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**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7780**

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2016



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2016

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doi:10.4095/299202

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Recommended citation

Sinclair, W.D., Jonasson, I.R., Kirkham, R.V., and Soregaroli, A.E., 2016. Rhenium in Canadian mineral deposits; Geological Survey of Canada, Open File 7780, 1 .zip file. doi:10.4095/299202

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Introduction

Rhenium (Re) is a rare metal, with total world mine production in 2015 estimated at 46 tonnes (Polyak, 2016a). Although its production is relatively small compared to most other metals, Re has critical applications, primarily in high-temperature alloys and Pt-Re catalysts. In high-temperature alloys, addition of 3% Re improves the high-temperature strength of Ni-based superalloys that are precision cast into single-crystal turbine blades for aircraft engines and land-based turbines. The principal use of Pt-Re catalysts is in the petroleum industry, where they are used to produce high-octane gasoline and other petroleum products. Rhenium is used to a lesser extent in alloys, which have a diversity of applications that include electrical contacts, heating elements, thermocouples, electron tubes and targets, ionization gauges and vacuum tubes (Polyak, 2016a). In recent years, the demand for Re has increased, with the price rising from a low of about US\$300/kg in the mid-1990s to as high as US\$12,000/kg in August 2008, in part due to supply disruptions (Millensifer et al., 2014). The price has since fallen and in 2015 the average price of Re metal pellets was US\$2,900/kg (Polyak, 2016a).

In addition to its commercial value, Re has significant scientific applications. The Re content of molybdenite, for example, has proven to be highly effective for precise geochronological dating of mineralization by the Re-Os isotopic system due to its ability to withstand loss or redistribution of Re and Os during high-grade metamorphism and deformation (Stein et al., 2001a). The Re-Os isotopic system can also be applied to dating organic-rich sedimentary rocks (Selby and Creaser, 2003). And Re, along with Mo and Os, is used as a petrologic tracer for inferring the origin of detritus and/or redox conditions during sedimentation (Ravizza et al., 1991; Crusius et al., 1996).

Rhenium is one of the most widely dispersed elements in the earth's crust. Its abundance in most rocks is measured in parts per billion or less (e.g., Morris and Short, 1969) and minerals in which Re is a major constituent are rare. For example, elevated levels of Re occur in some minerals deposited around high-temperature volcanic fumaroles, which in exceptional cases may include the sulphide mineral rheniite (ReS_2). However, only two such occurrences of rheniite are known, the Usu volcano, Hokkaido, Japan (Bernard and Dumortier, 1986) and the Kudriavsky volcano on Iturup Island in the Kurile volcanic arc, western Pacific Ocean (Korzhinsky et al., 1994). Rheniite has also been identified at the Pagoni Rachi porphyry-type Mo-Cu-Te-Ag-Au occurrence in northern Greece (Voudouris et al., 2009) and the Phoenix Ni-Cu-PGE deposit in Botswana (Maier et al., 2008). Other Re-rich minerals include dzhezkazganite ($\text{ReMoCu}_2\text{PbS}_4$), recognized in the Cu ores of the Dzhezkazgan deposit, Kazakhstan (Genkin et al., 1994) and tarkianite ($((\text{Cu},\text{Fe})(\text{Re},\text{Mo})_4\text{S}_8)$), identified in the Hitura Ni-Cu-PGE deposit, Finland (Kojonen et al., 2004).

Despite its affinity for sulphide phases, the concentration of Re in most sulphide minerals such as chalcopyrite, bornite, pyrite and pyrrhotite is relatively low, on the order of a few tens of parts per billion or less (cf. Mather et al., 2000; Ying et al. 2014). However, the ionic radius of Re^{4+} is very close to that of Mo^{4+} , which allows for a limited substitution of Re for Mo in molybdenite and other Mo-rich minerals such as castaingite (CuMo_2S_5). Furthermore, Re commonly accompanies Mo through magmatic and related hydrothermal processes (Morris and Short, 1969), and is concentrated in molybdenite associated with various types of granite-related deposits, including porphyry, skarn, pegmatite and vein deposits. In these deposits, Re is almost invariably concentrated in molybdenite, which may contain traces up to maximum levels in excess of 4% Re (e.g., Melfos et al., 2001, Voudouris et al., 2009), although molybdenites from which Re is recovered commercially generally contain in the order of 200 to 1000 ppm Re (Millensifer et al., 2014). Molybdenites with high concentrations of Re are typically associated with Cu-rich deposits, particularly porphyry Cu deposits, and these deposits are the primary industrial source of Re. Molybdenites from some granite-related

vein Mo deposits also contain high concentrations of Re, averaging approximately 400 ppm at the Playter deposit in Ontario (Kilpatrick and Grieco, 2010) and more than 1000 ppm at the Merlin deposit in Australia (Horton, 2010). Other minerals in which Re may be concentrated in significant levels include castaingite (CuMo_2S_5), which can contain up to 1% Re (Kucha, 1990), and uraninite, which can contain up to 2700 ppm Re (Min et al., 2005).

Rhenium can also be transported by low-temperature hydrothermal and diagenetic processes (Xiong and Wood, 2001) and concentrated along with Mo and, in some cases Au and PGE, in anoxic sediments such as organic-rich black shales (e.g., Coveney and Nansheng, 1991; Lippmaa et al., 2011). Elevated contents of Re, ranging from 0.5 to >200 ppm, are present in sediment-hosted Cu deposits such as Dzhezkazgan in Kazakhstan (Ivanov et al., 1972) and in the Kupferschiefer of Poland and Germany (Morris and Short, 1969). At low concentrations of Mo, Re in these deposits may occur as independent sulfides such as dzhezkazganite ($\text{ReMoCu}_2\text{PbS}_4$); at higher concentrations, the Re may be present in molybdenite or jordisite (the latter has the same formula as molybdenite but is amorphous in appearance) (Morris and Short, 1969). In both cases, the Re-bearing minerals are associated with Cu sulfides and Re is recovered as a byproduct of the smelting of Cu ores. Sediment-hosted Cu deposits are currently the second most important primary source of Re.

Rhenium contents are also elevated in some sandstone-hosted U deposits. Samples from the Sun Valley deposit, Arizona for example contain up to 1000 ppm Re (Petersen et al., 1959) and Re content of U deposits of the Central Kyzylkum in Uzbekistan ranges from 0.5 to 15 g/t Re (Venatovskij, 1993). Uranium in the Uzbekistan deposits is recovered by in-situ leaching; Re is one of the byproducts.

In this report, we present the results of Re analyses of molybdenites from 181 Canadian mineral deposits and occurrences. We have also included analyses of heavy mineral concentrates from some sediment-hosted deposits in which molybdenite is not present, or at least not recognized, but which contain significant Re. Our primary objectives were to characterize Re contents in a wide spectrum of deposits and to examine variations within deposit types. The results show that porphyry deposits, particularly porphyry Cu and Cu-Au deposits, have some of the highest overall contents of Re and the highest concentrations of Re in molybdenite. In these and other granite-related deposits, the content of Re in molybdenite appears to be inversely proportional to the Mo grade. Possible factors that control the Re contents of molybdenite in granite-related deposits include composition and fractionation of parental magmas, physical and chemical conditions of hydrothermal transport and deposition, different polytypes of molybdenite, mass balance and different metal source regions (Giles and Schilling, 1972; Newberry, 1979b; Stein et al., 1998, 2001a; Xiong and Wood, 2002; Berzina et al., 2005).

Sediment-hosted deposits of Cu and U can also contain significant amounts of Re. Processes that affect the concentration of Re in these deposits involve transport of a neutral species such as $\text{Re}(\text{OH})_4^0$ in low-temperature, oxidizing conditions; mixing of the Re-bearing fluids with reduced, sulphur-bearing fluids or with cold water resulting in a sharp decrease in temperature; change in pH; or reduction by sulphide minerals (Xiong and Wood, 2001).

Samples and Analytical Methods

Samples of molybdenite for this study were collected from active and past-producing mines as well as from mineral deposits and occurrences. Samples were collected mainly by the authors and other geologists from the Geological Survey of Canada, with contributions from other organizations such as the British Columbia Geological Survey Branch (formerly BC Department of Mines). Some samples were obtained from archived collections from previous studies of Mo deposits in Canada, particularly those of Eardley-Wilmot (1925). Mill or pilot plant concentrates of molybdenite were obtained from active and developing mines whenever possible. For other deposits and occurrences, molybdenite concentrates were produced from hand samples or drill core, by hand picking coarse grains or by bench-scale floatation concentration. Coarse-grained concentrates were finely ground and mixed to ensure homogenization. In the case of deposits for which molybdenite concentrates could not be obtained, typical ore samples or heavy mineral concentrates obtained by panning were analyzed.

The Re contents of molybdenite concentrates and heavy mineral samples were determined by thermal neutron activation. When this study was initiated in the mid-1970s, analytical techniques for the analysis of low levels of Re involving dissolution were difficult and unreliable due to the volatility of Re and neutron activation was considered more reliable (e.g., Samadi et al., 1975; Schindler, 1975). Thermal neutron activation typically involves exposing the samples to a thermal neutron flux in a nuclear reactor. This irradiation causes most of the elements in the samples to become radioactive and to begin to emit radiation in the form of penetrating gamma rays. The γ -radiation of the decaying nuclei can be analyzed for energy and number of γ -rays at each energy using a gamma ray detector coupled to a multi-channel analyzer. The energies (or wavelengths) of the γ -rays are characteristic of particular elements and by comparing spectral peak positions with reference standards, elements can be qualitatively and quantitatively identified.

Neutron activation analyses were carried out by a number of different laboratories including Novatrack Analysts Limited at the University of British Columbia, Nuclear Activation Services, Ontario, Chemex Labs Limited, British Columbia and Becquerel Laboratories, Ontario. In addition to Re, samples were analyzed for Mo, Cu, Au. Selected samples were also analyzed for Pt and Pd, the results for which have been presented in a separate report (Sinclair et al., 2009). Four different molybdenite concentrates with average Re contents varying from 26 to 1224 ppm Re were selected as internal reference samples to cover the range of Re contents encountered in the majority of our samples. The reference samples were analyzed multiple times by different laboratories and the results are summarized in Table 1.

Analytical results for Mo, Cu, Re and Au in 426 samples, representing 181 Canadian and 11 foreign deposits or occurrences, are listed in Appendix 1 and summarized in Appendix 2. Because most of our molybdenite concentrates are impure, Re contents of molybdenite have been normalized to 100% molybdenite (60% Mo). For purposes of comparison and discussion, normalized values for Re are reported in the following sections unless otherwise indicated. This is reasonable considering that impurities in the concentrates, such as silicate and other sulphide minerals, typically contain very low levels of Re, and nearly all of the Re is likely to be concentrated in molybdenite.

Table 1. Composition of molybdenite concentrates used as internal reference samples.

Deposit/Sample Number	Element	n	Range	Average	Standard Deviation (%RSD)
Endako 7801ENDK	Mo %	5	51.1 - 61.9	55.1	4.8 (8.7)
	Cu %	3	0.03 - 0.1	0.07	0.04 (57)
	Re ppm	5	23 - 35	26	5 (19)
	Au ppm	3	0.1 - 0.3	0.2	0.1 (50)
Preissac 6011PRSC	Mo %	9	51.5 - 57.5	53.9	2.2 (4.1)
	Cu %	7	0.05 - 0.26	0.13	0.08 (61)
	Re ppm	9	23 - 29	27	2 (7.4)
	Au ppm	6	0.1 - 0.4	0.2	0.1 (50)
Lornex 7601LRNX	Mo %	15	51.3 - 61.5	55.0	3 (5.5)
	Cu %	15	0.08 - 1.53	0.90	0.36 (40)
	Re ppm	15	298 - 374	321	25 (7.8)
	Au ppm	15	0.1 - 14	1.2	3.5 (292)
Island Copper 80-025	Mo %	9	39.1 - 45.0	42.2	2.2 (5.2)
	Cu %	9	0.74 - 1.63	0.94	0.31 (33)
	Re ppm	9	1098 - 1308	1224	88 (7.2)
	Au ppm	9	0.7 - 1.4	1.1	0.2 (18)

Rhenium contents of molybdenite in foreign deposits are summarized in Appendix 3. For many of these deposits, as well as for some Canadian deposits, Re contents are based on published Re-Os age data. Re-Os dating, although very precise, is based on analysis of relatively small samples and Re contents can vary widely within a single deposit. Consequently, the average Re contents of molybdenite based on Re-Os dating may not be representative of the deposits. Also, the molybdenite samples used for Re-Os dating are not necessarily pure molybdenite concentrates, although this is not a concern for the calculation of age dates (Stein et al., 2001a). However, in many cases, data from Re-Os dating are the only Re data available and, despite the uncertainties, these data provide preliminary estimates of average Re contents and allow for comparisons between different deposits and deposit types.

Molybdenite polytypes

Molybdenite forms two polytypes based on the manner in which MoS₂ layers are stacked in the cell structure (Takeuchi and Nowacki, 1964; Frondel and Wickham, 1970). The most common polytype is hexagonal and has two MoS₂ layers in the unit cell (2H₁), whereas the less common polytype is rhombohedral and has three layers per unit cell (3R). From a study of molybdenites from Australia and Papua New Guinea, Ayres (1974) noted that Re appeared to be preferentially enriched in the 3R polytype. Newberry (1979a,b) suggested that the 3R polytype grows by a screw-dislocation related to high impurity contents, in particular Re, Ti, Sn, Bi, W and Fe, and that abundance of the 3R polytype in porphyry Cu, porphyry Mo and skarn Cu deposits generally correlates with Re content of the molybdenite. On the other hand, more recent studies did not find any change in polytype from 2H₁ to 3R despite order-of-magnitude differences in trace element concentrations (e.g., Ciobanu et al., 2013; Pašava et al., 2016).

As part of our study, molybdenite samples were analyzed for polytype by X-ray diffraction and the results included in Appendix 1. Most samples consisted mainly of the 2H₁ polytype. Of the 351 samples analyzed, 270 (76.9%) were 100% 2H₁ and 55 (15.7%) consisted of 90 to 95% 2H₁. These samples came from every deposit type and had Re contents that ranged from >1 to 1863 ppm Re. Of the remainder, 4 (1.1%) consisted of 70 to 80% 2H₁, 18 (5.1%) consisted of 50% 2H₁ and 4 consisted

of 20% 2H₁ (or 80% 3R). Of the four samples consisting of 80% 3R polytype, two were from skarn Cu deposits (Little Billy and War Eagle) and contained 759 and 707 ppm Re, respectively, one was from the Valley porphyry Cu deposit (294 ppm Re) and one was from the Sterling vein Mo deposit (25 ppm Re). Although two samples consisting of 50% 3R polytype contained as much as 8170 ppm Re (from the Mitchell (Sulphurets) porphyry Cu-Au deposit), samples consisting of 50 to 80% 3R polytype overall did not appear to correlate with higher Re content of the molybdenite or with any particular deposit type.

Porphyry Deposits

Porphyry deposits are large, low-grade, magmatic-hydrothermal deposits associated with shallow to subvolcanic, granitic intrusive rocks. They are characterized by diverse metal contents and can be divided into subtypes based on the main economic or potentially economic metals in the deposits (Kirkham and Sinclair, 1995; Sinclair, 2007). In addition to being an important source of Cu, Mo, Au and Ag, they account for as much as 80% of primary Re production, which is recovered as a by-product from the processing of molybdenite concentrates (John and Taylor, 2016).

The Re content of molybdenites from porphyry deposits varies widely, particularly with regard to metal subtype. Molybdenites from porphyry Cu-Au deposits have the highest Re contents, typically on the order of thousands of ppm Re and ranging as high as 8170 ppm Re (Mitchell) and 4609 ppm Re (Kemess South) in Canadian deposits (Appendices 1 and 2), but including comparatively low values of 180 ppm Re (Bronson Slope) and 154 ppm Re (Taseko). At the Island Copper deposit, which produced about 27 t Re from 1971 to 1994 (Perelló et al., 1995), the molybdenite had a Re content that averaged nearly 1800 ppm. Re-in-molybdenite contents of foreign porphyry Cu-Au deposits (Appendix 3) are also high, ranging up to 6310 ppm at Agarak (Armenia) and 3550 ppm in the Majdanpek (Serbia) deposit. Molybdenites from the Santo Tomas II Cu-Au deposit in the Philippines have the highest Re contents recorded for a porphyry deposit, ranging from 700 ppm to 15,400 ppm Re, and averaging about 10,000 ppm (Koopman, 1991).

Molybdenites from Canadian porphyry Cu deposits have Re contents that range from 59 ppm (Catface) to 1015 ppm at the Iona deposit in the Highland Valley district and 1072 ppm at the Don Rouyn deposit in Quebec. In foreign porphyry Cu deposits, the Re contents of molybdenites can be much higher, with average values ranging as high as 5500 ppm at Borly (Kazakhstan). However, for most porphyry Cu deposits, the average Re contents of molybdenite fall within a range of 200 to 1000 ppm Re.

Porphyry Cu-Mo deposits generally have lower Re-in-molybdenite contents than porphyry Cu and Cu-Au deposits, with average contents most commonly in the range of 100 to 800 ppm Re. In Canadian deposits, the overall range is mainly from 13 ppm Re (Whiting Creek) to 530 ppm Re (Highmont-East and West pits), except for relatively high values that range up to 1745 ppm Re in the Tribag-East Breccia Zone. In foreign deposits, Re contents in molybdenites from porphyry Cu-Mo deposits range from 3 ppm Re (Yuanzhuding, China) to 1496 ppm (Toquepala, Peru). Not included in this range are some possible porphyry-related Cu-Mo/Au occurrences in northern Greece, such as Pagoni Rachi, Kirki, Melitena and Maronia, which have molybdenites with exceptionally high Re contents that range from 7260 ppm to 4.7% (Melfos et al., 2001, Voudouris et al., 2009). Although these occurrences may indicate potential for porphyry deposits in their vicinity, they are as yet poorly explored, with no significant resources, and it is not clear whether or not they are associated with

larger porphyry systems. Pagoni Rachi, for example, may represent a type of epithermal deposit, similar to the Re-rich occurrences at the Kudriavoy volcano in the Kurile arc (Voudouris et al., 2009).

Porphyry Au deposits typically contain small or negligible amounts of molybdenite and Mo grades are rarely reported for these deposits. Where molybdenite does occur, the Re contents are generally high, on the order of hundreds of ppm. Among Canadian porphyry Au deposits, the highest Re-in-molybdenite values are in the Snowfield deposit in the Sulphurets area (British Columbia), where reported grades of 0.48 g/t Re and 0.008% Mo (Armstrong et al., 2011) correspond to an average content of 3600 ppm Re in molybdenite. In other Canadian porphyry-type Au deposits of Archean age such as Young-Davidson and Côté Lake (Ontario), Re contents in molybdenite range from 181 ppm to 946 ppm respectively. Among foreign porphyry Au deposits, the Re content of molybdenite ranges from as low as 5 ppm in the Boddington deposit (Australia) to as high as 7,031 ppm at Çöpler (Turkey). Boddington is a large Archean deposit formed by two superimposed magmatic-hydrothermal systems, the first one dated at about 2700 Ma and the second at about 2612 Ma. Molybdenite from the first-formed system contains an average of 485 ppm Re, whereas molybdenite from the second one, which contains the bulk of the mineralization, contains an average of 5 ppm Re (McCuaig et al., 2001; Stein et al., 2001b). Molybdenite from the Fort Knox deposit (Alaska) also has a relatively low Re content averaging 26 ppm (Selby et al., 2002). Çöpler (Turkey) is a porphyry-epithermal deposit in which intermediate-sulphidation epithermal-style Au mineralization has overprinted closely-related, low-grade, porphyry-style Cu-Au mineralization. Two molybdenite samples from the porphyry mineralization contained 2272 and 7031 ppm Re, averaging 4637 ppm Re (Imer et al., 2013).

Rhenium contents in molybdenites from Mo-dominant porphyry deposits are typically much lower than in molybdenites from Cu-dominant deposits (Giles and Schilling, 1972; Newberry, 1979b; Berzina et al. 2005). In Canadian porphyry Mo deposits, Re content of molybdenite ranges from 3 ppm (Cassiar Moly) to as high as 397 ppm (Endako), although average values for most porphyry Mo deposits have a more limited range of 12 ppm Re (Adanac) to 108 ppm Re (Mount Haskin). Higher values occur in molybdenites from porphyry-type occurrences such as Nithi Mountain (120 ppm Re), Fabiola (125 ppm Re) and Gabarus (170 ppm Re). However, the highest values are in molybdenites from three Endako samples that contained 204 to 397 ppm Re. These appear to represent a separate, anomalous population distinct from the other 12 Endako samples analyzed, including mill concentrate, which ranged from 15 to 67 ppm Re and averaged 35 ppm Re. Molybdenites from Endako analyzed by Selby and Creaser (2001a) had comparable Re contents that ranged from 6.5 to 38.5 ppm. Rhenium contents in molybdenites from foreign deposits ranged from <1 ppm Re (Shapinggou, China) to 182 ppm Re (Mount Tolman, Washington). No significant differences are apparent in Re contents in molybdenites between fluorine-rich and fluorine-poor porphyry Mo deposits. Re-in-molybdenite contents of fluorine-rich deposits ranged from 7 ppm Re (Henderson, Colorado) to as high as 145 ppm Re (Questa, New Mexico) and fluorine-poor deposits had comparable Re-in-molybdenite contents that ranged from 15 ppm Re (Endako) to 149 ppm Re (Quartz Hill, Alaska)(not including the anomalously high values at Endako).

Molybdenites from porphyry W-Mo deposits have Re contents similar to molybdenites from porphyry Mo deposits. In Canadian deposits, the range is from 6 ppm Re (Sisson, New Brunswick) to 190 ppm Re (Lake George, New Brunswick). Rhenium contents in molybdenites from foreign porphyry W-Mo deposits range from 1.7 ppm Re at Glen Eden, Australia (Hirt et al., 1963; Riley, 1967) to 115 ppm Re at (Koktenkol, Kazakhstan (Ivanov et al, 1972).

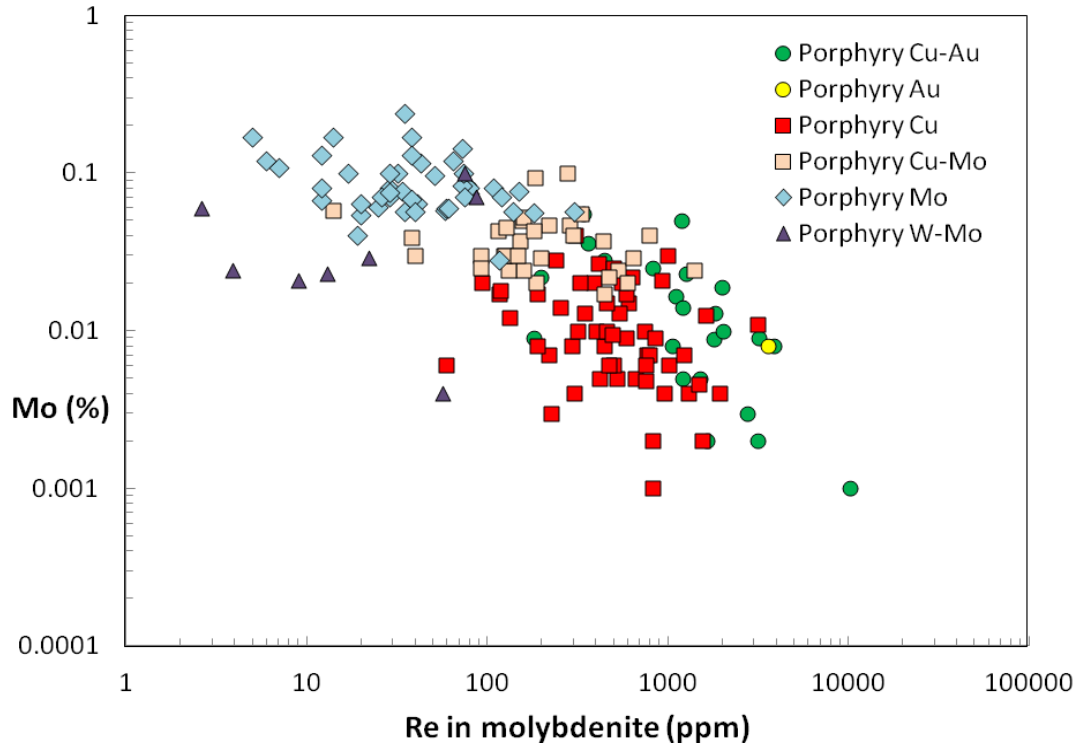


Figure 1. Plot of average Re content of molybdenite versus Mo grade of Canadian and foreign porphyry deposits ($r = -0.36$)(data from Appendices 2 and 3).

For porphyry deposits overall, an inverse relationship appears to exist between average Re contents in molybdenite and Mo grades in that increasing Re-in-molybdenite contents generally correlate with decreasing Mo grades of the deposits ($r = -0.36$, Fig. 1). In detail, this is an oversimplification as correlation appears to be weaker for individual deposit types such as porphyry Mo, Cu-Mo and W-Mo deposits. The variation in Re contents in molybdenite may be attributed, at least in part, to mass balance phenomena. The limited presence of molybdenite in Cu- and Au-rich porphyry deposits results in relatively high Re concentrations in molybdenite compared to Mo-rich porphyry deposits in which Re contents are diluted by much larger quantities of molybdenite (Giles and Schilling, 1972; Stein et al., 2001a).

Low Re-in-molybdenite values for porphyry Mo and porphyry W-Mo deposits also correlate with low to negligible Cu contents in these deposits. As Cu/Mo increases, Re content in molybdenite also increases (Fig. 2). Deposits such as Mount Tolman (Washington), which has a relatively high Re-in-molybdenite content for a porphyry Mo deposit (182 ppm) and an appreciable Cu content (0.09% Cu), appear to be transitional between porphyry Mo and porphyry Cu-Mo deposits; Lasmanis and Utterback (1995) consider Mount Tolman to be a hybrid deposit with characteristics of both Climax-type porphyry Mo deposits and porphyry Cu deposits. Zuun Mod (Mongolia) is another example of a transitional or hybrid porphyry Mo deposit with appreciable Cu (0.064%) and relatively high Re-in-molybdenite (up to 150 ppm)(Clark and Beaudry, 2011). On the other hand, other possible transition-type porphyry Mo deposits with significant Cu, such as Red Bird, British Columbia (0.068% Cu), El Creston, Mexico (0.059% Cu) and Zhireken, Russia (0.1% Cu) have Re-in-molybdenite values that are more typical of porphyry Mo deposits (6-43 ppm Re, 26 ppm Re and 12-57 ppm, respectively)(this study; Barra et al., 2005; Berzina et al., 2005). The Quartz Hill deposit, Alaska, where molybdenite

from a test concentrate has a relatively high Re content of 149 ppm (Appendix 1), has a negligible Cu content averaging 0.003% Cu (Ashleman et al., 1997).

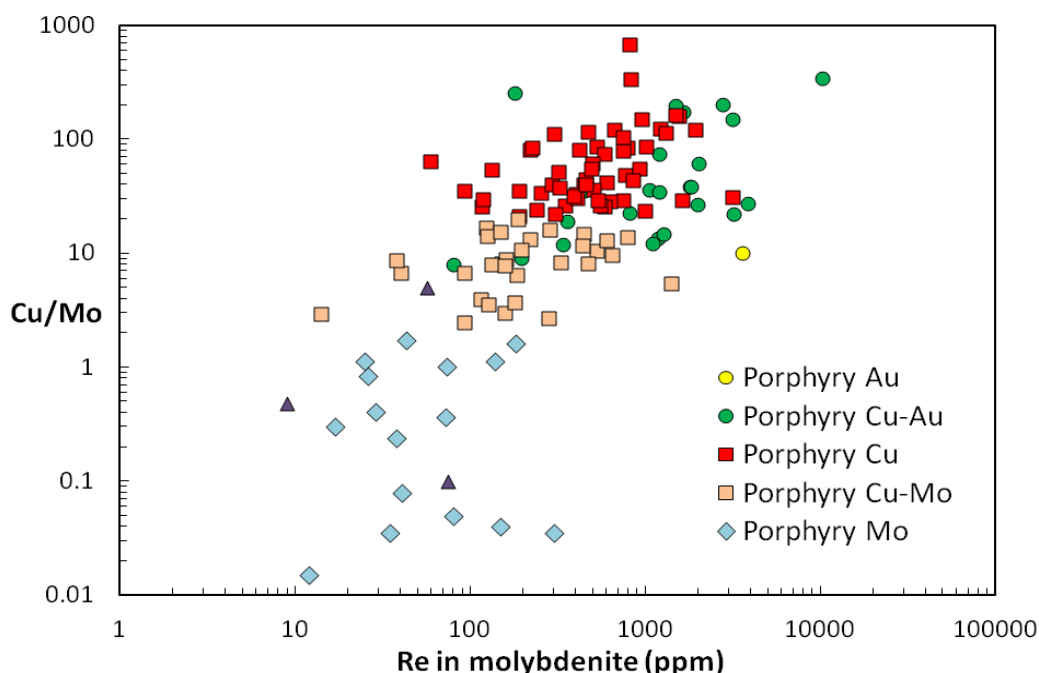


Figure 2. Plot of average Re content of molybdenite versus average Cu/Mo of Canadian and foreign porphyry deposits ($r = 0.40$)(data from Appendices 2 and 3).

Gold contents in porphyry deposits correlate weakly with Re contents of molybdenite ($r = 0.24$, Fig. 3). Porphyry Mo deposits have low Au grades (0.01 g/t or less) and low contents of Re in molybdenite compared to most Cu- and Au-rich porphyry deposits, although the Re content of molybdenites from porphyry Au and Cu-Au deposits varies considerably from as low as 5 ppm (Boddington, Australia) to more than 10,000 ppm (Santo Thomas II, Philippines). On the other hand, better correlation exists between Re grades and Au grades of deposits ($r = 0.53$, Fig. 4), indicating that Cu- and Au-rich porphyry deposits generally have higher overall Re contents than Mo-dominant, Au-poor deposits. Variation in Re contents in molybdenites from different types of porphyry deposits is therefore not solely a mass balance phenomenon whereby the limited presence of molybdenite in porphyry Cu and Cu-Au deposits leads to high Re concentrations in molybdenite compared to porphyry Mo deposits in which Re is diluted by large volumes of molybdenite (cf. Giles and Schilling, 1972; Stein et al., 2001a). The greater concentration of Re in Au-rich porphyry deposits may reflect a mantle contribution in the genesis of these deposits (Sinclair and Jonasson., 2014).

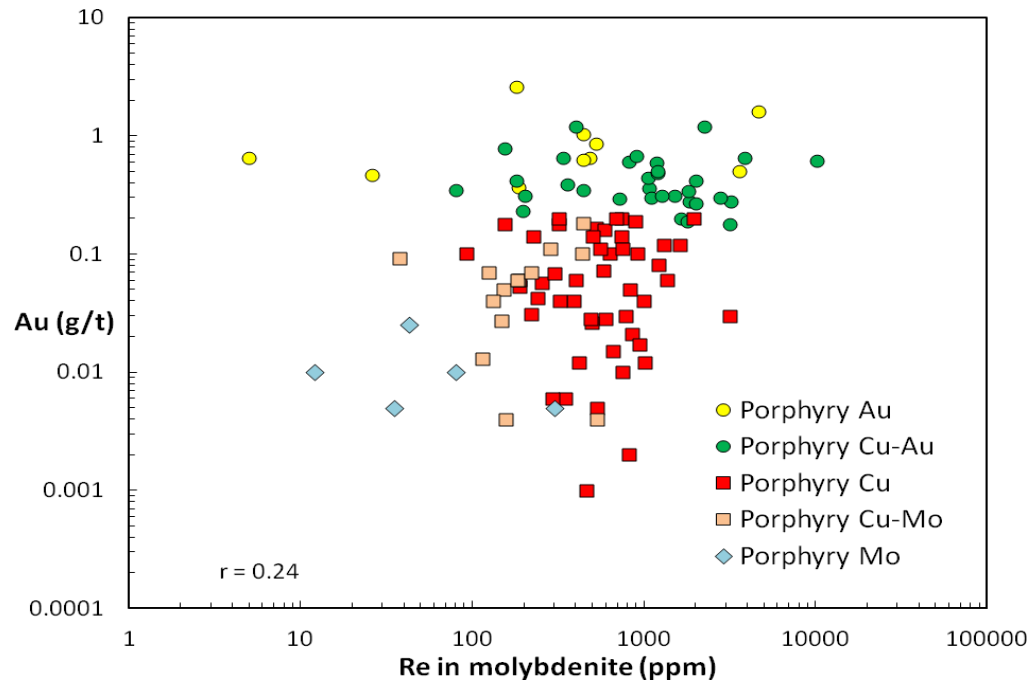


Figure 3. Plot of average Re content of molybdenite versus Au grade of Canadian and foreign porphyry deposit ($r = 0.24$)(data from Appendices 2 and 3).

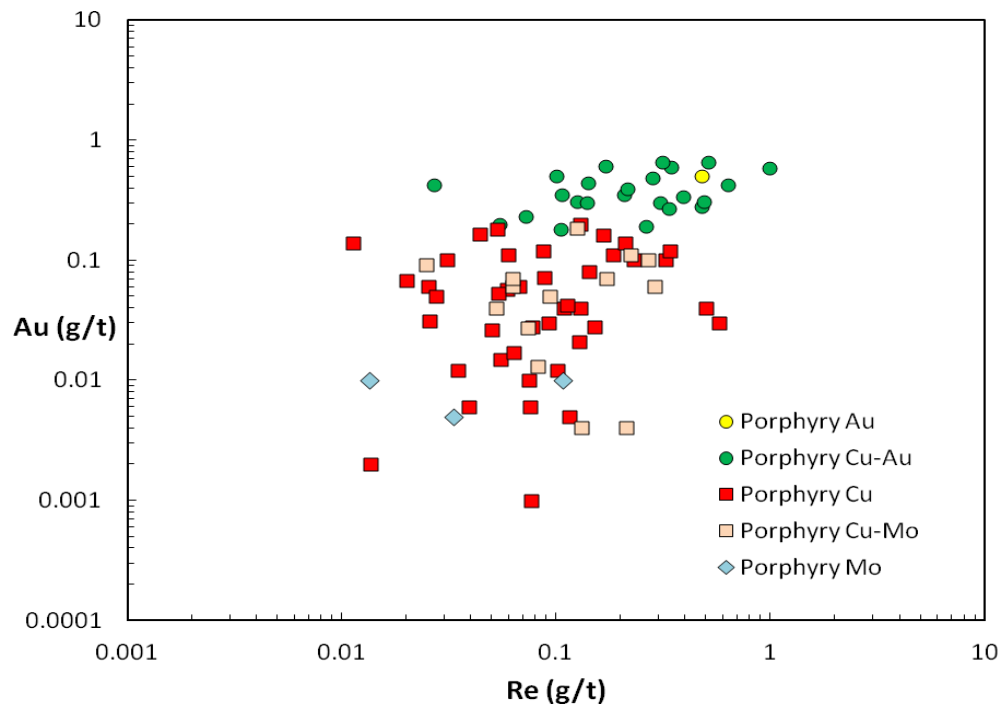


Figure 4. Plot of Re grade versus Au grade of Canadian and foreign porphyry deposits ($r = 0.53$)(data from Appendices 2 and 3).

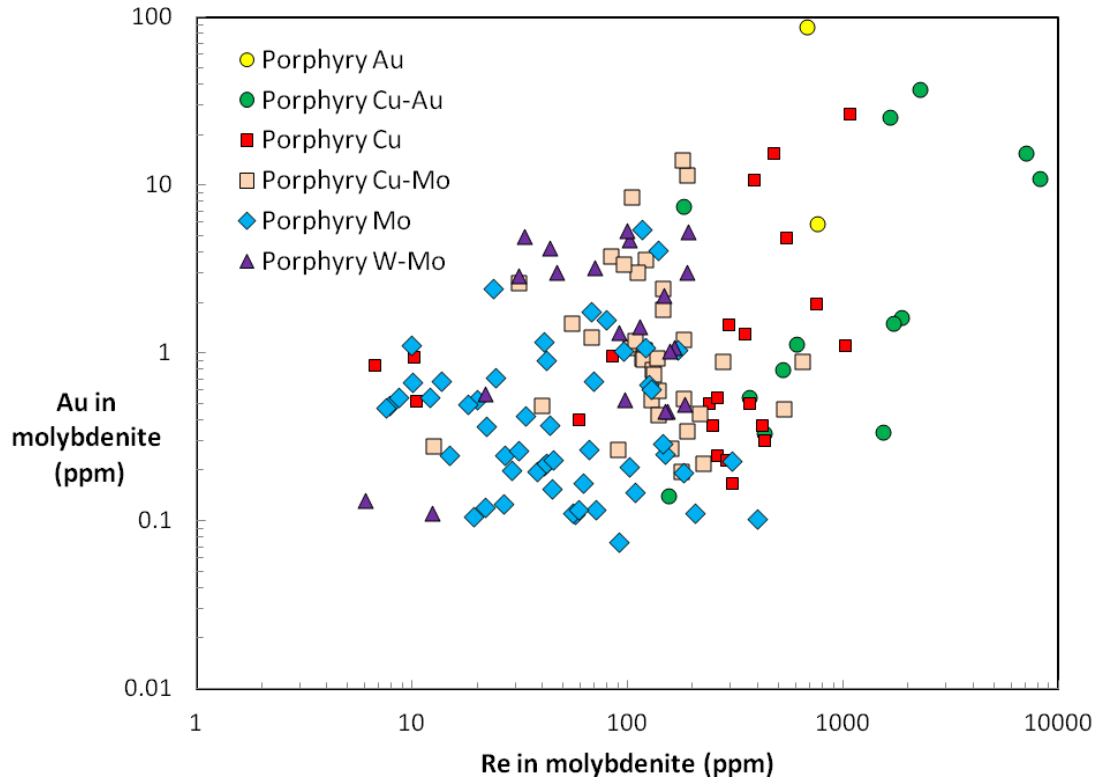


Figure 5. Plot of Re content of molybdenites versus Au content of molybdenites from porphyry deposits ($r = 0.28$); data from Appendix 1 (not including the anomalously high value of 2400 ppm Au for the McIntyre deposit).

Gold content of molybdenite in porphyry deposits

In addition to Re, which typically replaces Mo in the lattice, molybdenite can concentrate other metals, including Au, which mostly form inclusions or impurities (Ciobanu et al., 2013; Pašava et al., 2016). Our analyses of Au content of molybdenites from Canadian porphyry deposits range from ≤ 0.01 to 2400 ppm Au although most values fall within the range of 0.01 to 10 ppm Au (Appendix 1). Excluding the high value of 2400 ppm Au, there is weak to moderate correlation between the Au and Re contents in molybdenites ($r = 0.28$, Fig. 5). The highest Au content in molybdenite, from the McIntyre Cu-Au deposit, appears to be anomalous and is likely due to Au grains attached to molybdenite grains or otherwise present in the molybdenite concentrate that was analyzed. Other molybdenites with high Au contents in excess of 10 ppm are mainly from Au-rich porphyry deposits, including the Lac Dasserat Au occurrence (88 ppm Au in molybdenite), the Ingerbelle Cu-Au deposit (25 ppm Au) and the Mitchell Cu-Au deposit (11 and 15.4 ppm). Other deposits, such as the Ryan Lake-South Zone Cu-Mo deposit (14.2 ppm Au in molybdenite) and the MacLeod Lake Cu-Mo deposit (11.4 ppm) are not particularly Au-rich; they have measured Au grades of 0.092 and 0.06 g/t Au, respectively (Appendix 2). The Don Rouyn Cu deposit, with 11, 16 and 27 ppm Au in three different molybdenite samples (Appendix 1), does not have a measured Au grade, although Goldie et al. (1979) reported that one out of 20 samples analyzed contained 1 ppm Au; the other 19 contained less than 0.3 ppm Au.

Intradeposit variation in Re content of molybdenite in porphyry deposits

The distribution of Re in molybdenite can vary widely within individual porphyry deposits. Porphyry Mo and W-Mo deposits show the least variation, with maximum ranges of 15 to 397 ppm Re (Endako), 49 to 157 ppm Re (Boss Mountain) and 33 to 190 ppm Re (Lake George) among Canadian deposits. The maximum range for foreign deposits is 39 to 145 ppm Re (Questa, New Mexico). Much greater variations within individual deposits occur in porphyry Cu and Cu-Au deposits. Among Canadian deposits, the maximum range is 104 to 2280 ppm Re in the McIntyre Cu-Au deposit. However, some foreign deposits show even wider variations in the Re contents of molybdenites, ranging from 120 to 2000 ppm Re (Bingham, Utah), 57 to 6310 ppm Re (Agarak, Armenia) to 700 to 15,400 ppm Re at the Santo Thomas II deposit in the Philippines (Appendix 3).

Intradeposit variations in the Re content of molybdenite are likely due to a variety of physical and chemical factors that affect the magmatic-hydrothermal solutions in which Re and associated metals such as Mo, Cu and Au are transported. These factors, which include temperature, pressure and oxygen fugacity, can result in spatial variations manifested in vertical and lateral zoning of metals, including Re, and in temporal variations reflected in different stages of mineralization.

Zoning patterns in porphyry deposits have been well studied with respect to the dominant metals such as Cu, Mo and Au and numerous examples are included in Schroeter (1995), Titley (1982) and Titley and Hicks (1966). At the Bingham deposit (Utah), as at many other Cu-dominant porphyry deposits, the Cu zone forms the shape of an inverted cup with the Mo zone overlapping and extending inward and below the Cu zone; the Au-rich zone coincides closely with the higher grade, central part of the Cu zone (Gruen et al., 2010). According to Austen and Ballantyne (2010), Re grade averages 0.55 ppm Re in the central Cu-Mo-Au-rich core of the Bingham deposit and 0.19 ppm Re in the deeper, Mo-dominant part of the deposit. Based on the average Mo grades in the Cu-Mo-Au-rich core and deeper Mo zone (0.1060% and 0.0957% Mo, respectively), average Re content of molybdenite is 311 ppm Re in the core of the deposit and 119 ppm Re in the deeper Mo zone. Above and peripheral to the core of the deposit, Re-in-molybdenite values are as high as 2000 ppm Re (Giles and Schilling, 1972). Filimonova et al. (1985) described a similar spatial distribution pattern for porphyry Cu-Mo deposits in Kazakhstan, including Kounrad, where molybdenites from lower-grade Cu zones with associated quartz-K-feldspar alteration had lower Re contents than molybdenites from peripheral higher-grade Cu zones with associated quartz-sericite alteration. Comparable patterns of Re distribution likely exist in Canadian porphyry deposits but have not been documented.

Porphyry deposits are typically formed by multiple stages of fracturing and mineralization that are accompanied by changes in mineralogy with each successive stage (e.g., Soregaroli, 1975). Such changes represent temporal variations and may be reflected by changes in the Re content of molybdenite in different stages of mineralization. For example, in the Lime Creek (Kitsault) porphyry Mo deposit, molybdenites from four successive mineralization stages increased in Re content from 36 to 129 ppm and in the Questa (New Mexico) porphyry Mo deposit they increased progressively in four stages from 42 to 113 ppm Re (Giles and Schilling, 1972). At the Endako porphyry Mo deposit, Selby and Creaser (2001a) recognized two periods of Mo mineralization, the first represented by quartz vein stockworks with molybdenite characterized by a Re content of 20.0 ppm, and the second by ribbon-textured quartz veins with molybdenites containing 6.5 to 38.4 ppm Re. Molybdenites from these two stages represent the bulk of Mo mineralization at Endako and are similar in Re content to the majority of our samples from Endako, which averaged 35 ppm Re. The three molybdenite samples with substantially higher Re contents (204 to 397 ppm) suggest that a third stage of mineralization may be present. Molybdenites from Nithi Mountain, about 15 km to the southeast of Endako, have Re contents that range from 77 ppm Re (Selby and Creaser, 2001a) to 116 ppm (this study, Appendix 1).

Based on Re-Os dating (Selby and Creaser, 2001a), the Nithi Mountain molybdenite mineralization (~154 Ma) is slightly older than the bulk of Endako molybdenite mineralization (~148 to ~145 Ma). The three molybdenites at Endako with high Re contents appear to represent a separate, apparently minor stage of mineralization that may be similar in age to the Nithi Mountain molybdenite, or possibly some other stage of undetermined age.

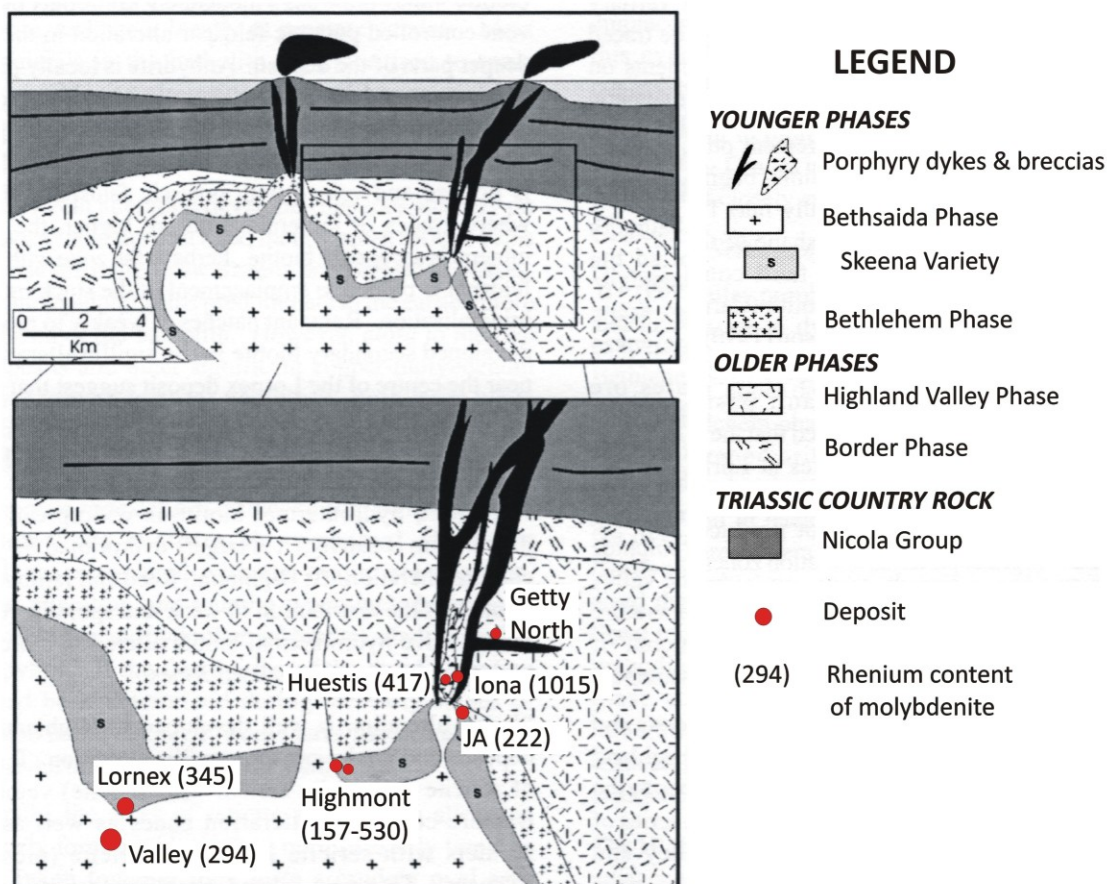


Figure 6. Schematic cross section depicting the relative depths and geological setting of porphyry deposits associated with the Guichon Creek batholith, British Columbia (modified after Casselman et al., 1995). Rhenium contents of the molybdenites tend to be higher in deposits related to the older, higher-level Bethlehem phase of the batholith and lower in deposits associated with the younger and deeper Bethsaida phase.

Interdeposit variation in Re content of molybdenite in porphyry deposits: Highland Valley district, British Columbia

Spatial and temporal variations in Re distribution among different deposits can also be significant on a district scale. In the Highland Valley district in south-central British Columbia, porphyry Cu and Cu-Mo deposits are related to the Late Triassic Guichon Creek batholith, a composite, calc-alkaline intrusion consisting of roughly concentric phases that are progressively younger from the border of the batholith inward. The major phases of the batholith include 1) a border phase of mafic-rich diorite or quartz diorite, 2) the Highland Valley phase, which ranges from quartz diorite to granodiorite in composition, 3) the Bethlehem phase, consisting mainly of granodiorite, and 4) the Bethsaida phase, which varies from granodiorite to quartz monzonite (Northcote, 1969;

McMillan, 1976, 1985). Mineralization episodes in the batholith were associated mainly with the two youngest phases (McMillan, 1976). The first main mineralization event followed emplacement of the Bethlehem phase and produced the Iona, Jersey and Huestis deposits, as well as the Krain (Getty North) and Trojan (Getty South) deposits. The second, more important episode, was associated with emplacement of the Bethsaida phase and resulted in the Highmont, Lornex, Valley and JA deposits. According to McMillan (1976), the deposits formed in settings that reflect increasing depth and temperature of formation as schematically illustrated in Figure 6. The Iona and Huestis deposits are associated with subvolcanic breccias and porphyry dike swarms and appear to have formed in the shallowest and coolest settings. The Highmont deposit, which is associated with a large porphyry dike and minor breccia, and the Lornex and Valley deposits, which have few associated dikes and no associated breccia, formed in progressively deeper and hotter settings. The setting of the JA deposit, which is associated with an aplitic stock that intruded near the contact of the Bethlehem and Guichon phases, is ambiguous but considered to be slightly deeper than that of the Highmont deposit (McMillan, 1976).

Table 2. Rhenium contents of molybdenites from porphyry deposits in the Highland Valley district (data from Appendix 2).

Name	Re ppm				Size (Mt)*	Cu%	Mo%	Au g/t	Re g/t	Cu/Mo
	n	Ave	Min	Max						
Deposits associated with the Bethlehem phase of the Guichon Creek Batholith:										
Huestis (Bethlehem)	1	417			1.4	0.4	0.005	0.012	0.035	80.0
Iona (Bethlehem)	1	1015			29.5	0.52	0.006	0.012	0.102	86.7
Deposits associated with the Bethsaida phase of the Guichon Creek Batholith:										
JA (Bethlehem)	4	116	7	234	268	0.43	0.017		0.033	25.3
Lornex	5	347	286	427	956	0.34	0.013	0.006	0.075	26.2
Valley	1	294			2369	0.32	0.008	0.006	0.039	40.0
Highmont-East & West Pits	1	530			123	0.25	0.024	0.004	0.212	10.4
Highmont-West Pit	2	157	137	176	15	0.15	0.05	0.004	0.131	3.0

*Geological resource, including production plus measured, indicated and/or inferred reserves.

The average Re contents of molybdenites from Highland Valley deposits vary from 116 to 1015 ppm Re (Table 2). Deposits related to the Bethlehem phase have the highest Cu/Mo values (≥ 80) and include the deposit (Iona) with the highest Re-in-molybdenite content (1015 ppm Re). Deposits related to the Bethsaida phase have lower Cu/Mo values (3 to 40) and their molybdenites generally have lower Re contents in the range from 116 ppm to 530 ppm Re. The different values for molybdenites associated with the Highmont deposit require some explanation. The Highmont deposit consists of at least two zones that were mined separately. The lower value (157 ppm Re) is an average of two samples collected from the Highmont West Pit, which ranged from 137 to 176 ppm Re. The higher value (530 ppm Re) is from a sample of mill concentrate collected in 1982, when production was from both the Highmont East Pit and the Highmont West Pit. The mill concentrate thus represents a composite of the two Highmont zones and is likely more representative of the Highmont deposits as a group. The lower values in the samples from the West Pit likely reflect variation that can occur on a deposit scale.

Rhenium distribution in deposits associated with the Guichon Creek batholith may be a result of the crystallization history of the batholith. The earliest-formed deposits associated with the

Bethlehem phase (Iona, Huestis) are more Cu-rich ($\text{Cu}/\text{Mo} \geq 80$) and molybdenite in concentrate from the Iona deposit has the highest Re content in the district (1015 ppm Re). In contrast, later-formed deposits related to the Bethsaida phase are more Mo-rich ($\text{Cu}/\text{Mo} \leq 40$), with lower contents of Re in molybdenite (116 to 530 ppm).

Skarn Deposits

Skarn refers to assemblages of dominantly calcium and magnesium silicates formed in calcareous or dolomitic rocks either by metasomatic replacement related to thermal metamorphism adjacent to igneous plutons or as a result of regional metamorphism. Like porphyry deposits, skarn deposits can be divided into subtypes based on the dominant economic or potentially economic metal present.

The Re content of molybdenite from Canadian skarn deposits appears to follow a similar pattern to Re content of molybdenite from porphyry deposits in that it is significantly higher in molybdenites from Cu-dominant skarns compared to molybdenites from Mo- and W-dominant skarns (Fig. 7). The range of Re levels, however, is more restricted. Rhenium contents of molybdenites from Cu-dominant skarn deposits not associated with porphyry deposits range from 7 ppm Re in the Cowley Park deposit in the Whitehorse Copper Belt to 759 ppm Re in the Little Billie deposit on Texada Island. Molybdenite from the Needle Mountain skarn deposit of Gaspé Copper contains 353 to 371 ppm Re, a higher level than in molybdenite from the associated Copper Mountain porphyry Cu deposit, which contains 187 ppm Re. Molybdenites from foreign skarn Cu, Cu-Mo and Cu-Au

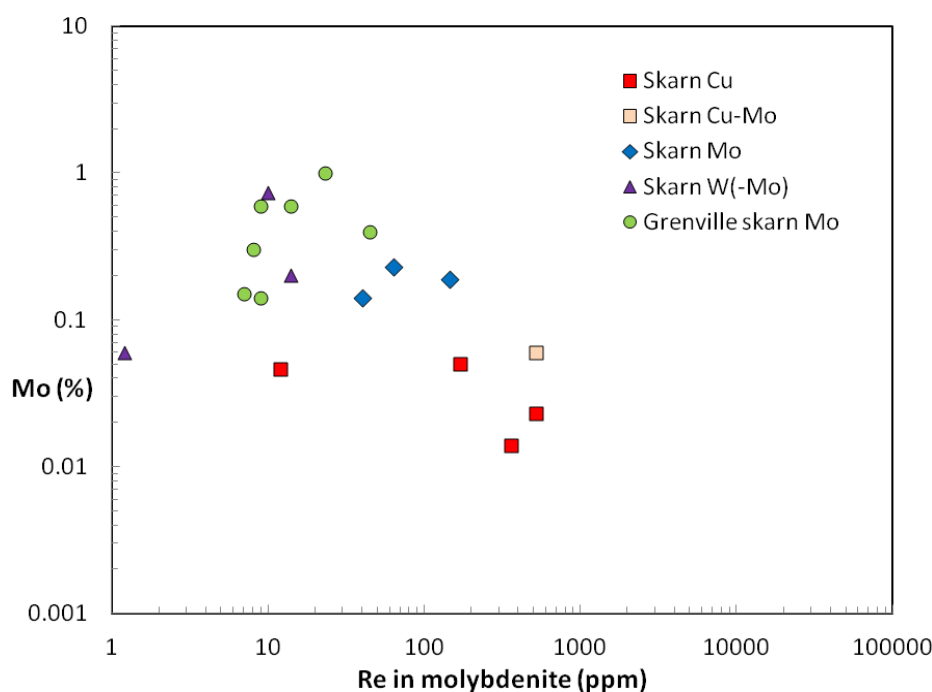


Figure 7. Plot of average Re content of molybdenite versus Mo grade of Canadian and foreign skarn deposits ($r = -0.43$)(data from Appendices 2 and 3).

deposits have Re contents that range from 291 ppm Re (Dongguanshan, China) to 1152 ppm Re (Jiguanzui, China). The El Tierrero skarn Au deposit in the Nambija district of Ecuador contains molybdenite with as much as 2500 ppm Re (Chiaradia et al., 2009).

In the two examples of Canadian skarn Mo deposits, Re content of molybdenite ranges from 131 to 160 ppm Re in the Red Mountain (Coxey) deposit in British Columbia to 215 ppm Re in the Newman occurrence in Ontario. Two skarn Mo deposits in China (Xiaojiayingzi, Yangjiazhangzi) contain molybdenite with Re contents in the range of 22 to 163 ppm.

Molybdenites from Canadian W-dominant skarns have relatively low Re contents, ranging from mainly from 5 to 47 ppm, except for Mount Fitton where molybdenite contains as much as 138 ppm. In foreign skarn W deposits, the range is 3.1 ppm Re (Tyrnyauz, Russia) to 75 ppm Re (Pine Creek, California); an exception is the Brownstone Mine deposit (California), where molybdenite contains as much as 428 ppm Re. Molybdenite in Sn-rich skarns is relatively scarce but has some of the lowest Re contents. We have no data for molybdenites from Canadian skarn Sn deposits, but Re contents in molybdenites from foreign deposits ranges from 0.1 ppm Re (Moina, Australia) to 39 ppm Re (Kafang, China).

Grenville skarn Mo deposits

Deposits of Mo in moderate to high-grade metamorphic rocks of the Grenville Supergroup are widespread throughout Ontario and Quebec and have been considered as a subtype of skarn Mo deposits (e.g., Vokes, 1963). The deposits typically consist of coarse-grained molybdenite erratically disseminated in pyroxene-rich rocks, with or without feldspar, mica and calcite, that occur within gneissic metasedimentary rocks including crystalline limestone or marble. Pyrite and pyrrhotite are commonly associated with molybdenite and locally form massive lenses within the pyroxene-rich rocks. In some places, the molybdenite-bearing, pyroxene-rich rocks and associated crystalline limestone or marble occur at or near contacts with granitic plutons or intrusions of granitic pegmatite and are considered to be contact metasomatic skarn deposits, e.g., Hunt (Lentz, 2000) and Zenith (Salvi, 2000). In other places, no associated carbonate-rich rocks or granitic intrusions are present in the vicinity of the deposits, e.g., American Molybdenite (Vokes, 1963). This led Karvinen (1973) to suggest that all Grenville skarn Mo deposits are primarily metamorphogenic in origin, Mo having been mobilized and concentrated from Mo-rich sedimentary rocks during regional metamorphism. The Re content of molybdenites from Grenville skarn Mo deposits is relatively low and ranges overall from <1 ppm Re at the Zenith deposit to 83 ppm Re at the Hunt deposit (Appendix 1).

Pegmatite-aplite Deposits

Pegmatite-aplite Mo deposits in Canada range from simple to zoned pegmatites, to more complex deposits associated with granitic stocks cut by aplitic dikes, pegmatite bodies and irregular quartz veins and stringers. Molybdenite is commonly the only sulfide in these deposits and typically occurs as fine- to coarse-grained flakes disseminated in pegmatite, aplite and quartz. Minor amounts of pyrite, chalcopyrite and bismuthinite may also be present. Although some deposits are high grade in places, they are generally small, irregular in form and erratic in Mo content. The pegmatite and aplite host rocks are predominantly granitic in composition, with quartz and K-feldspar as the chief mineral constituents. One notable exception is the Mount Copeland deposit in British Columbia, in which molybdenite occurs in syenitic pegmatite and aplite lenses at the contact of nepheline syenite gneiss that is part of the Shuswap Metamorphic Complex (McMillan, 1973). Molybdenite is also associated

with some uraniferous pegmatites in the southwestern Grenville Province of Ontario and Quebec, notably the Madawaska U deposit near Bancroft, Ontario (Alexander, 1981).

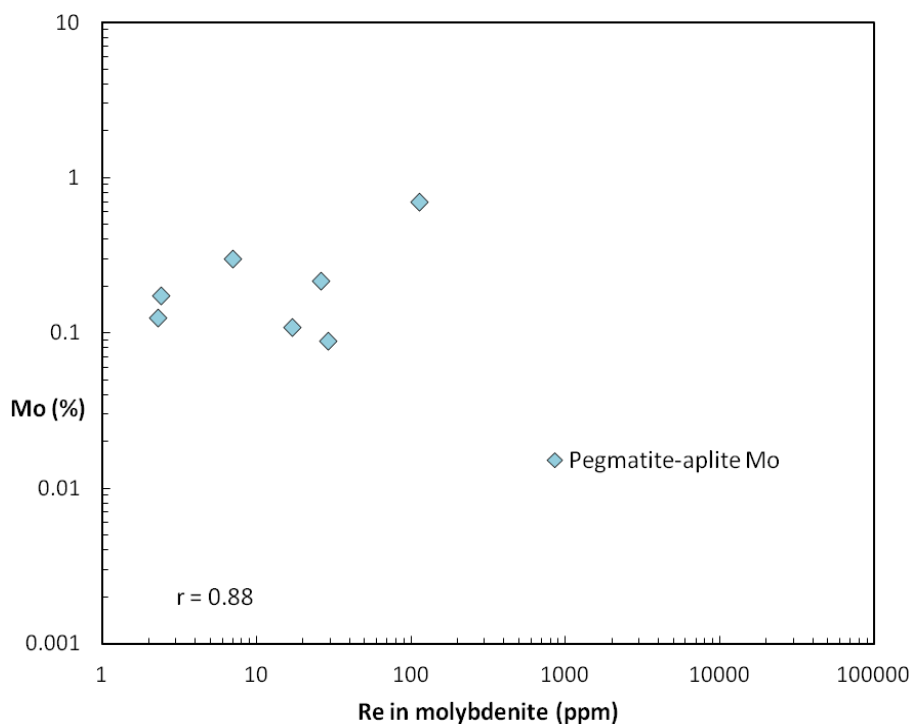


Figure 8. Plot of average Re content of molybdenite versus Mo grade of Canadian and foreign pegmatite-aplite deposits ($r = 0.88$)(data from Appendices 2 and 3).

Molybdenites from most pegmatite-aplite Mo deposits have Re contents comparable to those in molybdenites from porphyry Mo deposits (Fig. 8). In Canadian deposits Re content ranges from <1 ppm Re (Ray) to as much as 160 ppm Re (Coates Moly), although for many of these deposits the Re content of the molybdenite is less than 100 ppm Re (Appendix 1). One significant exception is the Aubé (Cheabella) occurrence in Quebec, from which molybdenites in two separate hand samples contained anomalously high values of 516 and 945 ppm Re. The reason for these anomalous values is not obvious. The molybdenite occurred within a pegmatite dike cutting ultramafic rocks that are in contact with siliceous metasedimentary rocks impregnated with traces of Cu- and Ni-bearing sulfides. No obvious relationship between the molybdenite and the Cu- and Ni-bearing sulfides was evident according to Van de Walle (1978). Rhenium contents of molybdenites from pegmatite-aplite U deposits range from 28 to 79 ppm Re.

Molybdenites from pegmatite-aplite Mo deposits in foreign countries have comparable Re contents that range from 0.5 to 131 ppm Re (Appendix 3). Deposits with Re concentrations in molybdenite at the low end of the range include the Kåtaberget, Allebuoda and Munka deposits in northern Sweden, which occur in aplitic and granitic rocks that are intercalated with biotitic gneisses of the Svecofennian Orogen. Stein (2006) interpreted the aplitic and granitic rocks as leucocratic migmatites and considered the low Re content of the molybdenites (<20 ppm) to be diagnostic of metamorphic derivation. The Knaben deposit in southern Norway occurs in quartz veins, silica-rich gneiss, pegmatites and aplites associated with amphibolite facies gneiss of the Sveconorwegian Orogen and is likely related to granitic magmatism that was coeval with regional high-grade

Sveconorwegian metamorphism (Bingen et al., 2014). Knaben may be similar in some respects to the Swedish deposits but the molybdenite from Knaben has marginally higher Re contents that range from 1 to 28 ppm Re (Fleischer, 1959; Giles and Schilling, 1972). Grenville skarn Mo deposits, also considered to be metamorphic in origin, may also be comparable in some respects to the Scandinavian deposits although molybdenites from Grenville skarn Mo deposits have slightly higher Re contents that range from <1 to 83 ppm Re (Appendix 1).

Vein Deposits

Vein deposits included herein encompass a variety of deposits that are primarily structurally controlled and occur in faults, fault systems and related breccia zones. Associated replacement zones may be present in adjacent country rocks. Vein deposits containing molybdenite are widespread in Canada and highly varied in their composition. In addition to Mo-dominant deposits, they include deposits of Cu, W-Mo, Pb-Zn-Ag, Au and U.

Rhenium content of molybdenites from vein deposits ranges overall from <1 to 1690 ppm Re, although for most deposits the maximum content is less than 300 ppm Re (Appendices 2 and 3). The average Re content of molybdenite in vein deposits appears to correlate closely with increasing Mo grade of the deposit ($r = 0.90$, Fig. 9). The highest values in Canadian molybdenites are from the Golconda vein Cu-Mo deposit in British Columbia, a small deposit that consists of chalcopyrite- and molybdenite-bearing quartz veins in shear zones cutting ultramafic to alkaline rocks of the Middle Jurassic Olalla intrusion (BC Minfile 082ESW016). Molybdenites analyzed from the Golconda vein contained 1095 to 1335 ppm Re. Molybdenites from other Canadian vein Cu and Cu-Mo deposits contained 11 to 356 ppm Re and, except for the Golconda deposit, Re-in-molybdenite contents do not appear to be substantially higher for vein Cu and Cu-Mo deposits than for other types of vein deposits.

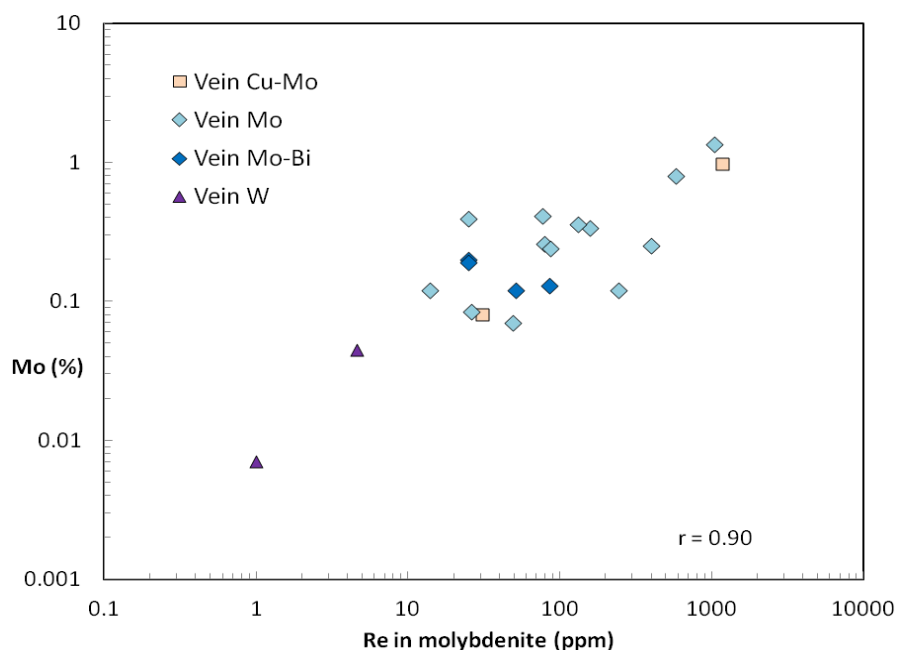


Figure 9. Plot of average Re content of molybdenite versus Mo grade of Canadian and foreign vein deposits ($r = 0.90$)(data from Appendices 2 and 3).

Foreign Cu-dominant vein deposits include the Baimashi Cu-Mo deposit in China (23-38 ppm Re in molybdenite) and the Mount Morgan Cu-Au deposit in Australia, from which molybdenite was found to contain 1690 ppm Re (Riley, 1967).

With the exception of the Playter deposit (discussed below), molybdenites from Canadian vein Mo deposits have Re contents that range mainly from 7 to 177 ppm, comparable to porphyry Mo deposits. Representative of this class are vein Mo-Bi deposits in the Abitibi region of western Quebec, which were the principal source of Canadian Mo production from the 1940s to 1972. These deposits are associated with the Archean Preissac-Lacorne batholith, a composite intrusive body that consists of at least two distinct phases, an early phase consisting of metaluminous plutons that range from gabbro to granodiorite in composition and a slightly younger phase of peraluminous plutons that are typically zoned from biotite-rich to muscovite-rich monzogranite (Boily, 1995). Molybdenite- and bismuthinite-bearing quartz veins are associated mainly with monzogranite or related pegmatitic phases, except for the Lacorne deposit, which occurs on the periphery of a small stock of granodiorite, and the Belpat-LaPause occurrence, which is associated with an albitite dike cutting volcanic country rocks. Rhenium-in-molybdenite contents for these deposits (based on average values from hand specimens and mill concentrates) range from 24 to 104 ppm Re, comparable to the content of Re in molybdenites from porphyry Mo deposits.

Molybdenite from the Playter deposit in northern Ontario is exceptional among Canadian vein Mo deposits, with Re contents ranging from less than 200 to more than 1000 ppm Re, based on drill intercepts on different parts of the vein. The deposit consists of a massive quartz vein as much as 23 metres wide in places and more than one kilometer in length. Molybdenite is the main sulfide mineral and is accompanied in places by minor amounts of pyrite and trace amounts of chalcopyrite and galena. The Mo content of the deposit averages 0.25% Mo; the Re content of the molybdenite overall averages about 400 ppm Re (Kilpatrick and Grieco, 2010).

Foreign vein Mo deposits have molybdenite with Re contents ranging from 13 to 1039 ppm Re (Appendix 3). Molybdenite from vein Mo deposits and occurrences in Japan had Re contents that ranged overall from <1 to 240 ppm Re (Ishihara, 1988); three of the largest deposits, Daito, Higashiyama and Seikyū, had Re-in-molybdenite contents that averaged 132, 79 and 87 ppm Re, respectively (Appendix 3). The highest Re contents in molybdenite are from the Everton and Merlin deposits in Australia. At Everton, Re-in-molybdenite content averaged 580 ppm Re (Appendix 3). Molybdenite from the Merlin deposit has an average Re content of 1039 ppm Re, the highest of any Mo-dominant vein deposit. However, Merlin is an unusual vein-type deposit. According to Brown et al. (2010), Mo mineralization at Merlin is broadly stratabound within metamorphosed Proterozoic sedimentary rocks, but post-dates the metamorphism. The host rocks are brecciated and molybdenite occurs as fine-grained, semi-massive to massive concentrations filling open spaces and replacing host rock fragments, and as disseminated grains in the metasedimentary host rocks. And, whereas most vein Mo deposits, such as Everton and Playter, consist of molybdenite disseminated in quartz veins, the Merlin deposit is distinguished by the absence of quartz. Also, in contrast to Mo deposits in quartz veins, which typically contain an average of 0.1 to 0.3% Mo, the grade of the identified mineral resource at the Merlin deposit is much higher, averaging 1.3% Mo (Horton, 2010). Such a high content of Mo, combined with the high Re content of the molybdenite, makes Merlin an exceptional if not unique vein-type Mo deposit.

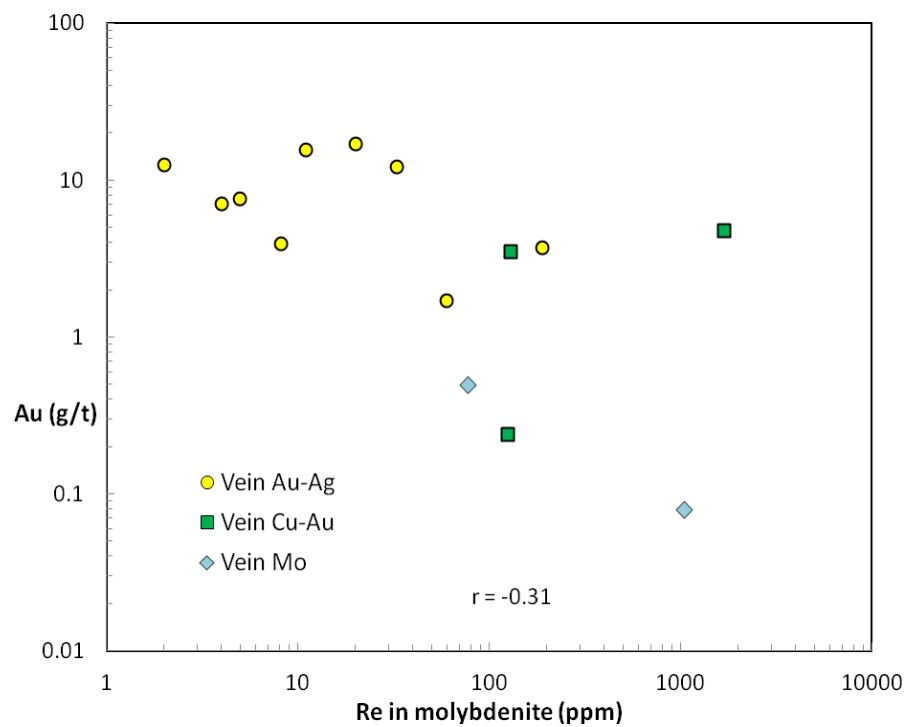


Figure 10. Plot of average Re content of molybdenite versus Au grade of Canadian and foreign vein deposits ($r = -0.31$)(data from Appendices 2 and 3).

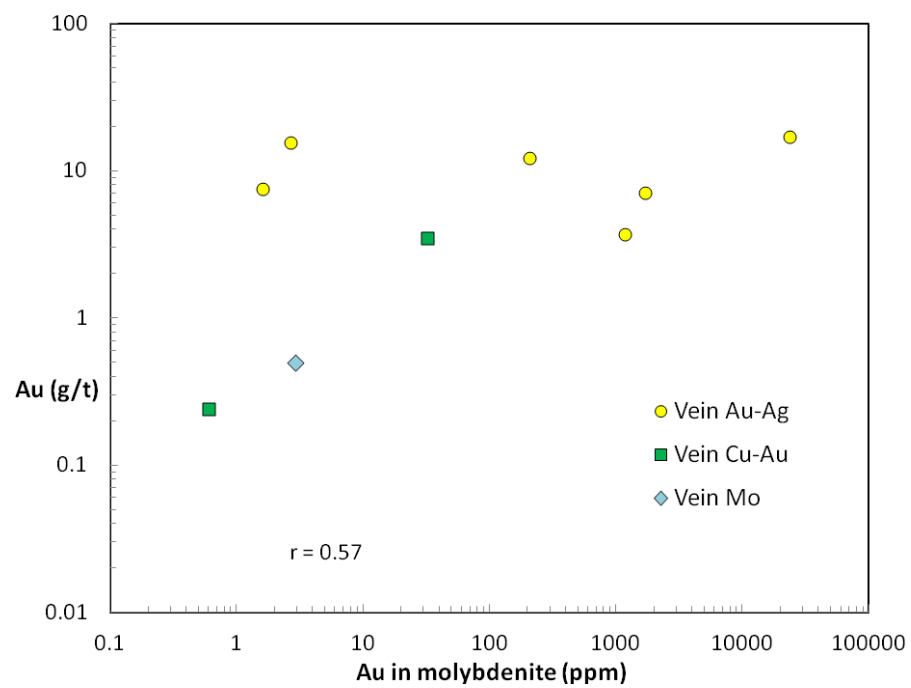


Figure 11. Plot of average Au content of molybdenite versus Au grade of Canadian vein deposits ($r = 0.57$)(data from Appendix 2).

Rhenium content of molybdenite from Canadian vein W-Mo deposits is generally low, ranging from <1 to 13 ppm Re at Burnt Hill, New Brunswick and up to 80 ppm Re in occurrences at Square Lake, New Brunswick. Molybdenites from foreign vein W(-Mo) deposits have Re contents that range from <0.01 to 7.5 ppm (Appendix 3).

Molybdenite is generally sparse in vein Pb-Zn-Ag deposits and has relatively low Re contents that range from 1 to 160 ppm Re (Appendix 1).

Trace to minor amounts of molybdenite are associated with many vein Au-Ag deposits in Canada, notably in the Kirkland Lake deposits (Thomson et al., 1950). Rhenium contents of molybdenites from vein Au-Ag deposits range from 4 to 189 ppm and tend to decrease with increasing Au grade of the deposit ($r = -0.31$, Fig. 10). Molybdenites from vein Au-Ag deposits have the highest Au contents, ranging from <2 ppm to >20,000 ppm Au ($r = 0.57$, Fig. 11). In the case of the latter, from the Lakeshore mine in Kirkland Lake, such a high value is most likely due to impregnations of Au grains in molybdenite (cf. Boyle, 1979). In foreign vein Au-Ag deposits, Re contents in molybdenite range from 0.2 to 114 ppm Re (Appendix 3).

Molybdenite from the Powerline Pond vein U deposit contained 260 ppm Re (Appendix 1).

Mafic- and Ultramafic-hosted Deposits

Mafic and ultramafic-hosted deposits include a broad group of magmatic deposits containing Ni, Cu and, in some cases, platinum-group elements (PGE) that occur as sulphide segregations in mafic and ultramafic magmatic rocks. Rhenium content in magmatic Ni-Cu deposits is relatively low, generally <10 ppb Re in most Canadian Ni-Cu ores (Hulbert, 1997). However, Re is present at more elevated levels in many PGE-rich Ni-Cu deposits. Although data on grades of Re in Ni-Cu-PGE are generally lacking, Re contents of ore samples analyzed for Re-Os dating range from <1 ppb to 970 ppb Re (Appendix 4). Because they are based on relatively few analyses, average contents of Re in magmatic Ni-Cu-PGE deposits indicated in Appendix 4 should be considered as first order approximations. Based on these approximations, overall Re grades range from about 7 ppb Re (Voisey's Bay) to as high as 320 ppb Re in the Creighton deposit in the Sudbury district. At Creighton, the relatively high Re content is accompanied by high PGE content (2.0 g/t Pt and 2.2 g/t Pd) and 0.07 g/t Au. In comparison, the PGE-poor McCreedy East deposit in the Sudbury district has significantly less Re (about 39 ppb) and less Au (0.008 g/t).

The mineralogy of Re in mafic- and ultramafic-hosted deposits is varied. In some deposits, the Re occurs as tarkianite and unnamed Re-bearing sulphide minerals (Dare et al., 2010); in others it is concentrated mainly in base metal sulphides such as pyrrhotite, pentlandite and pyrite (Dare et al., 2011). Molybdenite is rare in mafic- and ultramafic-hosted deposits. We obtained one sample of molybdenite from the Northrock (Ontario) Cu-Ni deposit, which contained 87 ppm Re. In contrast, molybdenite from the Talnakh Cu-Ni-PGE deposit in Russia contained as much as 3.8% Re, concentrated mainly in central zones of the grains (Kovalenker et al., 1974).

Sediment-hosted Deposits

Sediment-hosted Cu deposits

Sediment-hosted Cu deposits consist of disseminated to veinlet Cu sulphides that occur in zones more or less concordant with the stratification of their sedimentary host rocks. They account for nearly one-quarter of the world's production and reserves of Cu and are important sources of Ag and Co (Hitzman et al., 2005). They also account for about 10 to 15 per cent of world Re production, from the Lubin deposit in Poland and the Dzhezkazgan deposit in Kazakhstan. The nature of the occurrence of Re in sediment-hosted Cu deposits is not well understood. Rhenium is recovered from the processing of Cu concentrates and some Re may be present in the main Cu minerals, such as chalcopyrite, bornite and chalcocite. However, Re is also present in other minerals. For example, at Dzhezkazgan, Re is present in the sulphide mineral dzhezkazganite ($\text{ReMoCu}_2\text{PbS}_4$), which is closely associated with the Cu ores (Genkin et al., 1994) and, in the Lubin deposit, Re-bearing minerals include castaingite (CuMo_2S_5) and molybdenite (Kucha, 1990).

Molybdenite is scarce in most sediment-hosted Cu deposits and Re contents of Canadian deposits and occurrences are based on analysis of Cu concentrates prepared from hand samples (Appendix 5). From the estimated Cu content of the concentrates, the results were arbitrarily normalized to 4% Cu, which is the grade of the Redstone deposit. Although there is considerable uncertainty, the results suggest that average contents are on the order of 1-10 ppm Re. Three samples from the Redstone deposit (Northwest Territories) have an average normalized content of 1.6 ppm Re, which is typical of sediment-hosted Cu deposits worldwide (Table 3). For example, the Re content of the ore at Dzhezkazgan (Kazakhstan) averages 1.4 ppm Re (Hitzman et al. 2005) and in the Lubin deposit (Poland) it averages 1.14 ppm Re (H. Kucha, personal communication, 2007). The deposits of the Mansfeld-Sangerhausen district (Germany) had a comparatively high content of 21 ppm Re based on historical production data in Jankowski (1995) and Krüger (2006).

Table 3. Rhenium contents of sediment-hosted Cu deposits.

Country	Deposit	Size (Mt)*	Cu%	Mo%	Ag g/t	Re g/t	Re (t)	References
Canada	Redstone (Coates Lake)	37	3.9		11.3	1.6	59	This work; Ruelle (1982)
Germany	Mansfeld-Sangerhausen	155	2.5	0.015	129	21	3255	Jankowski (1995); Krüger (2006)
Kazakhstan	Dzhezhkazgan	2,000	1.1		20	1.4	2800	Hitzman et al. (2005)
Kazakhstan	Zhaman-Aibat (Zhomart)	161	1.69		19.1	1.45	233	Box et al. (2012)
Poland	Kupferschiefer (Lubin)	3,400	2	0.003	40	1.14	3876	Hitzman et al. (2005); Kucha (pers. comm., 2007)

*Geological resource, including production plus measured, indicated and/or inferred reserves.

Sediment-hosted U deposits

Some U deposits formed in permeable sandstones and conglomerates also contain trace to minor amounts of other metals including Mo and Re (Table 4). In the late 1960s, significant amounts of Re were recovered as a by-product from the mining of U deposits in sedimentary rocks in the Falls City area south of San Antonio in Texas (Millensifer, 1997). More recently, Re production has been reported from in situ solution mining of sediment-hosted U deposits in the Central Kyzylkum region of Uzbekistan (Chekmarev et al., 2004).

Table 4. Rhenium contents of sediment-hosted U deposits.

Country	Deposit	Size (Mt)*	U ₃ O ₈ %	Mo%	Re g/t	Re (t)	References
Canada	Anna Lake (NL)	5	0.044	0.014	0.2	1	Fraser and Giroux (2009)
Canada	Angilak (NU)	2.8	0.69	0.17	?	?	Dufresne et al. (2013)
Canada	Roughrider (SK)	0.4	1.98	0.03	?	?	Keller et al. (2011)
Columbia	Berlin	8.7	0.11	0.062	6.8	59	Inwood et al. (2012)
Kazakhstan	Suluchekinskoye	330			1.5	495	Dahlkamp (2009a)
United States	Palangana (TX)	4.3	0.07	0.016	2	9	Goddard (1984); Dahlkamp (2010)
United States	Runge (SD)			0.015-0.63	<70-70		Myers et al. (1960)
United States	Sun Valley (AZ)			0.07-1.5	50-1000		Peterson et al. (1959)
Uzbekistan	Sugrally	30		0.004-0.26	12.5	375	Dahlkamp (2009b)

*Geological resource, including production plus measured, indicated and/or inferred reserves.

The nature of the occurrence of Re in sediment-hosted U deposits is not well understood. In roll-type U deposits, Mo is typically concentrated in reduced sandstone at the distal edges of the mineralized zone (Harshman, 1974). At Palangana (Texas) and other sediment-hosted U deposits, Re is closely associated with Mo and is likely concentrated in jordisite, an amorphous Mo mineral with the same composition as molybdenite (MoS₂) (Goddard, 1984). At the Sun Valley U mine (Arizona), Re is associated with jordisite and the water-soluble Mo mineral ilsemanite (Mo₃O₈.nH₂O) (Petersen et al., 1959).

Rhenium content in sediment-hosted U deposits ranges from 0.2 to 12.5 ppm Re or more (Table 4). Rhenium is largely unreported in Canadian sediment-hosted U deposits, with the exception of the Anna Lake deposit in Labrador, which contains 0.2 ppm Re (Fraser and Giroux, 2009). However, some contain significant amounts of Mo, for example the Roughrider deposit in the Athabasca Basin in Saskatchewan, which has an overall grade of 0.03% Mo (Keller et al., 2011), and the Angilak U deposits in the Baker Lake Basin (Nunavut), which contain 0.17% Mo (Dufresne et al., 2013). The possibility that significant Re may be associated with the Mo in these deposits merits consideration. Among foreign deposits, the Re grade sediment-hosted U deposits ranges from 1-2 g/t at the Suluchekinskoye deposit in Kazakhstan (Dahlkamp, 2009a) to 10-15 g/t in the Sugrally deposit in the Central Kyzylkum region of Uzbekistan (Dahlkamp, 2009b). Individual samples from the Sun Valley mine in Arizona range as high as 1000 ppm Re (Peterson et al., 1959).

Epithermal Gold Deposits

Epithermal Au deposits typically form as veins and disseminations in near-surface volcanic environments, in many cases associated with hot springs. In addition to Au (and Ag), some deposits may contain base metals such as Cu, Pb and Zn. Molybdenum is less common but is present in significant amounts in the Hemlo Au deposits in Ontario, averaging 0.1% Mo in the Golden Giant deposit. Molybdenite from the Golden Giant deposit contains 10 ppm Re. Molybdenite from the Ridgeway deposit in South Carolina (USA) contains 9 ppm Re.

Volcanic-associated Deposits

Volcanic-associated Cu-Zn deposits

Volcanic-associated deposits include volcanogenic massive sulphide deposits of Cu-Zn that typically consist of concordant semi-massive to massive sulphide lenses in volcanic sequences. Based on Re analyses of ores for Re-Os dating, overall Re contents of volcanic-associated Cu-Zn deposits range from 2 ppb to 1.53 ppm, with average contents from different deposits ranging from 10 ppb to 0.47 ppm (Table 5). Molybdenite is relatively rare in volcanic-associated Cu-Zn deposits. In the few examples from Canadian deposits, molybdenites had relatively low Re contents ranging from 11 ppm in the Harper Creek (British Columbia) deposit to 85 in the Kelly Creek (British Columbia) deposit (Appendix 1). Molybdenite from the Mount Lyell Cu-Au deposit (Australia) contained 7.3 ppm Re (Morgan et al., 1968; Appendix 3).

Table 5. Rhenium contents of volcanic-associated Cu-Zn deposits.

Country	Deposit	Deposit subtype	Re ppm				Size (Mt)*	Re (t)	References
			n	Ave	Min	Max			
China	Gacun	Kuroko	7	0.47	0.08	1.53	124	58	Hou et al. (2003)
Japan	Hitachi	Kuroko	20	0.02	0.002	0.14	27	0.5	Nozaki et al. (2014)
Japan	Fukazawa	Kuroko	5	0.07	0.05	0.12	6.5	0.4	Terakado (2001a)
Japan	Kosaka	Kuroko	3	0.04	0.004	0.09	15	0.7	Terakado (2001a)
Japan	Shakanai	Kuroko	2	0.12	0.004	0.23	0.5	0.06	Terakado (2001a)
Japan	Hanaoka	Kuroko	1	0.01			44	1	Terakado (2001a)
Japan	Iimori	Besschi	11	0.12	0.02	0.26	2.7	0.3	Nozaki et al. (2010)
Japan	Wanibuchi	Kuroko	4	0.03	0.004	0.05			Terakado (2001b)
Turkey	Küre	Kuroko	6	0.28	0.13	0.63	29	8	Akbulut et al. (2016)

*Geological resource, including production plus measured, indicated and/or inferred reserves.

Volcanic-associated U deposits

Volcanic-associated U deposits typically consist of disseminations and veins of uraninite and/or pitchblende in felsic to peralkaline volcanic rocks. Significant amounts of Mo may be present in some deposits such as the Aillik Bay (Makkovik South) deposit (Labrador), which has a Mo grade of 0.162% Mo (Kirkham et al., 1982). Molybdenite from the Aillik Bay deposit contains 2 ppm Re. Molybdenite from the Rexspar U deposit (British Columbia) contains 13 ppm Re (Appendix 1).

Iron Oxide Copper-Gold Deposits

Iron oxide copper-gold (IOCG) deposits include a variety of polymetallic deposits of hydrothermal origin that are characterized by a high content (>20%) of magnetite and/or hematite (Corriveau, 2007). Molybdenum is not one of the metals normally enriched in these deposits and molybdenite is generally scarce. Average Re content of molybdenite in Canadian IOCG deposits ranges from 37 to 146 ppm (Appendix 2). Average Re content of molybdenite in foreign IOCG deposits ranges from 68 to 140 ppm, not including the Kalman (Australia) deposit (Appendix 3). Molybdenite from Kalman contains 1650 ppm Re and seems anomalous with respect to other IOCG deposits. Although Kalman is classified as an IOCG deposit by Leahy et al. (2010), it does not have a high content of magnetite or hematite. The high Re content of the molybdenite is more typical of a porphyry Cu-Au deposit.

Rhenium Resources

Estimates of Re resources in individual deposits are included in Appendices 2 and 3. Except for the rare cases where Re grades are included along with assay data for other metals in a deposit (e.g., Snowfield, Hushamu and Playter in Canada and Muratdere in Turkey), Re grades for the deposits have been calculated based on the average Re content of molybdenite and the Mo grade of the deposit. This assumes that all Mo and Re is contained in molybdenite, which is reasonable considering that molybdenite is the only significant Mo mineral in most deposits and that the Re content of other sulfides is negligible, typically on the order of parts per billion or less (cf. Mathur et al., 2000). A second assumption is that the average Re contents of molybdenite recorded are representative of the deposits, which is reasonable where Re analyses are based on large samples such as mill concentrates. However, Re analyses based on hand samples and drill core can vary widely, especially in large deposits such as porphyry deposits, which are characterized by metal zonation, and Re grades based on such analyses are more uncertain. Rhenium contents obtained from Re-Os dating, although very precise, are based on analysis of relatively small samples and the Re grades based solely on such data have the greatest uncertainty. Despite these uncertainties, the grade calculations allow for preliminary estimates of Re resources and for comparisons between different deposits and deposit types.

Rhenium resources in porphyry deposits

Rhenium grades in porphyry deposits range from <0.01 to nearly 1 g/t Re. They are highest in porphyry Cu-Au deposits, which average 0.33 g/t Re in Canadian deposits, and lowest in porphyry W-Mo deposits, which have an average content of 0.05 g/t Re. Average Re grades of porphyry Mo, Cu-Mo and Cu deposits are 0.07, 0.14 and 0.06 g/t Re, respectively. The higher Re grades in Au-rich porphyry deposits relative to Mo-dominant porphyry deposits contrasts with the preliminary observation of Giles and Schilling (1972) that no appreciable differences appeared to exist between the overall Re contents of Mo-dominant porphyry deposits and Cu-dominant porphyry deposits of comparable size (tonnage). Our grade estimations suggest that variations in Re content of molybdenite in porphyry deposits are not due primarily to simple mass balance phenomena that would relate the Re content of molybdenite inversely to the amount of molybdenite, i.e., the more molybdenite in a deposit, the lower its Re content, and vice versa (cf. Stein et al., 2001a).

Because of the large size of porphyry deposits, their total Re contents can be considerable. The Pebble deposit in Alaska, for example, with its relatively high grade of Re (0.49 g/t) and estimated resources of 10.8 Bt, contains more than 5000 t Re. This is equivalent to about 100 years of total world production at current rates and is one of the largest resources of Re in the world. Other Cu-dominant porphyry deposits with Re resources in excess of 1000 t include El Teniente (1623 t), Collahuasi (1299 t), Los Pelambres-El Pachon (1122 t) and Toquepala (1222 t). Canadian Cu- and Au-bearing porphyry deposits with substantial Re resources include Mitchell (1780 t) and Snowfields (1057 t). Others with significant Re resources are Hushamu (245 t), Schaft Creek (229 t), Kemess South (109 t) and the Highland Valley district, which in total contained 205 t Re prior to mining. Island Copper, Canada's only known producer of Re, is estimated to have contained about 95 t Re, of which approximately 27 t was recovered (Perelló et al., 1995). Despite their generally lower Re grades, large porphyry Mo deposits may contain significant amounts of Re, e.g., Quartz Hill (303 t) and Climax (127 t). Overall Re content of the Endako deposit prior to mining was on the order of 21 t Re, although no production of Re from Endako has been reported, likely due to the low content of Re in molybdenite (~35 ppm Re).

Rhenium resources in skarn deposits

Rhenium grades in skarn deposits are comparable to those in porphyry deposits, ranging from 0.01 g/t Re in the Cowley Park (Yukon) Cu deposit to 0.52 g/t Re in the Suoerkuduke (China) Cu-Mo deposit. Although some porphyry-associated skarn Cu deposits can be large, ranging up to 320 Mt in size (Dawson and Kirkham, 1996), most are relatively small and Re contents are correspondingly low, generally <1 t Re. Exceptions are Needle Mountain (Quebec) (6 t Re) and Suoerkuduke (China) (6 t Re).

Skarn Mo deposits in China include some large deposits with Re reserves of 11 t (Xiaojiayingzi) and 17 t (Yangjiazhangzi). However, the amount of Re in most other types of skarn deposits, particularly Grenville skarn Mo deposits, is negligible compared to porphyry deposits.

Rhenium resources in pegmatite-aplite deposits

Rhenium grades in pegmatite-aplite Mo deposits are comparable to those in porphyry Mo deposits, generally no more than 0.1 g/t Re. Because the deposits are small, Re resources are limited. The largest in Canada is the Pidgeon Molybdenum (Ontario) deposit, which has a resource of 0.6 t Re. Mount Copeland (British Columbia), which had a higher Re grade (1.32 g/t) but smaller size (0.17 Mt of ore produced), contained on the order of 0.2 t Re. The Knaben deposit in Norway contained about 0.3 t Re.

Rhenium resources in vein deposits

Rhenium grades in vein deposits are highly varied, ranging from <0.01 g/t Re to more than 23 g/t Re. However, most vein deposits are small and have limited resources of Re. In Canada, the Golconda (British Columbia) Cu-Mo deposit has a Re grade of 19.1 g/t Re but a resource of no more than 1 t Re. The Playter (Ontario) vein Mo deposit has a lower grade (1.7 g/t Re) but has a slightly larger resource of 1.5 t Re. Foreign deposits have comparable resources, most containing <1 t Re. A singular exception is the Merlin deposit (Australia), which is not only relatively large for a vein Mo deposit (6.7 Mt ore) but also has a high Re grade of 23.1 g/t and a substantial resource of 155 t Re.

Rhenium resources in mafic- and ultramafic-hosted deposits

Copper-Ni-PGE deposits associated with mafic and ultramafic rocks represent a potential source of Re. According to Besser et al. (1997), as much as 400 kg of Re is concentrated annually in the flue dusts resulting from the smelter operations associated with the Noril'sk-Talnakh Cu-Ni-PGE deposits in Russia, although apparently none of this Re is recovered at the present time. Based on an overall grade of 0.16 g/t Re, estimated from Re-Os data on ore samples reported by Malitch and Latypov (2011), the Noril'sk-Talnakh deposits have a combined Re resource of about 300 t Re. Our estimate for the PGE-rich Creighton deposit in the Sudbury district is 90 t Re at a grade of 0.32 g/t Re. Other PGE-rich Cu-Ni deposits with significant Re include Wellgreen in Yukon (6.6 t Re) and Pechenga in Russia (9.7 t Re). In comparison, PGE-poor deposits generally have less than 1 t Re, e.g., the McCreedy East deposit in the Sudbury district has a Re grade of about 0.04 g/t Re and a resource of 0.5 t Re (Appendix 5).

Rhenium resources in sediment-hosted Cu deposits

Rhenium resources in sediment-hosted Cu deposits are substantial and comparable to those of large porphyry deposits (Table 3). The Lubin deposit in Poland, for example, contains nearly 4000 t Re at a grade of slightly more than 1 g/t. At Dzhezhkazgan (Kazakhstan) resources are on the order of 3000 t Re at a grade of 1.4 g/t Re. The Mansfeld-Sangerhausen deposits, although smaller, were higher grade (21 g/t Re) and contained a resource of more than 3000 t Re. The Redstone (Coates Lake)

deposit in Canada is smaller and contains about 59 t Re at an estimated grade of approximately 1.6 g/t Re.

Rhenium resources in sediment-hosted U deposits

Sediment-hosted U deposits represent a potentially significant source of Re. Although many such deposits have limited resources, for example the Anna Lake deposit in Labrador contains about 1 t Re at a grade of 0.2 g/t Re, other deposits such as Suluchekinskoye in Kazakhstan and Sugraly in Uzbekistan contain 495 t Re and 375 t Re, respectively. Molybdenum commonly occurs in Re-bearing U deposits and a rough correlation may exist between Mo and Re (cf. Table 4). If this is the case, then deposits such as the Angilik deposits in Nunavut, which contain 0.17% Mo, may have potential for Re despite the fact that no Re has been reported.

Rhenium resources in other deposits

Most other types of deposits appear to have limited potential for resources of Re. Epithermal Au deposits are poorly represented and only the Hemlo-Golden Giant deposit has a measurable resource, which amounts to 0.4 t Re. Volcanic-associated Cu-Zn deposits typically have very low Re contents, ranging mainly from 0.01 to 0.12 ppm Re. Only the Küre deposit in Turkey and Gacun in China have higher Re contents of 0.3 and 0.5 ppm Re, respectively. Because of its large size (124 Mt ore), the Gacun deposit has a significant Re resource estimated at 58 t. Estimated Re resources in volcanic-associated U deposits are small - 0.015 t Re or less. The only iron oxide Cu-Au deposit with an estimated resource is the Kalman deposit in Australia, which has an estimated resource of 66 t Re. However, the classification of Kalman as an iron oxide Cu-Au deposit is questionable; it may be better classified as a porphyry Cu-Au deposit. Two unclassified deposits, Gee Lake and Spurrjack Island, both in Saskatchewan, have no estimated Re resources.

Summary

Porphyry Cu, Cu-Mo and Cu-Au deposits are currently the most important source of primary Re, which is produced from the processing of Mo concentrates that contain in the order of 200 to 1000 ppm Re. The Re contents of molybdenites from Canadian porphyry Cu, Cu-Mo and Cu-Au deposits range from 10 to 8170 ppm Re, although most Re-in-molybdenite values for these deposits fall within a range of 200 to 2000 ppm Re. Estimated Re grades for these deposits range from <0.01 to nearly 1 g/t Re and are highest in porphyry Cu-Au deposits, which average 0.33 g/t Re. Average grades for Canadian porphyry Cu and Cu-Mo deposits are 0.06 and 0.14 g/t Re, respectively. Porphyry Cu, Cu-Mo and Cu-Au deposits have the most resources and the greatest potential for Re production in Canada, although it is not clear if any Re is recovered from them at the present time (Polyak, 2016b). Porphyry Mo and W-Mo deposits contain significant amounts of Re but do not currently produce Re because of their relatively low Re-in-molybdenite contents, which are mainly in the range of 10 to 100 ppm Re. Estimated grades for porphyry Mo and W-Mo deposits range from <0.01 to 0.14 g/t Re and average 0.07 and 0.05 g/t Re, respectively.

Sediment-hosted Cu deposits are the second most important source of primary Re production in world, mainly from deposits in Poland and Kazakhstan. Rhenium resources in the Lubin deposit in Poland amount to nearly 4000 t Re at a grade of 1.14 g/t Re. At Dzezhkazgan in Kazakhstan, they total 2800 t Re at a grade of 1.4 g/t Re. We estimate the Redstone deposit in Canada contains a resource of 39 t Re at a grade of 1.6 g/t Re but this must be considered speculative, considering the uncertainty of our data.

Rhenium resources in Canadian sediment-hosted U deposits may be significant, but data are scarce. The Anna Lake deposit in Labrador, which contains 0.2 g/t Re, is comparatively small. Worldwide, sediment-hosted U deposits can contain 2 to more than 10 g/t Re, which is generally associated with Mo. Canadian U deposits with significant Mo (0.03-0.17%) include the Angilak deposits in the Baker Lake Basin and the Roughrider deposit in the Athabasca Basin. In these and other Mo-bearing U deposits for which Re data are lacking, investigation of the potential for Re as a by-product may be warranted.

Platinum-group-element-rich Ni-Cu deposits associated with mafic and ultramafic deposits contain significant amounts of Re. Our estimated resource for the PGE-rich Creighton deposit in the Sudbury district is 90 t Re at a grade of 0.32 g/t Re. In contrast, the PGE-poor McCreedy East deposit has an estimated grade of about 0.04 g/t Re and a resource of 0.5 t Re.

Vein deposits are typically small with limited Re resources, although some deposits may have relatively high Re grades. The Golconda vein Cu-Mo deposit in British Columbia, for example, contains about 1 t Re at an estimated grade of 19.1 g/t Re. The Playter (Ontario) vein Mo deposit has an average grade of 1.7 g/t Re and an inferred resource of 1.5 t Re.

Acknowledgements

The authors are grateful to many colleagues in the Geological Survey of Canada (GSC), provincial geological surveys and various mining and exploration companies who donated samples for this study or assisted in their collection over a 30-year period. A collection donated by officers of the B.C Geological Survey; viz., W. Johnson, A. Panteleyev and N.C. Carter, got the project rolling. Particular appreciation is accorded to V.L. Eardley-Wilmot, who studied Mo deposits for the Mines Branch of the Canada Department of Mines in the 1920s and 1930s, and whose historical collection was the source of many useful (and nowadays inaccessible) samples for this study. The field collections (1970s) of F.M. Vokes (GSC) were the source of many molybdenite specimens, mainly from Ontario and B.C. However, the study could not have been initiated without the active participation of A.E. Soregaroli (formerly of Noranda, UBC, GSC, Westmin, and Teck Corp), who conceived the study and provided numerous key samples from many Canadian deposits and occurrences. The comprehensive collections of R.V. Kirkham and W.D. Sinclair ultimately provided the majority of Canadian and U.S. specimens that sustained the project.

One early challenge was to devise procedures to crush, grind and sieve drill core and often bulky “hand specimens” to optimize molybdenite recoveries. It was soon discovered that each location required specific recipes for success. P.J Laverne (GSC) carried out these tasks and also devised the various sequences of superpanning, hand picking, froth floatation and heavy liquid purification steps that were employed to yield at least several grams of relatively pure molybdenite (>90% MoS₂) that was sent for analysis. The main contaminant was found to be quartz. Where possible, reject materials were retained and processed to recover chalcopyrite, pyrite, pyrrhotite and scheelite. A.C Roberts assisted by identifying unknown heavy mineral grains using XRD methods. G.M.LeCheminant devised methods and supervised determinations of proportions of molybdenite polytypes by XRD in all separates. Advice and assistance in the analysis of molybdenite concentrates by thermal neutron activation methods was provided by Novatrack Analysts Limited, Neutron Activation Laboratories and, in particular, S. Simpson of Bequerel Laboratories Inc.

We are most grateful to a succession of Directors of several Divisions of the Geological Survey of Canada who encouraged and supported us with generous funding to cover the costs of contract analyses. The project was also funded by Targeted Geoscience Initiative 3 with the support of R.G. Anderson (GSC).

We are also grateful to numerous colleagues who shared insights and/or data, in particular R. Blair (Consulting Geologist), A. Lipmann (Lipmann Walton & Co Ltd), H. Stein (AIRIE Program, Colorado State University), R. Cann (Entrée Gold Inc.), S. Ishihara (Geological Survey of Japan), Q. Zeng (Chinese Academy of Sciences) and X. Liu (Chinese Academy of Sciences). C.J.M. Lawley (GSC) reviewed the manuscript and provided many helpful suggestions.

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