high-susceptibility population, with the exception of one sample classified as quartz-sericite-pyrite altered. This sample, collected from deeper levels within the porphyry (294 m), may have been previously strongly potassically altered or may only have a weak phyllic overprint. Petrographic analysis will help determine the nature of the magnetite and degree of overprinting alteration. Otherwise, quartz-sericite-pyrite–altered BFP samples are associated with consistently low susceptibilities (ranging from 0 to 0.65×10^{-3} SI units).

Four potassically altered sedimentary samples were collected and these had relatively high susceptibilties (with an average of 15.06×10^{-3} SI units), relative to a background argillite sample (0.13×10^{-3} SI units) and quartz-sericite-pyrite–altered sediments (with an average of 0.22×10^{-3} SI units). The potassically altered sedimentary samples do not appear to yield as high susceptibilities as potassically altered BFP at Bell (Figure 11, top).

It is not obvious why BFP intrusive rocks at Bell are associated with strong magnetic anomalies, whereas anomalies are relatively weak over similar rocks in the Granisle and Morrison areas. Magnetite destructive phyllic overprints seem to be as intense in the Bell area as for the other two deposits, and Granisle, in fact, yields the highest susceptibility BFP rocks from the Babine porphyry suite. The strong magnetic signature may have to do with Bell being a larger or deeper system. It has been suggested that the lower extent of the Granisle porphyry system was essentially reached during mining, whereas Bell mineralization is thought to continue further to depth, and indeed, strongly potassically altered BFP is encountered at depth in the sampled Bell drillholes (Dirom et al., 1995).

Morrison

Deposit Geology

The Morrison deposit occurs in association with an Eocene BFP that intruded into siltstone and silty argillite units of the Bowser Lake Group (Figure 12). Later, northwest-trending strike-slip faulting bisected the main BFP intrusive body at Morrison. Mineralization is focused within and around the BFP. Alteration at Morrison is manifested as a potassic core of biotite and magnetite, which grades outward into a propylitic (chlorite-epidote-carbonate) halo. Early potassic alteration is overprinted by phyllic (quartz-sericite-pyrite) and finally by later, argillic (clay-sericite) alteration, which is locally controlled by late faults (Ogryzlo et al., 1995). Mineralization occurs predominantly within and marginal to the biotite-magnetite core. Magnetic data collected over the Morrison deposit during the Geoscience BC VTEM survey show local moderate magnetic anomalies over the dissected BFP intrusive body, as well as over similar BFP dikes in the area. Surrounding sedimentary rocks appear to be nonmagnetic (Figure 12).

Magnetic Susceptibility

For this study, hand sample and outcrop magnetic susceptibility measurements were made on BFP intrusive and sedimentary rocks at the site of the deposit, but the majority of samples and measurements are derived from seven drillcores extracted from different locations within the mineralized zone (Figure 12). Susceptibility measurements were collected on 39 samples. Potassic, phyllic and argillic alteration zones were sampled; propylitically altered rocks were not encountered. Susceptibility measurements were also made at approximately 4–4.5 m intervals along the same seven drillholes (downhole measurements not included in this report).

Figure 13 shows susceptibility data measured from Morrison BFP and sedimentary samples. Potassically altered

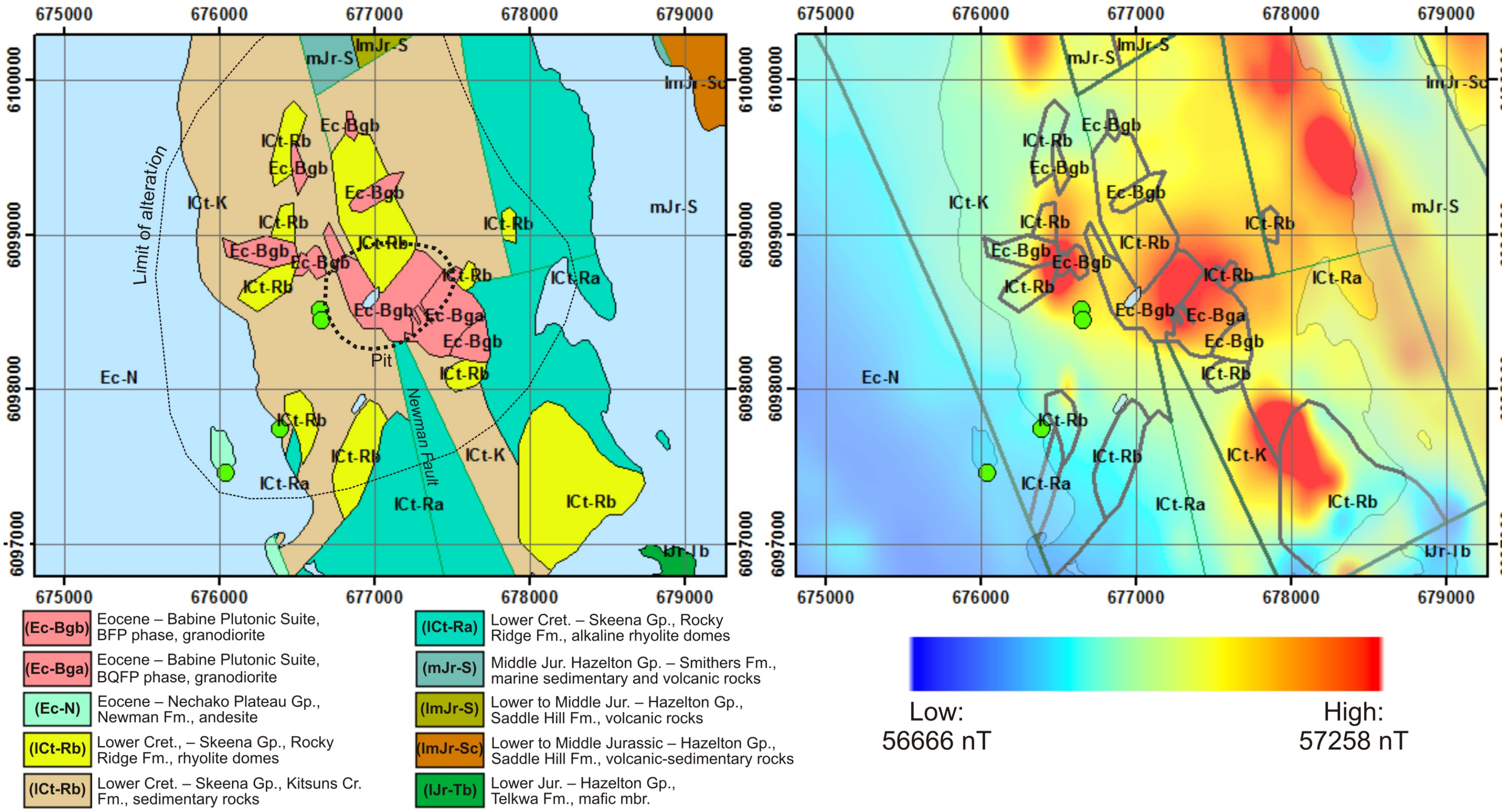

Figure 10. Map of Bell deposit area geology, central British Columbia (left), showing pit outline (dotted line), limit of alteration and location of hand samples (green circles) collected from the perimeter of the open pit and from the margins of the alteration halo. Base map is from Geoscience BC QUEST geology compilation (Williams and Ma, 2010). Pit outline and alteration limits are from Dirom et al. (1995). Magnetic data (right) are from the Bell deposit airborne variable time-domain electromagnetic (VTEM)/magnetic infill survey, Aeroquest Limited (2009).

BFP and samples where phyllic alteration has overprinted potassic alteration are the most magnetically susceptible samples ranging from 0.24 to 63.8 × 10^{-3} SI units and averaging 12.06 × 10^{-3} SI units. Least-altered (primary magnetite-bearing, based on extrusive equivalents; see Granisle sample data) and biotite-magnetite–altered BFP are likely the cause of the magnetic highs at Morrison. Phyllic and argillic alteration of BFP overprints potassic alteration, causing magnetite to break down and susceptibilities to drop significantly. Phyllic (quartz-sericite-pyrite–altered) samples have an average susceptibility of 0.23 × 10^{-3} SI units and argillic (clay-altered) samples average 0.18 ×10^{-3} SI units.

The sedimentary rock samples collected from the Morrison deposit for this study are all affected by phyllic alteration. Since mineralization is focused on the BFP intrusive body, the surrounding sedimentary rocks would spatially generally correlate with the more distal alteration assemblages. Phyllic-altered sedimentary rock samples generally have low susceptibilities, averaging 1.62 × 10^{-3} SI units. Future petrographic work should help resolve if two higher susceptibility phyllic-altered sedimentary rock samples represent samples that were previously altered to potassic assemblages, but later overprinted. Phyllic and argillic alteration of sedimentary rocks would likely not be distinguishable from weakly magnetic background sedimentary units.

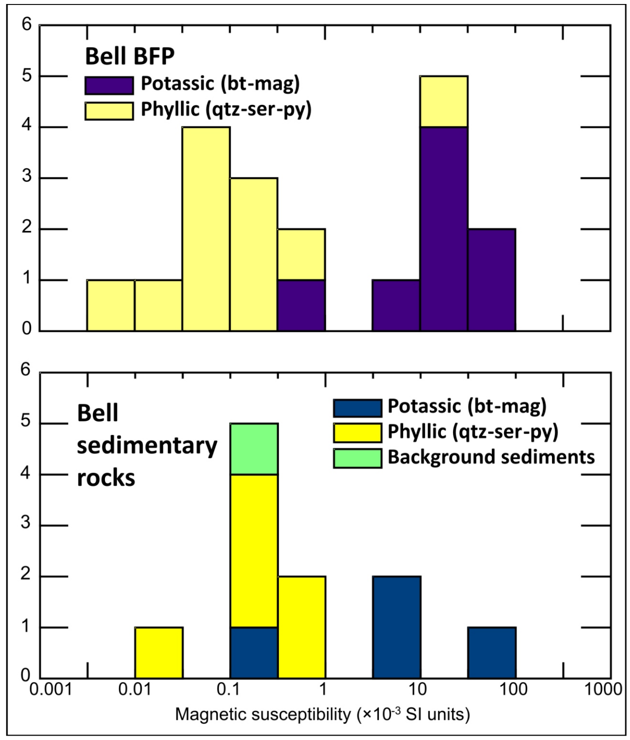

Figure 11. Histograms showing magnetic-susceptibility data for variably altered intrusive (top) and sedimentary (bottom) rock samples from the Bell deposit, central British Columbia. Abbreviations: BFP, biotite-feldspar porphyry; bt, biotite; mag, magnetite; py, pyrite; qtz, quartz; ser, sericite.

Conclusions

Physical properties of variably altered hostrocks and intrusive rocks vary significantly between different BC porphyry deposits and no specific unifying geophysical model exists that can be uniformly applied during exploration. Knowledge of local background geology and local physical property variations is necessary as hostrocks and intrusive rock compositions can vary depending on magmatic affinities, and alteration styles will vary reflecting magmatic affinities, crustal depth and influence of meteoric water.

At a very general level, a district-scale exploration strategy would involve an attempt to locate intrusive bodies, which are commonly magnetic (but not exclusively), resistive and low in density. Correlations should not necessarily be expected between density and magnetic susceptibility, because porphyry-related intrusive rocks, although usually associated with low densities due to high abundances of low-density feldspar and quartz, may or may not contain primary magnetite or could be altered to develop secondary magnetite or undergo magnetite destruction. Deposit-scale ground geophysics might image potassic alteration zones that can be magnetic in both alkalic and calcalkalic systems. It must be remembered, however, especially in the case of calcalkalic porphyry deposits, that later phyllic and argillic alteration is likely to have destroyed magnetite. Low resistivities and densities might aid in locating the typically more porous phyllic and argillic zones. Again, all geophysical data must be interpreted with at least some background knowledge of local rock types and in light of the expected deposit model and associated magmatic and hydrothermal processes. This type of information can in many cases easily be gathered from previous exploration records and from government and academic geological summaries of the areas and their known deposits.

Future Work

Conductivity and density data for the Morrison, Bell and Granisle deposits will be compiled and interpreted in early 2011. It will be of interest to see if BFP intrusions altered to sericite-rich phyllic assemblages yield low conductivities similar to phyllic- and argillic-altered samples from the Endako and Huckleberry deposits, and to determine if similar trends exist between porosity, density and conductivity. Additional XRD analyses will be completed on samples from the Endako, Huckleberry, Granisle, Bell and Morrison deposits to further assess links between mineralogy and magnetic susceptibility, density and conductivity. Physical property data collected during this study will eventually be used to constrain magnetic and electromagnetic geophysical inversions to generate 3D models for each of the six porphyry deposits surveyed during the QUEST and QUEST-West projects.

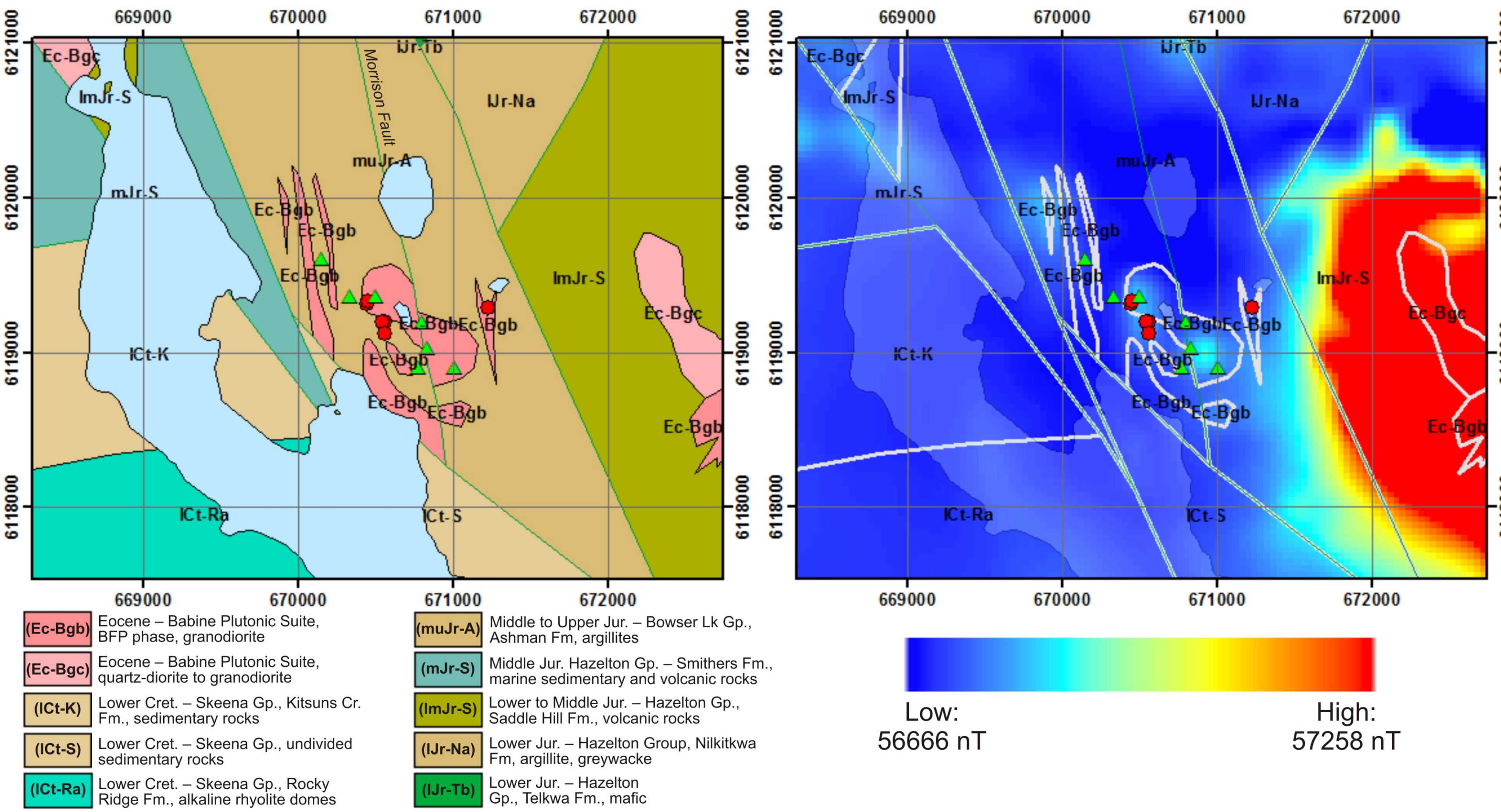

Figure 12. Map of Morrison deposit area geology, central British Columbia (left), showing the location of hand samples collected from the Morrison deposit site (red circles) and the location of drillholes sampled for this study (green triangles). The base map is from Geoscience BC QUEST geology compilation (Williams and Ma, 2010). Pit outline and alteration limits are from Dirom et al. (1995). Magnetic data (right) from Morrison deposit airborne variable time-domain electromagnetic (VTEM)/magnetic infill survey, Aeroquest Limited (2009).

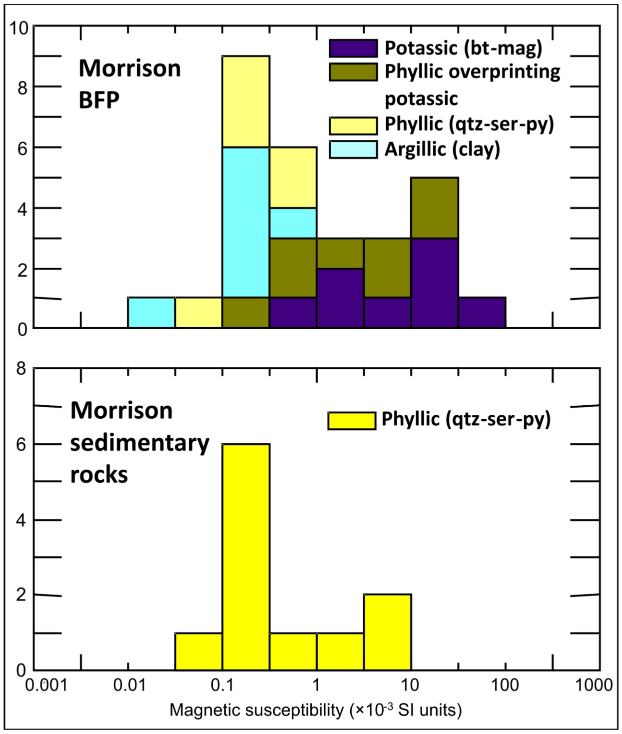

Figure 13. Histograms showing magnetic susceptibility data for variably altered intrusive (top) and sedimentary (bottom) rock samples from the Morrison deposit. Abbreviations: BFP, biotite-feldspar porphyry; bt, biotite; mag, magnetite; py, pyrite; qtz, quartz; ser, sericite.

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References

Aeroquest Limited (2009): Report on a helicopter-borne AeroTEM® system electromagnetic and magnetic survey; Geoscience BC, Report 2009-6, 28 p., URL <http://www.geosciencebc.com/s/2009-06.asp> [November 2010].

BC Geological Survey (2010): MINFILE BC mineral deposits database; BC Ministry of Forests, Mines and Lands, URL <http://minfile.ca/> [November 2010].

Dirom, G.E., Dittrick, M.P., McArthur, D.R., Ogryzlo, P.L., Pardoe A.J. and Stothart P.G. (1995): Bell and Granisle porphyry copper-gold mines, Babine region, west-central British Columbia; *in* Porphyry Deposits of the Northwestern Cordillera of North America, T.G. Schroeter (ed.), Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46, p. 256–289.

Enkin, R.J., Paradis, S. and Simandl, G.J. (2011): Physical properties of carbonate-hosted nonsulphide Zn-Pb mineralization in southern (NTS 082F/03) and central(NTS 093A/14E, 15W) British Columbia; *in* Geoscience BC Summary of Activities 2010, Geoscience BC, Report 2011-1, p. 169–180.

Jago, C.P. (2008): Metal- and alteration-zoning and hydrothermal flow paths at the moderately-tilted, silica-saturated Mount Milligan Cu-Au alkalic porphyry deposit; M.Sc. thesis, The University of British Columbia, 210 p.

Jensen, E.P. and Barton, M.D. (2000): Gold deposits related to alkaline magmatism; *in* Gold in 2000, S.G. Hagemann and P.E. Brown (ed.), Society of Economic Geologists, Reviews in Economic Geology, v. 13, p. 279–314.

Lowell, J.D. and Guilbert, J.M. (1970): Lateral and vertical alteration-mineralization zoning in porphyry ore deposits; Economic Geology, v. 65, p. 373-408.

Massey, N.W.D., MacIntyre, D.G., Desjardins, P.J. and Cooney, R.T. (2005): Geology of British Columbia; BC Ministry of Forests, Mines and Lands, Geoscience Map 2005-3, scale 1:1 000 000, URL <http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/Maps/GeoscienceMaps/Pages/2005-3.aspx> [November 2010].

Mitchinson, D.E. and Bissig, T. (2010a): Enhancing geophysical interpretation and mineral deposit modelling through knowledge of physical rock properties: magnetic susceptibility studies for porphyry deposits in the QUEST and QUEST-West areas (NTS 093E, K, N); *in* Geoscience BC Summary of Activities 2009, Geoscience BC, Report 2010-1, p. 53–64, URL <http://www.geosciencebc.com/i/pdf/SummaryofActivities2009/SoA2009_Mitchinson.pdf> [November 2010].

Mitchinson, D.E. and Bissig, T. (2010b): Enhancing geophysical interpretation and mineral deposit modelling through knowledge of physical rock properties: magnetic susceptibility studies for porphyry deposits in the QUEST and QUEST-West areas (NTS 93E, K, N); poster presentation, Mineral Exploration Roundup, Vancouver, January 18, 2008, URL <http://www.geosciencebc.com/i/pdf/Roundup2010/Mitchinson_Roundup10.pdf> [November 2010].

Muller, L.D. (1967): Density determinations; *in* Physical Methods in Determinative Mineralogy, J. Zuaaman (ed.), Academic Press, p. 459–466.

Natural Resources Canada (2004): Canadian digital elevation data; Earth Sciences Sector, Centre for Topographic Information, URL <http://www.geobase.ca/geobase/en/data/cded/description.html> [October 2004].

Natural Resources Canada (2010): Atlas of Canada – base maps; *in* The Atlas of Canada, Canada Centre for Remote Sensing, GeoAccess Division, URL <http://geogratis.cgdi.gc.ca/geogratis/en/option /select.do?id=0BCF289A-0131-247B-FDBD-4CC70989CBCB> [November 2010].

Ogryzlo, P.L., Dirom G.E. and Stothart P.G. (1995): Morrison-Hearne Hill copper-gold deposits, Babine region, west-central British Columbia; *in* Porphyry Deposits of the North-western Cordillera of North America, T.G. Schroeter (ed.), Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46, p. 290–303.

Oldenburg, D.W., Li, Y. and Ellis, R.G. (1997): Inversion of geophysical data over a copper gold porphyry deposit: a case history for Mt. Milligan; Geophysics, v. 62, p. 1419–1431.

Ralph, J. and Chau, I. (2010a): Augite: augite mineral information and data; Mindat.org, URL <http://www.mindat.org/min-419.html> [November 2010].

Ralph, J. and Chau, I. (2010b): Actinolite: actinolite mineral information and data; Mindat.org, URL <http://www.mindat.org/min-18.html> [November 2010].

Ralph, J. and Chau, I. (2010c): Albite: albite mineral information and data; Mindat.org., URL <http://www.mindat.org/min-96.html> [November 2010].

Ralph, J. and Chau, I. (2010d): Microcline: microcline mineral information and data; Mindat.org., URL <http://www.mindat.org/min-2704.html> [November 2010].

Raudsepp, M. and Pani, E. (2003): Application of Rietveld analysis to environmental mineralogy; Chapter 8 *in* Environmental Aspects of Mine Wastes, J.L. Jambor, D.W. Blowes and A.I.M. Ritchie (ed.), Mineralogical Association of Canada, Short Course Series, v. 31, p. 165–180.

Telford, W.M., Geldart, L.P. and Sheriff, R.E. (1990): Applied Geophysics, Second Edition; Cambridge University Press, 770 p.

Williams, S.P. and Ma, F. (2010): QUEST project compilation, version 1.0; Geoscience BC, Report 2010-9 < http://www.geosciencebc.com/s/2010-009.asp [November 2010].