

# PLATINUM GROUP ELEMENTS IN ALKALINE PORPHYRY DEPOSITS, BRITISH COLUMBIA

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## INTRODUCTION

The alkaline suite is a distinctive group of porphyry copper-gold deposits that occur in the Cordillera of British Columbia (Barr *et al.*, 1976; Lang *et al.*, 1995a). These deposits are associated with alkaline to subalkaline plutons, small stocks, dikes and sills, which were emplaced into two allochthonous terranes, Quesnellia and Stikinia, prior to accretion of these terranes onto the ancient continental margin of North America (McMillan *et al.*, 1995). Textural and

geological evidence suggest that these intrusions were emplaced at a variety of paleodepths. Mineralization occurs in sulfide/oxide vein systems, breccias and disseminated zones. The deposits or camps consist of several discrete zones that cumulatively amount to significant tonnages (Lang *et al.*, 1995a). The Copper Mountain and the Iron Mask Batholith have been mined extensively and significant resources exist at Galore Creek, Mt. Polley and Mt. Milligan. In addition to the petrological association and the style of mineralization, these deposits are characterized by unusual alteration assemblages that include potassic (orthoclase, biotite, magnetite), calc-potassic (garnet, diopside, biotite, orthoclase), and sodic/sodic-calcic (albite, diopside) all showing a distinct lack of associated quartz veining. The relationships among these styles of alteration are complex but all are directly associated with mineralization (Lang *et al.*, 1995b).

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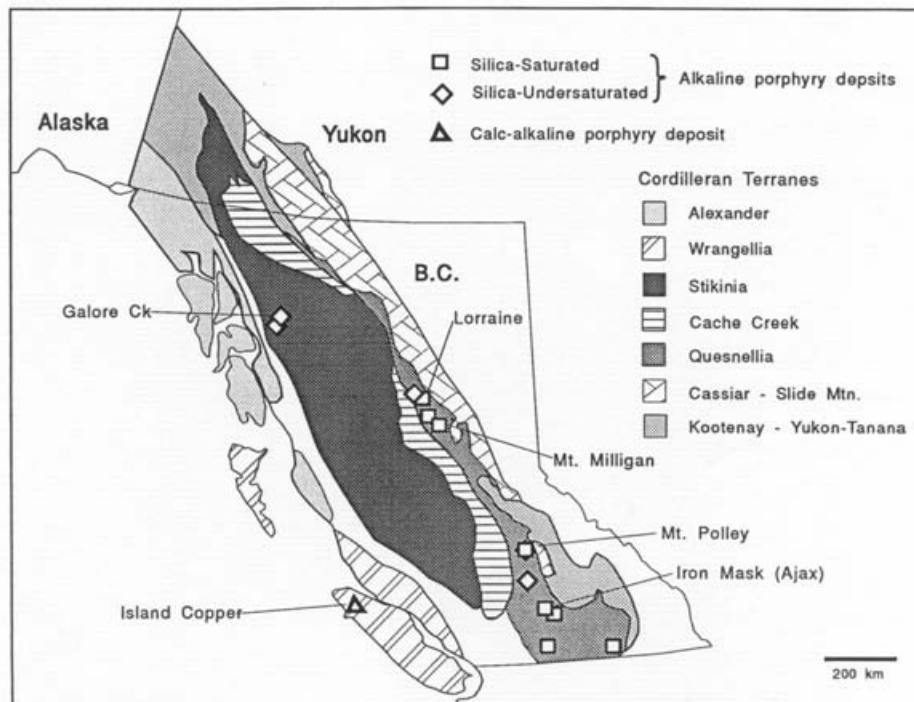


Figure 1. Map of the Cordillera of western Canada showing the major allochthonous terranes, the location of porphyry deposits belonging to the alkaline suite, and the deposits sampled for this study. The location of the Island Copper deposit, associated with calc-alkaline intrusions, is also identified.

Petrological characteristics of the alkaline intrusions permit definition of silica-saturated and silica-undersaturated subtypes (Lang *et al.*, 1995a). The silica-undersaturated intrusions are characterized by both modal and normative feldspathoids, and by the presence of igneous melanitic garnet (Lueck and Russell, 1994; Lang *et al.*, 1995c). Silica-saturated intrusions cover a more normal range of compositions (diorite, monzonite and locally syenite). The petrogenetic relationship between silica-saturated and silica-undersaturated intrusions is uncertain but some complexes contain individual intrusions of both subtypes (*e.g.*, Mt. Polley). The spatial, temporal and metallogenic association between subtypes suggest that they define a single suite of alkaline magmas. Mineralogy, geochemistry and isotopic data indicate that this suite of intrusions belong to a distinctive variety of alkaline arc magmas that were largely derived from an enriched mantle source region (Lang *et al.*, 1995c). The majority of the intrusions in Stikinia and Quesnellia are Early Jurassic in age (~205-195 Ma) although some intrusions in Quesnellia are distinctly younger (~185 Ma; Mortensen *et al.*, 1995). Based on these ages and other geological evidence, Lang *et al.* (1995c) suggest that alkaline intrusions were emplaced during collisional events (arc-arc or arc-continent) that resulted in the cessation of active subduction, a model that has also been proposed for other belts of alkaline arc magmatism (*e.g.*, McInnes and Cameron, 1994).

Deposits associated with alkaline intrusions in Quesnellia and Stikinia contain significant Cu in the form of chalcopyrite and/or bornite. In addition, mineralization is always enriched in Au, and to a lesser extent Ag, but rarely contains significant Mo (Lang *et al.*, 1995a). The Cu/Au ratio varies among districts, and among and within zones in individual districts (Lang *et al.*, 1995a). These relationships suggest that alkaline porphyry systems are enriched in these elements primarily as a result of magmatic and magmatic-hydrothermal processes (from source region to volatile generation), but that the absolute Cu and Au concentrations and Cu/Au ratio of mineralization are dependent on processes and conditions at the site of deposition.

Elevated levels of platinum group elements (PGE), particularly Pd and Pt, have been reported from mineralization associated with several of the alkaline porphyry deposits (O'Neill and Gunning, 1934; Mutschler *et al.*, 1985; Evenchick *et al.*, 1986; Rublee, 1986). At least three prospects hosted by alkaline intrusions in British Columbia have been explored for their Pd-Pt potential (the Python, Maple Leaf and Sappho prospects). Until recently, published analytical data for the deposits in B.C. are limited to those presented by Mutschler *et al.* (1985) from Copper Mountain-Ingerbelle, Galore Creek, Franklin Camp and Sappho. Although this is a small dataset, and consists of a mixture of concentrates and ore samples, the results suggest locally elevated Pd and Pt. Mutschler *et al.* (1985) also report elevated Pd and Pt values from mineralization related to alkaline intrusions in other areas. Analyses for the full spectrum of PGEs, with moderate levels of Pt, Pd and Au, have also been reported from the Skouries porphyry deposit in northern Greece (Eliopoulos and Economou-Eliopoulos, 1991) and limited data have been

reported from Santo Tomas II in the Philippines (Tarkian and Koopmann, 1995).

The purpose of this communication is to present new PGE data from several of the alkaline porphyry deposits in British Columbia. In addition, analyses from the calc-alkaline Island Copper deposit of Jurassic age are provided for comparison. These reconnaissance results add to the small existing database and indicate that more data are needed.

## PLATINUM GROUP ELEMENT DATA

### SAMPLE SUITE

Samples were collected from five deposits or prospects associated with alkaline intrusions between 1991 and 1993; four deposits are in Quesnellia (Lorraine, Mount Milligan, Mount Polley and Ajax East), and one is in Stikinia (Galore Creek; Figure 1). Descriptions of the deposits that were sampled in this study have been published in papers in CIM Special Volume 46 (Schroeter, 1995). Following the initial results, four additional samples from Mount Milligan were analyzed; these samples were composites from several drill holes prepared by Placer Dome for metallurgical testing and each is representative of a mineralized zone. Two samples were also collected from the Island Copper deposit on Vancouver Island (Perello *et al.*, 1995). Island Copper is a porphyry Cu-Mo-Au deposit associated with a rhyodacite porphyry of calc-alkaline affinity. These samples were included for comparative purposes. The locations and descriptions of the samples are given in Table 1.

### ANALYTICAL METHODS

Each sample was crushed to approximately -80 mesh except the composite samples from Mount Milligan which were pulverized previously. In order to improve analytical detection, samples were prepared as heavy mineral concentrates using a Wilfley table. The concentrates were inspected microscopically and estimates made of modal mineralogy. Samples contained a mixture of sulfides (bornite, chalcopyrite and/or pyrite), oxides (magnetite and hematite), and less than 5% silicates (Table 1). No attempt was made to generate pure sulfide concentrates because fine-grained mixtures of sulfides and oxides were noted in polished sections from some deposits and the host for Au and PGE was unknown. The heavy mineral concentrates were analyzed by Activation Laboratories, Ancaster, Ontario using a nickel sulfide fire assay followed by instrumental neutron activation analysis (INAA) for PGE and Au, Leco infrared spectrometry for S, and aqua regia extraction and ICP finish for Cu. Estimates of analytical detection limits for the PGE and Au are 0.1 ppb for Ir, Os and Rh, 0.5 ppb for Au, 2 ppb for Pd, and 5 ppb for Ru and Pt.

### RESULTS

Results for analyses of the concentrates are presented in Table 2. The Cu and S data are plotted in Figure 2, which also shows the composition of stoichiometric chalcopyrite

**TABLE 1**  
**LOCATION AND DESCRIPTION OF SAMPLES ANALYZED FOR COPPER,**  
**GOLD AND PLATINUM GROUP ELEMENTS**

<b>Sample Number</b>	<b>Deposit and Location</b>	<b>Description</b>
<b>GC92-1500</b>	Galore Creek: Central zone, DDH 395	Disseminated/veinlet Cp-Py in garnet-biotite-Kfeldspar alteration
<b>GC92-1523</b>	Galore Creek: Central zone, DDH 120	Disseminated Bn(-Py) in biotite-Kfeldspar-magnetite alteration
<b>GC92-1541</b>	Galore Creek: Central zone, DDH 97	Disseminated/veinlet Cp-Py-Bn in biotite-Kfeldspar alteration
<b>GC92-1553</b>	Galore Creek: Southwest zone, DDH 381	Disseminated Cp-Py-Bn in biotite-Kfeldspar-magnetite alteration
<b>L91-4</b>	Lorraine: Extension zone, DDH L91-4	Disseminated/veinlet Bn(-Py) in pyroxene-biotite alteration
<b>MBX</b>	Mt. Milligan: MBX zone, bulk sample	Disseminated/veinlet Py-Cp in biotite-magnetite alteration
<b>66Z</b>	Mt. Milligan: 66 zone, bulk sample	Disseminated Py in biotite-chlorite-albite-epidote alteration
<b>WBX</b>	Mt. Milligan: WBX zone, bulk sample	Disseminated/veinlet Py-Cp in biotite-magnetite alteration
<b>SST</b>	Mt. Milligan: Southern Star zone, bulk sample	Disseminated/veinlet Py-Cp in biotite-magnetite alteration
<b>MMSS-1</b>	Mt Milligan: Southern Star zone, DDH 771	Disseminated/veinlet Py-Cp in biotite-magnetite alteration
<b>88-148</b>	Mt. Polley: Main zone, DDH 88-148	Disseminated Bn-Cp-Py in magnetite-rich alteration
<b>89-143</b>	Mt. Polley: Main zone, DDH 89-143	Disseminated/veinlet Cp-Py in biotite-Kfeldspar-magnetite breccia
<b>89-150</b>	Mt. Polley: West zone, DDH 89-150	Veinlet Cp-Py in Kfeldspar-actinolite-magnetite altered breccia
<b>AE-1</b>	Ajax: East deposit: 930m Bench	Disseminated/veinlet Cp-Py in albite-rich alteration
<b>ICU-1</b>	Island Copper: -200 Level	Veinlet Cp-Py in biotite-magnetite alteration
<b>ICU-2</b>	Island Copper: -200 Level	Veinlet Cp-Py in biotite-magnetite alteration

All samples are from Triassic-Jurassic alkaline porphyry deposits in British Columbia with the exception of the Jurassic calc-alkaline Island Copper deposit on Vancouver Island (*see* Figure 1). Bulk samples from Mt. Milligan are composites of samples from several drill holes representing typical mineralization.

**TABLE 2**  
**COPPER, GOLD AND PLATINUM GROUP ELEMENT CONTENTS OF HEAVY MINERAL CONCENTRATES FROM**  
**ALKALINE PORPHYRY DEPOSITS AND ONE CALC-ALKALINE DEPOSIT**  
**(ISLAND COPPER) IN BRITISH COLUMBIA**

<b>Sample</b>	<b>S</b> <b>%</b>	<b>Cu</b> <b>%</b>	<b>Au</b>	<b>Pd</b>	<b>Pt</b>	<b>Rh</b>	<b>Os</b>	<b>Ir</b>	<b>Ru</b> <b>ppb</b>
<b><i>Galore Creek</i></b>									
GC92-1500	13.16	7.63	5200	407	17	0.1	n.d.	0.1	5
GC92-1523	10.25	21.54	68000	1039	54	0.5	n.d.	0.1	9
GC92-1541	23.2	18.06	3600	103	15	0.1	n.d.	0.1	n.d.
GC92-1553	13.16	13.16	60000	1581	107	0.5	n.d.	0.2	5
<b><i>Lorraine</i></b>									
L91-4	6.48	13.32	940	19	11	1.7	2	1.2	6
<b><i>Mt. Milligan</i></b>									
MBX	49.06	0.71	6923	112	28	0.7	0.7	0.2	n.d.
66Z	39.14	0.01	2705	51	17	0.3	0.3	0.1	8
WBX	15.71	1.59	5322	124	23	2.2	1.9	1.3	32
SST	38.34	0.56	7339	588	62	0.9	0.6	0.3	33
MMSS-1	34.2	6.75	18500	6312	111	2.1	0.7	0.6	7
<b><i>Mt. Polley</i></b>									
88-148	17.43	20.6	23600	320	33	0.2	n.d.	n.d.	n.d.
89-143	1.28	1.15	6200	83	17	0.7	n.d.	0.2	n.d.
89-150	2.43	1.91	1600	23	7	0.3	n.d.	0.1	n.d.
<b><i>Ajax</i></b>									
AE-1	33.1	26.25	990	140	8	1.5	n.d.	0.4	5
<b><i>Island Copper</i></b>									
ICU-1	9.41	2.85	63	21	n.d.	0.3	n.d.	0.1	n.d.
ICU-2	18.79	3.45	320	38	12	0.9	n.d.	0.2	n.d.

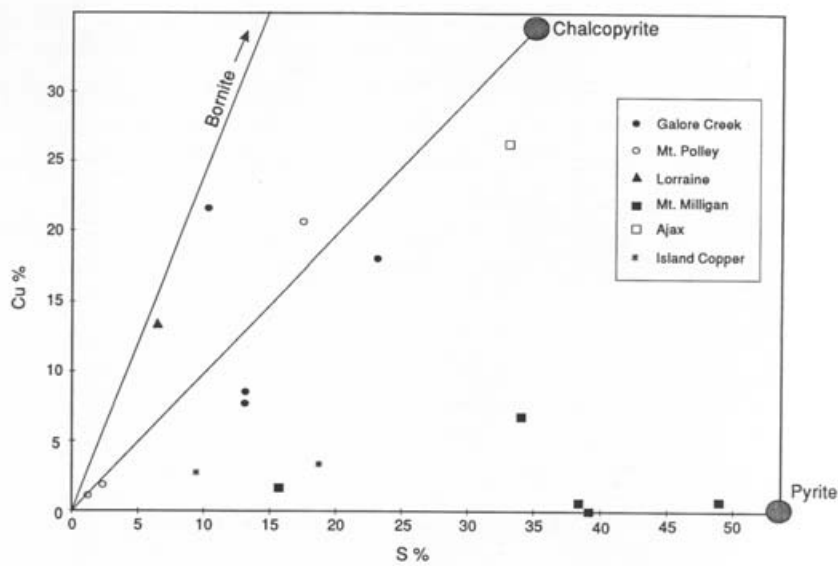


Figure 2. Cu versus S plot for samples analyzed for PGE and Au. Stoichiometric chalcopyrite and pyrite are plotted. Lines connecting stoichiometric bornite (not shown on the figure) and chalcopyrite to the origin provide a relative indication of the sulfide mineralogy in the samples.

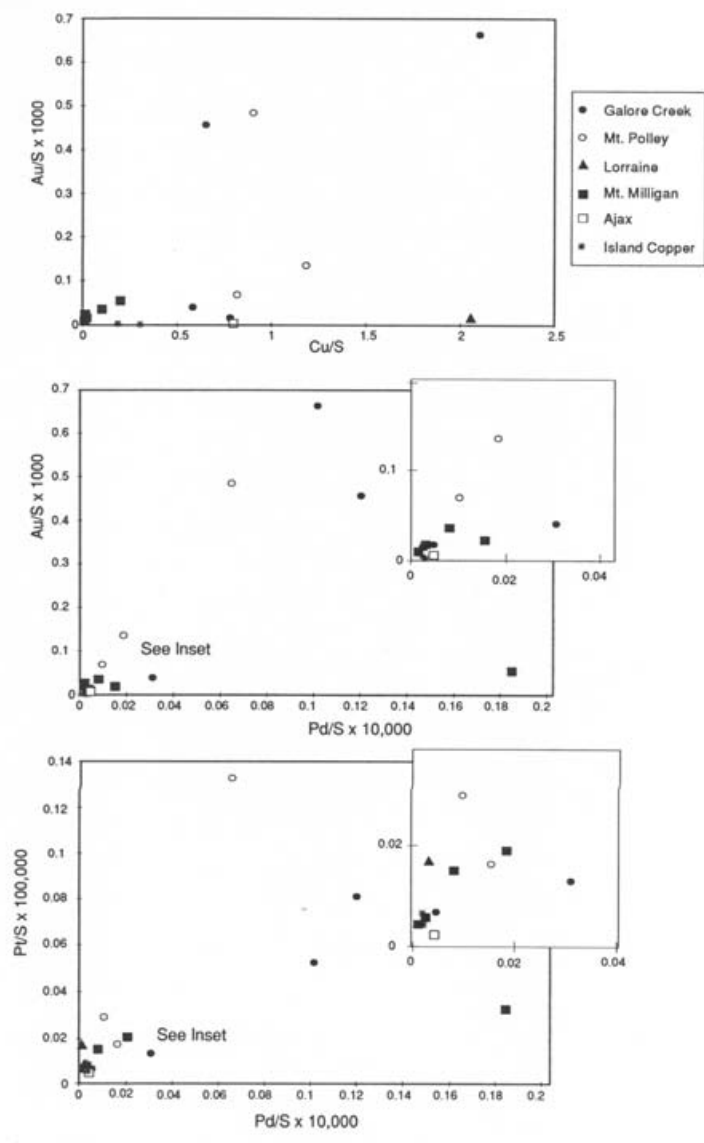


Figure 3. Binary plots of Cu/S, Au/S, Pd/S and Pt/S ratios from analyses from this study. Ratiating the raw data to the sulfur content of the sample provides a means of normalizing the variable sulfide content in the samples.

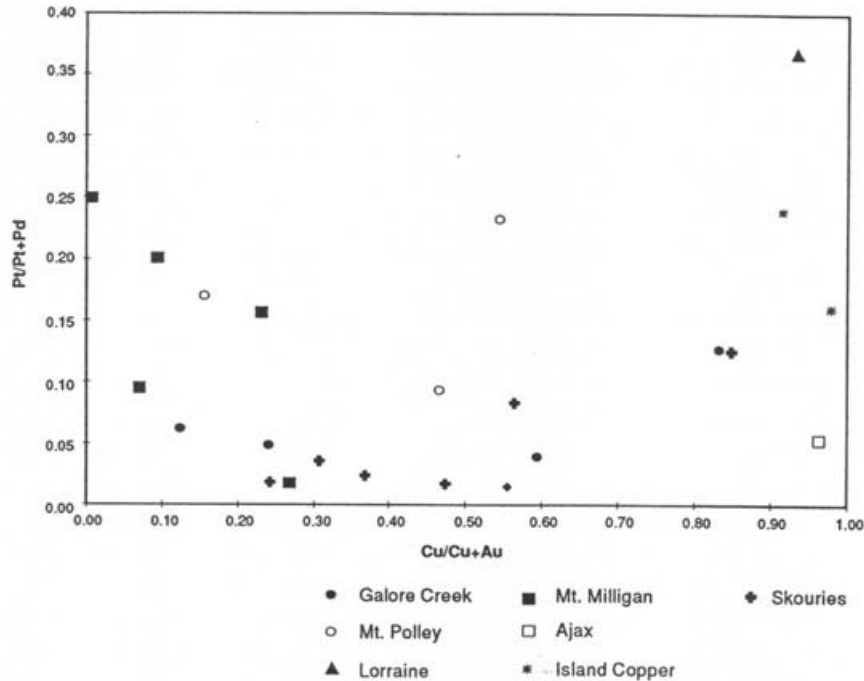


Figure 4. Ratio plot of Pt/Pt+Pd versus Cu/Cu+Au for analyses obtained in this study. Data from the Skouries porphyry deposit in Greece (Eliopoulos and Economou-Eliopoulos, 1991) are shown for comparison.

and pyrite, and lines connecting the composition of chalcopyrite and bornite to the origin. Figure 2 demonstrates that the sulfide mineralogy in the samples varies from bornite-dominant (one sample from Galore Creek and the sample from Lorraine) to pyrite-dominant (three samples from Mount Milligan). Most of the samples plot as mixtures of sulfides that, based on microscopic examination of the concentrates, consist largely of chalcopyrite and pyrite (Table 1). All the samples contain non-sulfide minerals, predominantly iron oxides; hence only two samples plot close to pure sulfide compositions on Figure 2.

High concentrations of Au occur in all samples consistent with the Au-enriched character of the alkaline suite of porphyry deposits. Elevated values of Pd also occur in several samples while Pt is present at lower concentrations. In most cases, Pd concentrations are two to three orders of magnitude lower than Au with Pt approximately one order of magnitude lower than Pd. With the exception of occasional elevated Ru and modest Rh, most of the other PGEs have low concentrations. The two samples from the Island Copper deposit have concentrations of Au and PGE well below those in most of the samples from the alkaline suite deposits. These reconnaissance data support the suggestion that the alkaline porphyry deposits in British Columbia contain Pd and Pt.

The results are presented on simple binary plots (Figure 3) and as a ratio plot (Figure 4). The binary plots (Figure 3) suggest weak correlations between Cu, Au, Pd and Pt, but with considerable scatter, particularly at high values. The ratio plot (Figure 4) demonstrates more variation in Cu: Au compared to Pt: Pd, both between deposits and within deposits. These observations are

consistent with the variation in Cu/Au ratios reported from the alkaline deposits in British Columbia by Lang *et al.* (1995a). Data from the Skouries deposit (Eliopoulos and Economou-Eliopoulos, 1991) are also plotted on Figure 4 and show similar large variations in Cu: Au at relatively constant Pt: Pd.

## DISCUSSION

### SOURCE OF PGE

The reconnaissance dataset presented herein confirms the existence of Pd and Pt, locally at appreciable levels, as well as minor amounts of other PGEs in mineralization hosted by and related to alkaline intrusions in British Columbia. The data also suggest an association with Cu and Au.

Geochemistry and isotopic data indicate that the Triassic-Jurassic alkaline intrusions in British Columbia were derived from an enriched mantle source region (Cassidy *et al.*, 1996), possibly following a hiatus in active subduction. This model is supported by the timing of crystallization of alkaline intrusions, which corresponds with regional tectonic events in both host terranes (Lang *et al.*, 1995c). A collision model has been proposed for similar alkaline rocks in the Tabar-Lihir-Tanga-Feni islands, northeastern Papua New Guinea (McInnes and Cameron, 1994). Evidence from xenoliths from this area suggests that slab dehydration following stalled subduction resulted in a large fluid flux into the overlying mantle wedge. This led to partial melting of the enriched mantle and generated oxidized alkaline magmas (B.I.A. McInnes pers. comm., 1996).

Lihir island hosts significant Au mineralization, the Ladolam deposit, which has indications of porphyry-style mineralization at depth (Moyle *et al.*, 1990). Although other petrogenetic models have been proposed for alkaline arc magmas (*e.g.*, Carmichael, 1991), the McInnes and Cameron (1994) model provides a mechanism for incorporating precious metals into the magmas by the destabilization of Fe-Ni-Cu sulfides in the mantle.

In addition to Cu, Au and PGE, the magma must also contain sufficient sulfur to form sulfide minerals in the porphyry environment. Sulfur concentrations must not exceed sulfur saturation, however, because PGE and Au will partition strongly into magmatic sulfides (Bezmen *et al.*, 1994) hence removing them prior to the formation of a volatile phase in the porphyry environment. McInnes and Cameron (1994) argue that the oxidized nature of alkaline magmas in the Tabar-Lihir-Tanga-Feni chain inhibited formation of magmatic sulfides during fractionation; hence the magmas retained elevated Cu, Au and Pd. The solubility of sulfur in alkaline melts is significantly higher than in quartz-saturated melts (Ducea *et al.*, 1994), and high oxidation states both increase the solubility of sulfur and cause sulfate to exsolve in preference to sulfide at saturation (Carroll and Rutherford, 1985). Evidence for the oxidized nature of alkaline intrusions in British Columbia includes the presence of abundant magnetite, Fe<sup>3+</sup>-rich amphibole and pyroxene, igneous andraditic garnet (melanite), and the local presence of the sulfate-bearing feldspathoids - vishnevite/cancrinite possibly after haüyne (Lueck and Russell, 1994; Lang *et al.*, 1995c).

Weak correlations among Cu, Au, Pd and Pt at low concentrations (Figure 3) may reflect the primary magmatic environment and source region. Unfortunately, the reconnaissance nature of this dataset is inadequate for testing this hypothesis and there is little comparative published data from deposits that formed in different environments. Although Pd and Pt concentrations are lower, the Pt:Pd ratios in the samples from the calc-alkaline Island Copper deposit are similar to ratios from the alkaline porphyry deposits (Fig 4). The Cu:Au, Cu:Pd and Cu:Pt ratios, however, differ from most of those of the alkaline deposits.

Based on the preceding discussion, PGE enrichment in porphyry deposits probably requires a mantle source region, liberation of mantle sulfides during partial melting in the source region, and an oxidized melt that effectively prohibits the formation of magmatic sulfides during fractionation. The petrogenesis of alkaline arc magmas appears to fit closely with these prerequisites, although other arc-related magmas may also satisfy some or all of these conditions in specific cases.

### **PGE TRANSPORT**

The availability of PGE in the magma is the first step in providing elevated concentrations in porphyry-style mineralization. The second step requires the transport of PGE to the site of deposition. Due to the lack of hydrothermal minerals containing good fluid inclusions, the temperature of deposition in the alkaline porphyry systems is poorly constrained. The Galore Creek deposit is the exception where

fluid inclusions in hydrothermal garnets contain moderate to high salinities and homogenize between 300-550°C (Dunne *et al.*, 1994), typical of the porphyry environment. Under acid and oxidizing conditions and temperatures up to 300°C, both Pd and Pt may be transported as chloride complexes (Gammons *et al.*, 1992; Wood *et al.*, 1992) with these complexes becoming increasingly important for Pd at higher temperatures (Sassani and Shock, 1990). Chloride transport is generally invoked for Cu and Au in the porphyry environment (*e.g.*, Sillitoe, 1993) and therefore the association of Cu, Au, Pd and Pt may be explained in part by a similar transport and deposition mechanism. Pd and Pt may also be transported as bisulfide complexes, but at levels one to three orders of magnitude lower than Au under the same conditions (Wood *et al.*, 1992). This difference in the efficiency of transport is similar to the relative difference in concentration between Au and Pd in the samples analyzed in this study. Therefore, in addition to the importance of the primary concentrations derived from the source region, hydrothermal processes probably influence the ratio of Pd and Pt to Cu or Au.

Although hydrothermal transport of Pd and Pt in the alkaline porphyry systems is strongly indicated by their association with Cu and Au in zones of hydrothermal alteration, pre-concentration in magmatic sulfides within associated intrusions is not ruled out. As discussed previously, early fractionation of sulfides may remove precious metals including Pd and Pt from the magma and hence from involvement in subsequent magmatic-hydrothermal processes. There is, however, evidence in some cases for sulfide precipitation during crystallization of high level intrusions or lavas, possibly as a result of the degassing of SO<sub>2</sub>. Magmatic sulfide blebs have been reported from submarine alkaline volcanic rocks in the Tabar-Lihir-Tanga-Feni chain (McInnes and Evans, 1996) and from latite dikes related to the Bingham porphyry deposit (Keith *et al.*, 1995). In both cases, these blebs locally contain elevated Au and Pd. Magmatic sulfide blebs may be subsequently oxidized or altered resulting in release of the metals to the volatile phase during magmatic-hydrothermal activity (Candela, 1989). If these sulfide blebs are enriched in precious metals, the hydrothermal fluid and resultant porphyry system may also be enriched. Bishop *et al.* (1995) report petrographic evidence for the existence of magmatic sulfides at the Lorraine alkaline porphyry prospect. In all other localities studied during the course of research on the alkaline porphyry deposits in British Columbia, intense hydrothermal alteration has destroyed any record of possible magmatic sulfides, and therefore the importance of pre-concentration by magmatic processes is difficult to evaluate.

### **VARIATION IN PGE VALUES**

The Cu, Au, Pd and Pt concentrations reported in this study are erratic. Variation within deposits or camps is as great as the variation between them. This strongly suggests that local depositional processes influenced the concentration of these metals, particularly at higher levels. If all of these metals were transported as chloride complexes, changes in  $\Sigma\text{Cl}$ ,  $\Sigma\text{S}$ , T,  $f\text{O}_2$ , and pH could result in deposi-

tion (Gammons *et al.*, 1992). Differences in the final concentrations of these metals reflect the relative efficiency of deposition for each metal under changing conditions. An evaluation of these processes is not possible in this case due to a lack of understanding of the mineralogical and paragenetic distribution of all of the precious metals and a limited thermodynamic database above 400°C for Au, Pd and Pt.

An alternative to the co-precipitation of Cu, Au, Pd and Pt with variations in depositional efficiency explaining different metal ratios is to invoke selective remobilization of individual metals. Some of the alkaline deposits show evidence for low temperature alteration overprinted on the high temperature mineral assemblages (Lang *et al.*, 1995a). Under lower temperature conditions (<300°C), bisulfide complexes may be important for remobilizing all of the precious metals and the relative efficiency of remobilization of individual metals may explain local enrichment. In contrast, Cu is unlikely to be mobile under these conditions. Evaluation of this possibility, with reference to the data reported herein, requires additional information on the mineralogical distribution of the metals, a subject for future work.

## CONCLUSIONS

This study reports the presence of PGE, particularly Pd and Pt, in heavy mineral concentrates prepared from samples from the alkaline suite of porphyry Cu-Au deposits in British Columbia. The results support previous work that indicated the existence of Pd and Pt and suggests concentrations are higher than in other types of porphyry deposits. A much larger database is needed to confirm the latter hypothesis.

The presence of Pd and Pt in mineralization associated with the alkaline suite of porphyry deposits is consistent with petrogenetic models for alkaline arc magmas. The models suggest that these magmas are derived from an enriched mantle source region, possibly following collision and the cessation of subduction. It is argued that partial melting destabilized mantle-hosted Fe-Ni-Cu sulfides rich in precious metals, which allowed them to be incorporated into the melt. The oxidized nature of alkaline arc magmas inhibits fractionation of sulfide; hence precious metals remain in the magmas and are available for transport by magmatic-hydrothermal fluids in the porphyry environment.

Variations in the levels of Cu, Au, Pd and Pt within and between the deposits indicate that transport and depositional processes influenced the final concentration of these metals regardless of the petrogenetic processes that supplied them initially. The mineralogical distribution of these metals has not been studied during this research. Without this information, and knowledge of the paragenesis and hydrothermal conditions for each sample, it is difficult to evaluate the processes that might favor one metal in preference to another. The limited thermodynamic database for conditions appropriate to the porphyry environment presents further problems.

This study clearly demonstrates the potential for further research. This includes the generation of comparative data from other types of porphyry deposits, detailed work on the distribution of precious metals among host minerals, and further research on the hydrothermal transport of PGE at elevated temperatures. Results from this kind of research may have implications for the evaluation of source regions and magmatic processes in different types of porphyry environments, provided that the effects of hydrothermal processes in controlling metal budgets and ratios can be more fully understood. If this is possible, the PGE concentration of fresh samples from volcanic rocks coeval with porphyry mineralization may indicate the sulfide fractionation history of the sequence and the potential for precious metal-rich porphyry mineralization.

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