Isotopic Investigation of the Adanac Porphyry Molybdenum Deposit in Northwestern British Columbia (NTS 104N/11): Final Project Report

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Smith, J.L. and Arehart, G.B. (2010): Isotopic investigation of the Adanac porphyry molybdenum deposit in northwestern British Columbia (NTS 104N/11): final project report; *in* Geoscience BC Summary of Activities 2009, Geoscience BC, Report 2010-1, p. 115–126.

Introduction

There are currently numerous poorly understood, relatively underexplored Mo deposits and occurrences in the North American Cordillera that have exploration potential. It would be of great benefit to the exploration community if more data about these Mo deposits in British Columbia are collected and published.

There are geochemical similarities (e.g., redox state of associated plutons; trace- and major-element chemistry of associated plutons; and mineral and elemental assemblages such as high Bi, Te and W, and low and peripheral Cu, Pb and Zn) between porphyry Mo deposits and 'intrusion-hosted' Au deposits (e.g., Tombstone belt; Figure 1; Stephens et al., 2004) that suggest a possible genetic link. The Adanac Mo deposit (MINFILE 104N 052; MINFILE, 2009) belongs to an important class of occurrences that lie within the Atlin mining camp. The Adanac deposit contains no Au itself, but placer Au is still being mined on the lower reaches of Ruby Creek below the deposit. Historically, it has always been assumed that the Mo deposit postdates Au mineralization, which occurs in quartz-carbonate–bearing shears in Paleozoic Cache Creek Group volcanic strata and as placer deposits. However, a study by Sack and Mihalynuk (2004) suggests that this may not be the case. Sack and Mihalynuk's work on Feather Creek suggests that at least some of the placer Au in the Atlin area may have been derived from the Cretaceous Surprise Lake batholith because some of the Au nuggets are associated with thorite and cassiterite. This is consistent with the presence of Au- and W-bearing quartz veins in the Boulder Creek drainage immediately to the south of the Adanac Mo deposit, because wolframite is commonly found peripheral to the molybdenite zone in porphyry Mo deposits (Wallace et al., 1978). Thus, the presence of Au in those wolframite veins raises the question of a potential link between Au-depleted Mo and Au-bearing W 'intrusion-related' deposits. Understanding this association (or lack thereof) is an important step toward focusing further exploration in the North American Cordillera for both of these deposit types.

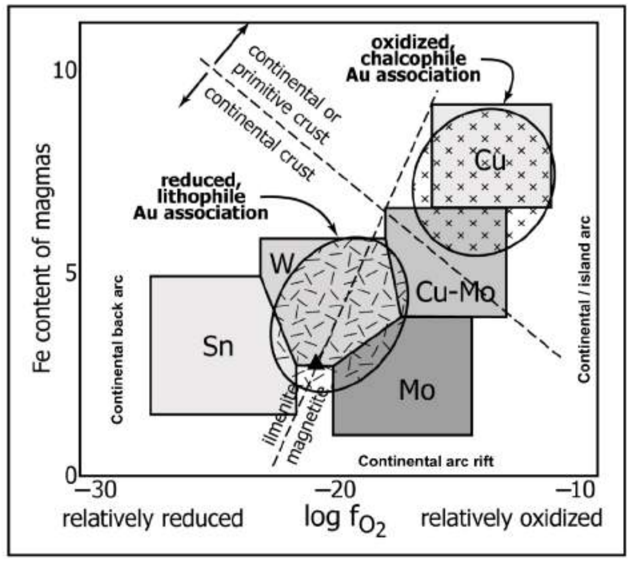

Figure 1. Plot of Fe content versus oxidation state for plutons and associated porphyry mineral deposits. Note that Au is found in both oxidized (porphyry Cu) and reduced (porphyry Sn-W-Mo) environments. The Surprise Lake batholith, British Columbia, plots approximately at the solid triangle. Fields from Thompson et al. (1999).

Geological Background

The Adanac Mo deposit is located in the northwestern corner of BC, near the town of Atlin (NTS 104N/11; Figure 2). The geology of the Atlin area was mapped by Aitken (1959) and the regional setting of the deposit was discussed by Christopher and Pinsent (1982). The Atlin area (Figure 3) is underlain by deformed and weakly metamorphosed ophiolitic rocks of the Pennsylvanian and/or Permian-aged Cache Creek Group (Monger, 1975). These rocks, which include serpentinite and basalt as well as limestone, chert and shale, have long been thought to be the source of much of the placer Au found in the Atlin area. The sedimentary and volcanic rocks are cut by two younger batholiths: north of the Adera fault, they are cut by a Jurassic granodiorite to diorite intrusion (Fourth of July batholith), and north and south of Surprise Lake they are cut by a Cre-

Keywords: *porphyry Mo, placer Au, Re-Os isotope, U-Pb isotope, Surprise Lake batholith, Atlin*

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taceous granitic to quartz monzonitic intrusion (Surprise Lake batholith). The rocks are locally strongly faulted and the Adanac deposit is located near the intersection of two major syn- to postmineralized fault systems within a satellite stock (Mount Leonard stock) of the Surprise Lake batholith.

The Surprise Lake batholith is a highly differentiated, F-rich (0.27%), U-rich (14.6 ppm), peraluminous granite (Ballantyne and Littlejohn, 1982). The batholith is a known host of quartz-vein stockworks (especially associated with the multiphased Mount Leonard stock) and skarn alteration that hosts base- and precious-metal mineralization including W, Sn, Mo, Cu, Co, Pb, Zn, U, F, Ag and Au that occur as both sulphides and oxides (Ballantyne and Littlejohn, 1982). An important deposit related to the batholith and occurring within 4.8 km (3 mi.) of the Adanac deposit is the Black Diamond W vein (Figure 4). The Black Diamond is a 060°-trending, 60°N-dipping quartz vein containing pyrite, scheelite and wolframite; minor chalcopyrite, arsenopyrite and molybdenite; and anomalous tellurium (Kikauka, 2002). This vein lies mostly within the coarse granite of the Mount Leonard stock, except for the eastern portion, which is in Paleozoic marble. Elevated Au values along with Pb, As and Sb anomalies also occur in this eastern portion. A soil sample survey in this area showed anomalous Cu, Pb, Ag, Sb, Bi and Au (Kikauka, 2002).

The deposit area was described by Sutherland Brown (1970), White et al. (1976), Christopher and Pinsent (1982) and Pinsent and Christopher (1995). The Adanac Mo deposit underlies the valley floor near the head of Ruby Creek, and is largely buried with very little surface expression. The geology underlying the valley floor is derived from drill data (Figure 5). The deposit is partially controlled by the Adera fault system, which trends approximately northeast and defines much of the southern boundary of the pre-ore Fourth of July batholith. This is a normal fault, dipping approximately 80° northwest. Mineralization is hosted within the multiphased Mount Leonard stock and entirely within plutonic rock. It forms at least two blanket-shaped and steeply dipping shells over and around porphyry domes, one in the area of the proposed main pit and another in an area to the west of the proposed pit. Mineralization is in the form of 3–4 cm sized molybdenite rosettes in a stockwork of smoky, ribbon-textured quartz veins. Some late-stage milky-white quartz veins carry smaller and less frequent rosettes, but are typically barren. There is very little fine molybdenite, and some molybdenite exists as paint on fractures and in faults. Other minerals present in the porphyry stockwork include wolframite and rare chalcopyrite, galena and sphalerite.

There were three stages of intrusion at Adanac: an early, generally coarse-grained stage that was deformed prior to the intrusion of several second-stage porphyry domes, and

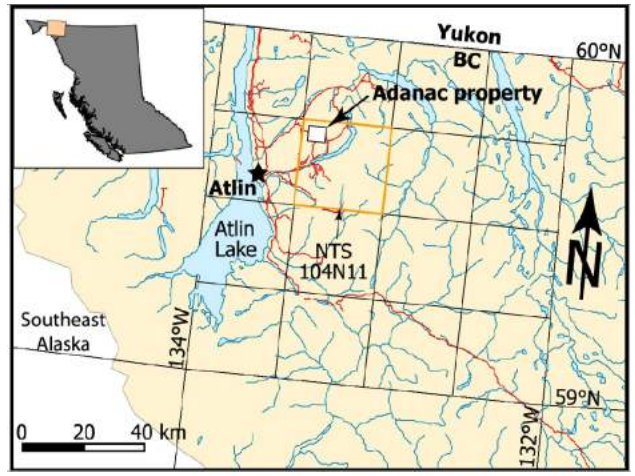

Figure 2. Location of the Adanac Mo deposit, British Columbia (from Pinsent and Christopher, 1995). The white box (Adanac property) is the approximate location of Figure 3 (local geology map). Inset is a location map of BC.

a late fine-grained stage that was injected through the porphyry domes and the early coarse-grained stage. All of the stages of intrusion at Adanac have very little chemical differences and are grouped based on textures and crosscutting relationships. All of the rocks are high-SiO_2, peraluminous alkalic granite formations, and have a Rb/Sr ratio of about 1. Whole-rock geochemistry studies (Smith, 2009) indicate that Adanac hostrocks resemble other hostrocks of Climax-type, high-F porphyry Mo deposits.

Hydrothermal alteration at Adanac is similar to Climax-type porphyry Mo deposits, although it is not as strong or pervasive as described at Climax. Alteration at Adanac consists of a high-SiO_2 'core', or silicification, at the western end of the deposit, and affecting the rest of the deposit area in the form of sill-shaped bodies of silicification trace-

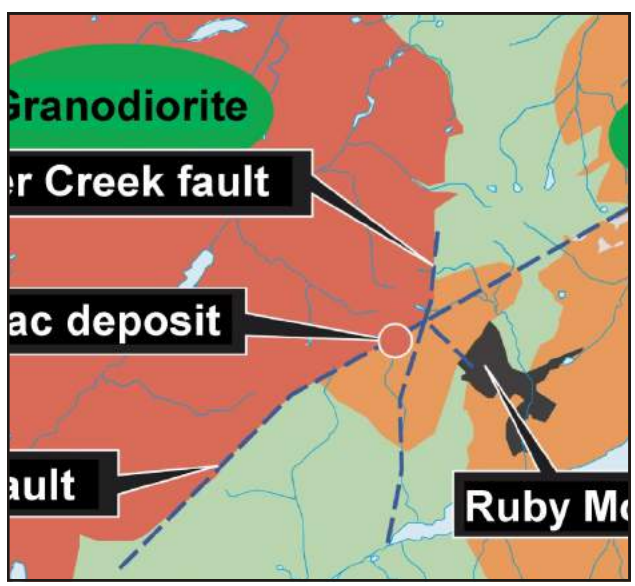

Figure 3. Generalized geology of the Adanac deposit area, British Columbia. Modified from Aitken (1959).

able from one drillhole to the next. Potassic alteration is also strongest at the west end, occurring as zones of pink feldspar flooding in drillcore several metres thick. In the rest of the deposit, potassic alteration is common as pink feldspar envelopes around quartz veins. Hairline fractures filled with quartz, sericite and pyrite are common, and are cut by other fractures filled with calcite, stilbite and sometimes fluorite. Fresher (unaltered) rocks from the deeper portions of drillcore have illite and kaolinite as clay alteration products, while fault gouge is composed of kaolinite and montmorillonite. There is a weak chlorite overprint on most of the rocks at Adanac, especially those distal to mineralization.

Research Objectives

Rhenium-osmium ages of molybdenite and U-Pb ages of various rock types at Adanac were determined to compare ages of mineralization and magmatism. One goal of this study was to identify the causative or mineralizing intrusion by matching a mineralization age with a

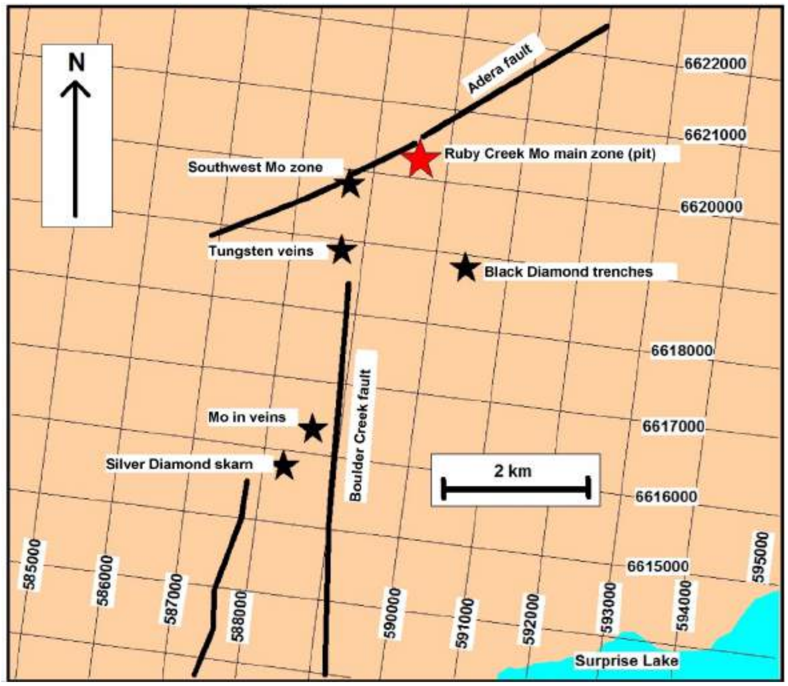

Figure 4. Boulder Creek and Ruby Creek area, showing main mineral occurrences of the Mount Leonard stock and local faults, British Columbia. The Ruby Creek Mo Main zone is the approximate location of Figure 5. Grid shows UTM Zone 9, NAD 83 co-ordinates.

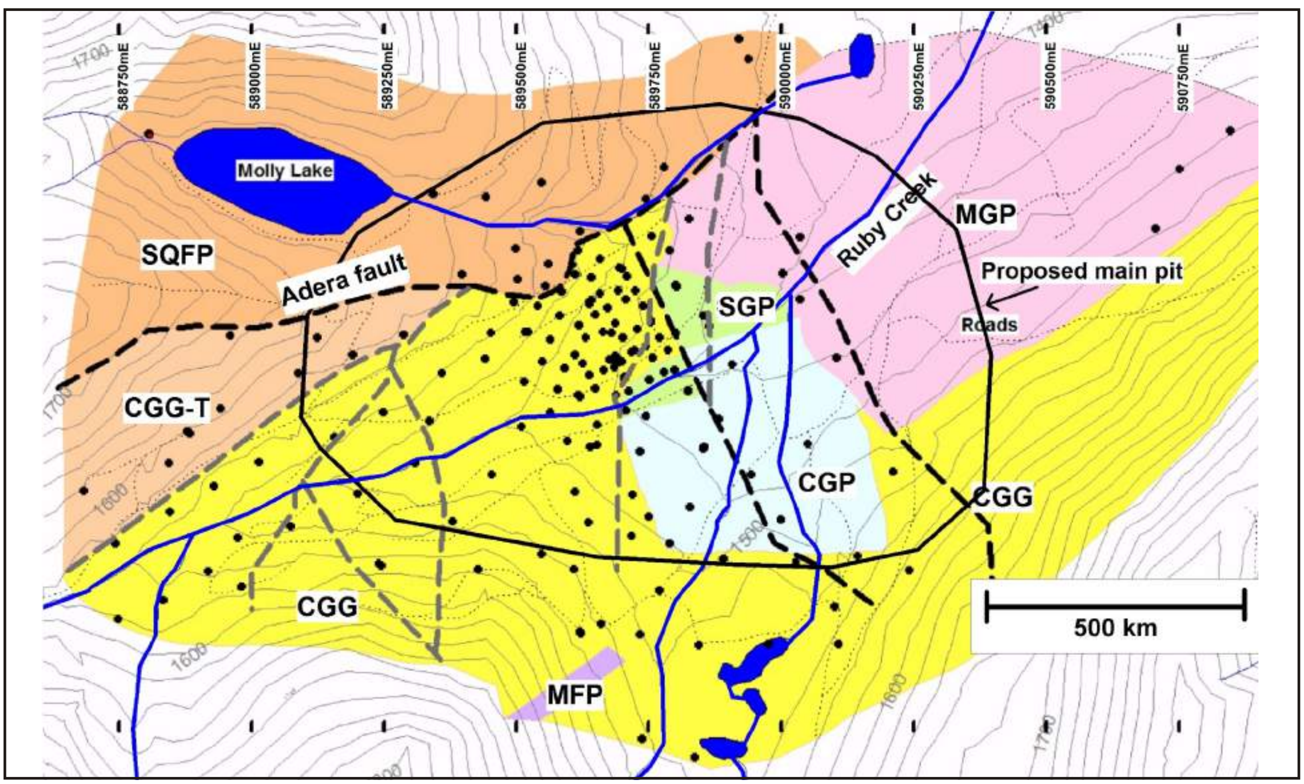

Figure 5. Surface geology of the Adanac Mo deposit (Mo main zone in Figure 4), British Columbia. The black dots are drillholes. The black dashed lines are strong faults that cause displacement, such as the Adera fault. The grey dashed lines are weak faults, or faults that cause no discernible displacement. Rock types CGG (coarse-grained granite), CGG-T (transitional phase), MGP (mafic granite porphyry) and SQFP (sparse quartz feldspar porphyry) are all the first phase of intrusion. The second phase is SGP and CGP (sparse and crowded granite porphyry). The third phase of intrusion, fine-grained aplite dikes, is not represented on the map, but cuts other units at more localized scales. The red lines are cross-sections for alteration- and trace-element zoning discussed in Smith (2009). The grid shows co-ordinates in UTM Zone 8, WGS 84.

Table 1. Molybdenite Re-Os samples. The sample ID refers to the drillhole and the depth from which it was taken.

Sample	Location	Hostrock	Vein Type	Associated Minerals	Probable Paragenesis
375-1054	southwest end	CGG	No vein, feldspar flood	feldspar	1
375-1036	southwest end	CGG	2 cm ductile ribbon textured vein with fine molybdenite	none	2
375-1125	southwest end	CGG	Large, 5 cm milky-white quartz vein with molybdenite rosettes	none	3
364-50	central mineralized blanket	CGG	4 cm milky-white quartz vein	pyrite, chalcopyrite, wolframite, magnetite	4

magmatic age. A second goal was to constrain the lifespan of the hydrothermal system at Adanac. The results of this study can also be used to compare Adanac to other porphyry Mo deposits, because the age of the deposit is an important consideration used in classification. Also, to test the theory of a possible linkage between Adanac and placer Au mineralization downstream of the deposit, the Os signature of Au from Ruby Creek was compared to the Os signature of magnetite from drillcore of the Adanac Mo deposit.

Mineralization Ages

Four samples of molybdenite were analyzed for a Re-Os age to constrain mineralization ages at Adanac. Samples are listed in Table 1, with a description and an inferred relative age based on crosscutting relationships or known characteristics of Climax-type porphyry Mo deposits (i.e., molybdenite associated with other base metals in porphyry deposits are usually later mineralization events). Figure 6 shows a schematic diagram illustrating crosscutting relationships seen in drillcore. All samples were hosted in CGG (coarse-grained granite).

The first three samples in the table are all from drillhole 375, which was drilled in the western end of the deposit where a suspected mineralizing intrusion is located (see Figure 5). They were selected based on differences in vein type (discussed below) or other host (feldspar flood). Their location in one drillhole within 9 m (30 ft.) of each other adds confidence to the assumption that any differences in ages are not correlated with their distance apart in the deposit but represent temporal changes in vein type. The last sample, 364-50, was chosen from the central part of the deposit, in the blanket of mineralization located above the SGP (sparse granite porphyry) and the CGP (crowded granite porphyry) intrusions. Below is a list (in expected paragenetic order from oldest to youngest) of the four molybdenite samples and associated description and occurrence.

1) 375-1054: This molybdenite was disseminated in a feldspar flood in the potassic-altered core of the deposit.
2) 375-1036: This molybdenite was in a ductile, ribbon-textured vein. The quartz in these vein types is usually dark and soot coloured, either from fine molybdenite or because it is smoky quartz. Veins that carry this type of molybdenite and exhibit dark, sooty coloration are usually small (~2 cm) and consistently bear molybdenite. Other quartz veins bearing molybdenite are commonly seen to cut these vein types.

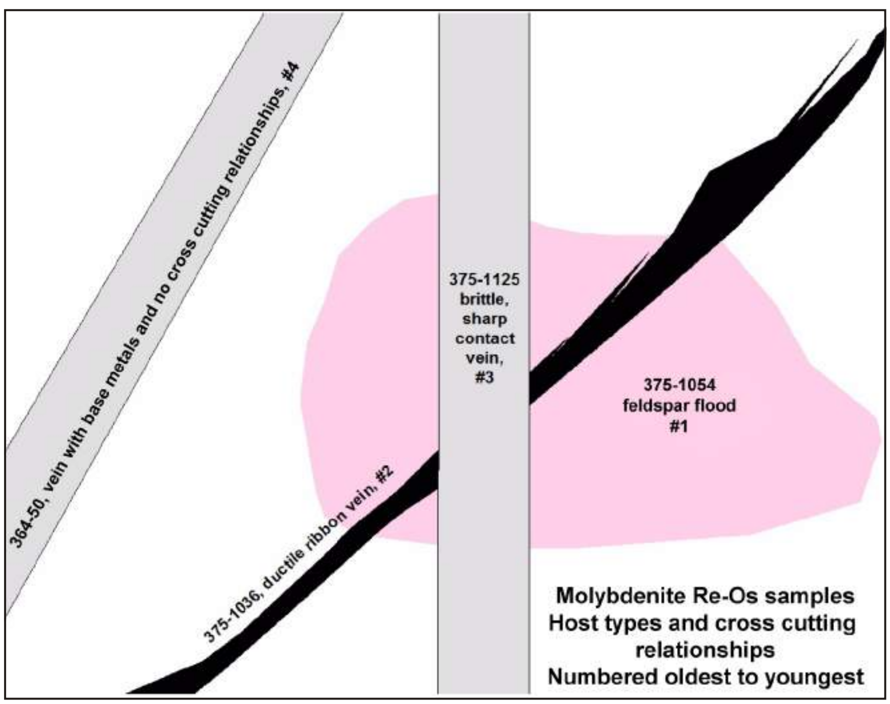

Figure 6. Schematic diagram showing paragenetic relationships (seen in drillcore) of the four Re-Os molybdenite samples. Samples are numbered from oldest to youngest. Sample 364-50 may have no crosscutting relationships with the other samples, but it is presumed to be youngest based on a high base-metal content in the quartz vein. Base metals are usually deposited after main molybdenite mineralization in alkalic porphyry Mo deposits.

Table 2. Summary of data for Re-Os mineralization dates.

Sample ID	Total Re (ppm)	^{187}Re (ppm)	^{187}Os (ppm)	Age (Ma)	Error 2σ (0.5%)	Sample Host	Relative Age (oldest–youngest) Expected	Measured
375-1054	9.521	5.96	7.036	70.87	0.36	Feldspar flood, in CGG	1	1
375-1036	8.011	5.015	5.828	69.71	0.35	Ductile ribbon vein, in CGG	2	2
364-50	5.572	3.488	4.048	69.61	0.35	With base metals, in CGG	4	2
375-1125	39	24.42	28.38	69.72	0.35	Large, brittle contact vein, in CGG	3	2

3) 375-1125: This molybdenite was in a large, 4–6 cm milky-white quartz vein. Molybdenite in these veins usually forms large 2–5 cm rosettes. The contact of the vein with the hostrock, in contrast to the previous sample, is sharp. These veins carry mineralization less frequently and are sometimes barren. This vein type commonly cuts other vein types.
4) 364-50: This molybdenite was taken from a vein cutting CGG that had an abundance of other visible opaque minerals, such as pyrite, chalcopyrite, wolframite and magnetite. No distinct temporal relationships with other vein types were observed. However, it is typical in Climax-type porphyry molybdenite deposits to have mineralizing events that have specific temporal relationships that can be partially defined by associated sulphides, such as early events that bear molybdenite only, and later events that bear molybdenite+pyrite (Westra and Keith, 1981). Therefore, this sample was dated to assess the possibility that this vein represents a separate and distinct late mineralizing event.

Samples were prepared by breaking apart the hostrock with a hammer on a clean surface (a sheet of paper) and the molybdenite was handpicked with tweezers. The molybdenite was ground in a steel mortar and pestle and placed in a small dish of water. Because molybdenite is a micaceous mineral, the surface tension of the water held the thin mineral particles at the top of the dish while feldspar, quartz and other impurities sank to the bottom. The water containing the floating molybdenite was decanted and allowed to evaporate. Samples were then examined under a binocular microscope and any other impurities were removed with tweezers. The tweezers, hammer, mortar and pestle, and dish were washed with soap and water between samples. Samples were then sent to the Re-Os geochronology lab at the University of Arizona at Tucson.

At the lab, samples were handpicked and loaded in a Carius tube and dissolved with 8 mL of reverse aqua regia. The tube was heated to 240°C overnight, and the solution was later treated in a two-stage distillation process for Os separation (Nagler and Frei, 1997). Osmium was further purified using a microdistillation technique similar to that of Birck et al. (1997), and loaded on Pt filaments with $Ba(OH)_2$ to enhance ionization. After Os separation, the remaining acid solution was dried and later dissolved in 0.1 N HNO_3. Rhenium was extracted and purified through a two-stage column using a AG®1-X8 (100–200 mesh) resin and loaded on Pt filaments with $Ba(SO)_4$. Samples were analyzed by negative thermal ionization mass spectrometry (NTIMS; Creaser et al., 1991) on a VG 54 mass spectrometer. Osmium was measured using a Daly multiplier collector and rhenium using a Faraday collector. Isochrons and weighted means were calculated using Isoplot (Ludwig, 2001).

Molybdenite ages are calculated using a ^{187}Re decay constant of 1.666×10^{11} years (Smoliar et al., 1996). Uncertainties for molybdenite analysis include instrumental counting statistics and in the ^{187}Re decay constant (0.31%). In this work, uncertainties are calculated using error propagation, taking into consideration the uncertainty in the Re decay constant. Results of the analysis are summarized in Table 2.

Sample 375-1054 was molybdenite disseminated in a feldspar flood on the western end of the deposit and, as expected, was the oldest sample at 70.87 ± 0.36 Ma. It was not surprising that this was the oldest sample because this molybdenite was disseminated in a feldspar flood, and potassic alteration is commonly early in the sequence of hydrothermal events. There was no distinction in ages (69.6 Ma) between the other three samples (375-1036, 364-50 and 375-1125) when one considers the error of 0.35 Ma. All three mineralization events occurred in a relatively restricted time of less than 1 Ma. Besides the calculated isotopic age, there are other factors to consider when determining paragenetic sequence. First, crosscutting relationships cannot be ignored. The molybdenite in smoky quartz veins with a ribbon texture and a ductile contact with the hostrock is consistently seen to be cut by thicker milky-white quartz veins that usually bear less molybdenite. Therefore, this vein type (sample 375-1036) is clearly older than veins with milky-white quartz, even if they may be part of the same mineralization event.

Based on Re-Os results, sample 375-1125 should be placed as the last and youngest sample, using the Re concentration as a proxy for fluid evolution. It makes more geological sense for molybdenite samples being deposited to maintain a somewhat consistent Re concentration until there is some change in the environment to force deposition of the element within the molybdenite. In other words, it is unlikely that the hydrothermal system went from depositing molybdenite with 8 ppm Re, then to molybdenite with 39 ppm Re and then back to molybdenite with 5.6 ppm Re. It is more likely that Re concentration jumped at the final stages of mineralization because the element has nowhere else to go, and molybdenite deposition at the final stage of the hydrothermal system must incorporate all the remaining Re, thus increasing the concentration.

It is a possibility that, because no crosscutting relationships were observed between the base metal–carrying vein and other samples, that the vein represents the same paragenetic stage as sample 375-1125, but locally, the Re in the fluid may have been divided between some of the other minerals—magnetite and chalcopyrite—although there is no analysis at Adanac for Re content in minerals other than molybdenite. An addition of Re to other minerals would explain the low Re concentration in sample 364-50. This scenario puts the paragenetic order of the base metal vein in line with what is observed in other porphyry Mo deposits, namely, that base-metal stages usually occur last (Westra and Keith, 1981).

Magmatic Ages

There has been previous work on magmatic ages of the Mount Leonard stock and the Surprise Lake batholith. Mihalynuk et al. (1992) report a U-Pb age of zircons from the Surprise Lake batholith as 83.8 Ma. Christopher and Pinsent (1982) obtained K-Ar ages of biotite from some rock types within the Adanac deposit. The average age was 70.6 Ma and the individual ages of each rock type are shown in Table 3.

For this study, a total of seven samples from Adanac were analyzed for U-Th-Pb ages in zircons to constrain the duration of magmatism of the Mount Leonard stock, to re-test some of the ages reported by Christopher and Pinsent (1982), to determine ages of some new rock types not tested previously and for which relative ages were obscure, and to identify the intrusion responsible for mineralization by comparing the ages of molybdenite to the ages of units.

Table 3. Summary of K-Ar dates from Christopher and Pinsent (1982).

Unit	Age (Ma)
CGG	71.6 ±2.2
MGP	70.3 ±2.4
SGP	71.6 ±2.1
MEG	71.4 ±2.1

Samples were collected on site at Adanac and crushed with a rock crusher before being bagged. In between samples, the crusher was washed with soap and water and vacuumed. Samples were then sent to the Arizona LaserChron Center in Tucson, Arizona. Here, samples were run through a pulverizer to reduce the sample to sand-sized grains. Between samples, the pulverizer was cleaned with soapy water and a wire brush, and then vacuumed. The samples then went through the first of two gravity separation steps and a Wilfley table separation, after which a hand magnet was used to remove magnetic grains. The samples were processed in methylene iodide, and magnetic grains were removed with a Franz magnetic separator. The zircons were stored and carefully labelled. Mounts were made by selecting and arranging zircons and standards on a piece of tape, epoxying the sample, sanding, labelling and finally imaging the sample with enough detail so that individual grains can be seen.

Uranium-lead geochronology of zircons was conducted by laser-ablation multicollector inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) at the Arizona LaserChron Center under the direction of V. Valencia during June 2008. The ablation of zircons was done with a New Wave/Lambda Physik DUV193 Excimer laser operating at a wavelength of 193 nm, using a spot diameter of 25 m. Ablated material was carried into a GV Instruments Ltd. isoprobe, where U, Th and Pb isotopes are measured simultaneously in static mode. Each individual zircon analysis began with a 20 s integration on peaks with the laser turned off (for backgrounds) and then twenty 1 s integrations were completed on each zircon with the laser firing. The laser operated at 23 KV with a repetition rate of 8 Hz. The resulting ablation pit was 12 m across. Interelement fractionation was monitored by analyzing crystals of SL-1, a large concordant zircon crystal from Sri Lanka with a known (by isotope dilution–thermal ionization mass spectrometry) age of 564 +4 Ma (2 ; G. Gehrels, unpublished data, 2005). The reported ages for zircons from Adanac are based entirely on $^{206}Pb/^{238}U$ ratios. The errors of $^{207}Pb/^{235}U$ and $^{206}Pb/^{207}Pb$ analyses were too large for the ages to be considered reliable because of the low-intensity signal (<0.5 mV) of ^{207}Pb from the young (<1 Ga) zircons. The $^{206}Pb/^{238}U$ ratios were corrected for common Pb by using the measured $^{206}Pb/^{204}Pb$, the common Pb composition as reported from Stacey and Kramers (1975) and an uncertainty of 1.0 unit on the common $^{206}Pb/^{204}Pb$.

Zircon crystals that were analyzed by the laser but showed evidence of lead loss or assumed to be metamictic were ignored. A crystal was determined to have suffered lead loss if, as the laser analyzed successive layers of zircon crystallization deeper into the centre of the crystal, these ages did not plateau or become stable (explained in more detail below). Also, the crystal could be visually determined to be metamictic by displaying a characteristic honey-brown colour, indicating radiation damage to the crystal and thus a mechanism for lead loss.

The reported age of each sample is the weighted mean of 30 individual zircon analyses, excluding crystals that were then statistically assumed to have experienced lead loss or statistically assumed to be inherited. A crystal was statistically identified as being inherited or suffering lead loss if its reported age was outside of a coherent population of ages (at the 95% level). The weighted mean of all the crystals believed to have a reliable age was calculated according to Ludwig (2001). The mean takes into account random errors (i.e., measurement errors). The age of the standard, the calibration correction from the standard, the composition of common Pb and the decay constant uncertainty are contributors to the error in the final age determination. All of these uncertainties are grouped as 'systematic error.' Rocks at Adanac displayed a range of 0.9–1.7% in systematic error. The error in the actual age of the sample is determined by quadratically adding the systematic and measurement errors. All age uncertainties are reported at the 2 level.

Dated units include CGG, CGG-T (transitional), SQFP (sparse quartz feldspar porphyry), MFP (megacrystic feldspar porphyry), MEG (medium-grained equigranular granite) and two samples of FGG (fine-grained granite). A summary of paragenetic ages of rock types based on crosscutting relationships is shown in Figure 7. The rock types CGG, CGG-T and SQFP are all essentially the same intrusion and are considered the first phase. They are certainly the oldest rocks as all other rock types in the deposit cut these, and they were affected by a deformational event prior to the intrusion of any other rock types in the deposit. The contacts between them are gradational; the coarse-grained unit (CGG) grades upward and outward into both a transitional (CGG-T) and hybrid (CGG-H) variety with increasing groundmass content, or becomes more of a porphyritic unit. Considered separately and slightly older than these three rock types are CQFP (crowded quartz feldspar porphyry, not dated) and SQFP, which are basically the porphyritic equivalents of CGG and its transitional and hybrid varieties. They were at one time the upper margin of the intrusion based on geographic location, but the Adera fault has dropped these units to the north. One sample each of CGG, CGG-T and SQFP were submitted for U-Pb zircon dating to obtain an older limit on magmatic ages at Adanac.

Based on crosscutting relationships, MGP (mafic granite porphyry) and then the SGP and CGP intrusions were emplaced. These are considered the second phase of intrusion. Like the CGG and CGG-T and CGG-H units, SGP and CGP are essentially the same intrusion with gradational contacts, and their designation as a separate unit is based on distinct geographic locations and differing phenocryst content. These three units were not dated because both older and younger units were tested, and this constrains the ages of these units to within a relatively small range of geological time.

The relative ages of MEG and MFP are somewhat less certain than other units. Medium-grained equigranular granite (MEG) occurs as an intrusion at depth on the southwestern end of the deposit, cuts both CGG and CGG-T, and is probably part of the second phase of intrusion. The MFP unit is a dike that cuts the CGG, CGG-T, SGP and CGP units. It is not known whether MEG is younger or older than SGP and CGP, nor is the age relationship between MFP and MEG visible. Because the hydrothermal alteration is the most intense in the southwest area above MEG, this unit is thought to have been responsible for mineralization. Mineralizing intrusions in other porphyry deposits are usually directly under the most intense hydrothermal alteration (Westra and

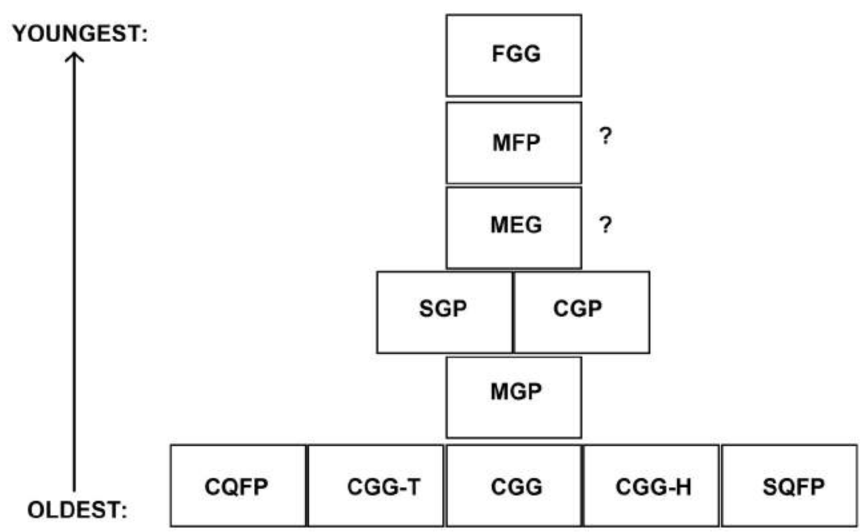

Figure 7. Summary of paragenetic ages for common rock types at Adanac based on crosscutting relationships. Abbreviations: CGG, coarse-grained granite; CGG-H, hybrid phase; CGG-T, transitional phase; CGP, crowded granite porphyry; CQFP, crowded quartz feldspar porphyry; FGG, fine-grained granite; MEG, medium-grained equigranular granite; MFP, megacrystic feldspar porphyry; MGP, mafic granite porphyry; SGP, sparse granite porphyry; and SQFP, sparse quartz feldspar porphyry.

Keith, 1981). Because mineralization cuts the SGP, CGP and MGP, the MEG was, therefore, assumed to be younger than these units as well. Megacrystic feldspar porphyry (MFP), because it is a dike that must have been emplaced after most or all of the previous units, is considered to be one of the younger units. Both MEG and MFP were dated by U-Pb.

Fine-grained granite (FGG) exists in the deposit as dikes that are always seen to cut everything else, and are the third and final phase of intrusion. However, two samples of FGG, one from the pit area and one from the southwest end, were dated to see if there is more than one generation of these dikes. It was recognized that if MEG and FGG have similar ages to the mineralization, it would mean that these units represented, or were at least synchronous with, the mineralizing intrusion.

The summary of the results of isotopic dating are shown in Figure 8. The complete results, including element concentrations, isotopic ratios and Concordia diagrams are included in the M.Sc. thesis associated with this paper (Smith, 2009).

The ages for rock types at Adanac span 77.5–81.6 Ma, giving the Mount Leonard stock a minimum lifespan of 1 Ma when factoring in errors. Most of the ages of the units are indistinguishable from one another due to uncertainties in the reported age. However, several relationships are apparent from these ages. On the basis of the geochronology, FGG from the pit area is older than CGG. This cannot be the case, as FGG cuts CGG. Also, FGG from the pit area returns an age that is older than FGG from the southwest area, and these rock types represent two different FGG intrusions or injections. This relationship is uncertain, however, due to the fact that FGG (pit area) has a suspect age. The U-Pb ages in Figure 8 also indicate that there is no intrusion that matches the age range for the mineralization. The temporal gap between the oldest possible mineralization (71.23 Ma) and youngest possible magmatism (74.5 Ma) is 3.3 Ma. From the earliest possible start of magmatism to the latest (or youngest) close of mineralization would be 13.4 Ma.

There are three possiblilities that could explain the difference in ages and the relationship between mineralization and magmatism. One possibility is that all of the reported magmatism ages are correct and the mineralizing intrusion has not yet been dated. This seems unlikely because the FGG (pit area) age is incorrect relative to CGG. Also, in porphyry Mo deposits, the mineralizing intrusion is usually directly under mineralization itself. The bulk of molybdenite mineralization at Adanac forms blankets directly above both MEG and SGP/CGP, and is therefore likely genetically related to either or both of them.

The second possibility is that the ages are correct, but that the intrusion stayed hot for long enough to account for the temporal gap between the mineralization and magmatism. This possibility still seems unlikely because the FGG (pit area) age cannot be correct.

The third possibility is that several aspects of the statistically calculated ages are not relevant or meaningful in this study. First, there is probably a high incidence of inherited zircons in each rock type that shift the mean age to what is older than reasonably expected. In any given 305 m (1000 ft.) drillhole at Adanac, there may be up to five igneous intrusive phases that would be passed through in close spatial relationship to each other. It is unlikely that each of these rock types did not inherit a significant number of zircons from rock types older than it, including from the Surprise Lake batholith. Second, zircons that probably did not experience lead loss were discarded as such, further skewing the ages to what is older than reasonably expected.

There are two ways that a zircon could have been considered to have undergone lead loss. If a zircon age fell statistically below 95% of the population, it was discarded as anomalous and was therefore likely experiencing lead loss (for example, see Figures A-23–A-35 in Smith, 2009). The other way to determine lead loss was more dependent on measurements taken directly from the zircon crystal. When each zircon from a rock is analyzed for an age, the laser fires many times and creates an ablation pit in the zircon. Each firing of the laser reports an age and analyzes successively deeper layers of the zircon crystal. The outer layers are expected to show some lead loss, and the ages get progressively older as the laser analyzes closer to the core. If

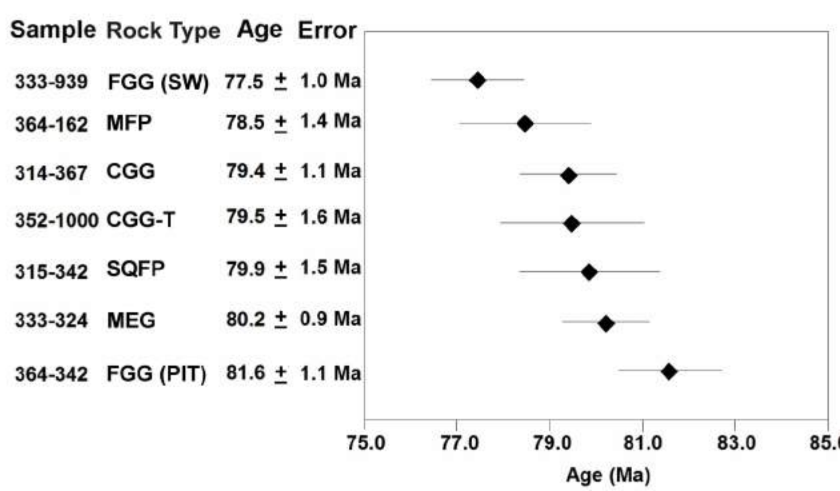

Figure 8. Results of U-Pb zircon ages for each rock type tested. The sample IDs are the drillhole, the footage depth and the rock tested. Uncertainties are reported at 2

the ages plateau, then the core is considered to represent a real crystallization age. If there is no plateau of ages, then the entire zircon is considered to have experienced lead loss, and that particular zircon is not included in the 30 tallied zircon crystals for the weighted mean. Analyses continue until there are a total of 30 crystals that show reliable core ages. Zircon crystals that did show a diagnostically reliable core age were discarded from the weighted mean because they were outside of 95% of the population. However, 95% of the population is not representative of an age for the rock because there are too many inherited zircons. Table 4 shows the lowest reported age for a zircon from each rock type. All of the zircons in the table had reliable plateau core ages.

Most of the ages in Table 4 are slightly older than the mineralization but not a single zircon gave an age that is lower or younger than one would expect considering the mineralization ages. If these zircons had experienced lead loss it would be reasonable to expect that at least some of them would be younger than the mineralization. This probably means that the ages seen here are real crystallization ages. The two samples of the FGG dikes did not contain any zircons that are younger than the other rock types. This is not surprising because the FGG dikes are low-volume rock types (not much of the rock exists at Adanac relative to the volume of other rock types in the deposit) and this makes it less likely that a zircon that crystallized completely within the dike would be sampled. Because the FGG dikes cut across all other rocks, they probably had a much higher incidence of inheritance relative to other rock types in the deposit.

Based on the fact that every unit dated has some zircons that show no lead loss and that closely resemble the age of mineralization, it is likely that all of the units at Adanac were experiencing some crystallization right before mineralization occurred. Therefore, using U-Pb zircon dating does not reliably identify a single intrusion that caused mineralization. What this does mean is that magmatism probably began by 82.7 Ma during the waning stages of crystallization of the Surprise Lake batholith and continued until at least 69 Ma. This represents a time span of about 13.7 Ma. There were a number of inherited zircons from the Surprise Lake batholith spanning from 85 Ma to about 90 Ma. There were no inherited zircons from the Fourth of July batholith, which is Jurassic in age. The crystallization ages of biotite using the K-Ar method from 1982 are likely recording the last hydrothermal event they were affected by, since the closing temperature of biotite using this method is 300°C.

Relationship between Adanac and Nearby Placer Gold Deposits

There are many similarities between porphyry Mo deposits and intrusion-hosted Au deposits such as Pogo and Fort Knox in Alaska. These similarities include redox states and trace- and major-element chemistry of the hostrocks, and mineral and elemental assemblages of the deposits themselves. Porphyry Mo deposits and intrusion-hosted Au deposits both are hosted in relatively reduced and alkalic or felsic magmas, and hostrocks typically belong to the S-type magma series (Thompson et al., 1999). The trace elements and mineral assemblages present in intrusion-hosted Au deposits are characterized by Bi, W, As, Sn, Mo, Te and Sb. While the Adanac deposit itself contains no minerals or trace elements in significant quantities other than Mo and W, within 4.8 km (3 mi.) of the deposit and clearly related to the Mount Leonard stock are several deposits and veins (Figure 4) that have the same trace elements as intrusion-hosted Au deposits (e.g., Donlin Creek or Fort Knox). These include elevated Te, As and Bi, along with wolframite, Au (unknown whether it is native Au or electrum), cassiterite, molybdenite and stibnite in quartz veins hosted in the same igneous rocks that host Adanac. Gold in intrusion-hosted deposits like Fort Knox can be concentrated in locations distal (1–3 km) to an intrusion, are correlated with Bi and Te, and typically occur in sheeted veins (Stephens et al., 2004). Molybdenum and tungsten can occur more closely to the intrusion. Therefore, the mineral assemblage at and within the vicinity of Adanac is consistent with that of intrusion-hosted Au deposits. Intrusion-hosted Au deposits are also associated with Phanerozoic arc settings and W-Sn provinces (such as Fort Knox; Thompson et al., 1999). This is consistent with the setting for the Adanac Mo deposit, which is very close to Logtung (MINFILE 104O 016; a porphyry W deposit) and other Sn deposits such as the Germaine porphyry Sn deposit (MINFILE 116 004) and the JC Sn skarn (MINFILE 105B 040).

Table 4. Lowest reported age for a zircon from each rock type. Because they were the lowest reported, the ages were excluded from the statistical mean. Each zircon had a plateau core age.

Sample	Unit	Youngest Age (Ma)
333-939	FGG (SW)	72.1 ±1.0
333-324	MEG	71.1 ±1.0
364-342	FGG (PIT)	74.6 ±2.3
314-367	CGG	69.0 ±1.2
352-1000	CGG-T	71.4 ±2.2
315-342	SQFP	72.5 ±1.3
364-162	MFP	73.1 ±1.1

Sack and Mihalynuk (2004) showed that Au from the Atlin mining camp may be at least in part derived from an intrusive source, because cassiterite, thorite and granitoid clasts were found to be intimately associated with some Au nuggets in the camp. The Surprise Lake batholith is enriched in Sn and is known to contain thorite. Because the Adanac deposit occurs at the head of two creeks (the Ruby and Boulder creeks) that have placer Au deposits on their lower drainages, Adanac presents a good opportunity to test for a possible genetic link between porphyry Mo deposits and intrusion-hosted Au deposits.

To test this theory, the Os ratios of Au from Ruby Creek were compared with Os ratios of magnetite from drillcore of the Adanac Mo deposit. Both the Au and magnetite samples were dissolved and homogenized using the same Carius tube technique as described for the molybdenite ages and analyzed by thermal ionization mass spectrometry (TIMS). This was done at the Re-Os geochronology lab at the University of Arizona, Tucson, and the results are summarized in Table 5.

Table 5. Results of the Au (Ruby Creek-1 and -1*; -1* is a duplicate of the same Au sample) and magnetite (Mt, Adanac 351-957) Re and Os analyses.

Sample	Phase	$^{187}Os/^{188}Os$	Error	$^{187}Re/^{188}Os$	Os (ppb)	Re (ppb)
Ruby Creek-1	Au	0.125	0.0005	0.016	345	1.16
Ruby Creek-1*	Au	0.125	0.0005	0.001	4538	0.82
Adanac 351-957	Mt	1.237	0.0110	872.250	0.015	2.42

The Au analyzed had little Re and a very small resulting Re/Os ratio. No age regression was possible for Au. For magnetite, there was not enough material submitted for multiple analyses, even though the largest known single magnetite crystal from Adanac was selected for the analysis. Therefore, no isochron could be made for magnetite because multiple analyses are needed for an isochron. Regardless of these problems, the question of whether Au is related to the hydrothermal system that generated the Adanac deposit can still be answered with reasonable certainty. The Au has a $^{187}Os/^{188}Os$ that is very primitive, even lower than the current mantle value of 0.129, and so is likely from the mantle, not from a porphyry deposit (see Figure 9). Also, the Os content of the Au sample is very high and variable, suggesting the presence of osmiridium grains, which would likely be in a source associated with chromite or peridotite, not a porphyry deposit. It is interesting that the Os and Re concentrations of the Au are very high in relation to other porphyry Au deposits, and are actually quite similar to the mantle-derived Witwatersrand in South Africa (Figure 9).

Although the results of this study suggest the Au on Ruby Creek is unrelated to the hydrothermal system at Adanac, this does not mean that none of the Au in the Atlin mining camp is related to Adanac. It likely would have been better to sample Au from placer deposits on Boulder Creek rather than Ruby Creek. Also, it may have been better to get multiple samples as well, because if some of the Au is derived from the Surprise Lake batholith (and the Mount Leonard stock), this means that Au in the Atlin mining camp is from mixed sources. Multiple samples would have increased the likelihood of identifying at least one sample that is igneous derived.

Conclusions

Rhenium-osmium analysis of molybdenite confirmed at least two generations of mineralization at 70.87 ±0.36 Ma and about 69.66 ±0.35 Ma, with the youngest mineralization occurring at the southwest end of the deposit above the MEG intrusion and disseminated in a feldspar flood. Uranium-lead ages of zircons from Adanac hostrocks place magmatism at 81.6 ±1.1 Ma to 69 ±1.2 Ma, giving the Mount Leonard stock a probable lifespan of almost 14 Ma. When using the weighted mean of 30 zircon analyses for each rock type, no appropriate age match was found for an intrusion and mineralization episode, and the FGG (pit) age is certainly incorrect. There are too many inherited zircon grains for a mean age to be reliable, and statistical methods for determining lead loss discredit ages that are most likely

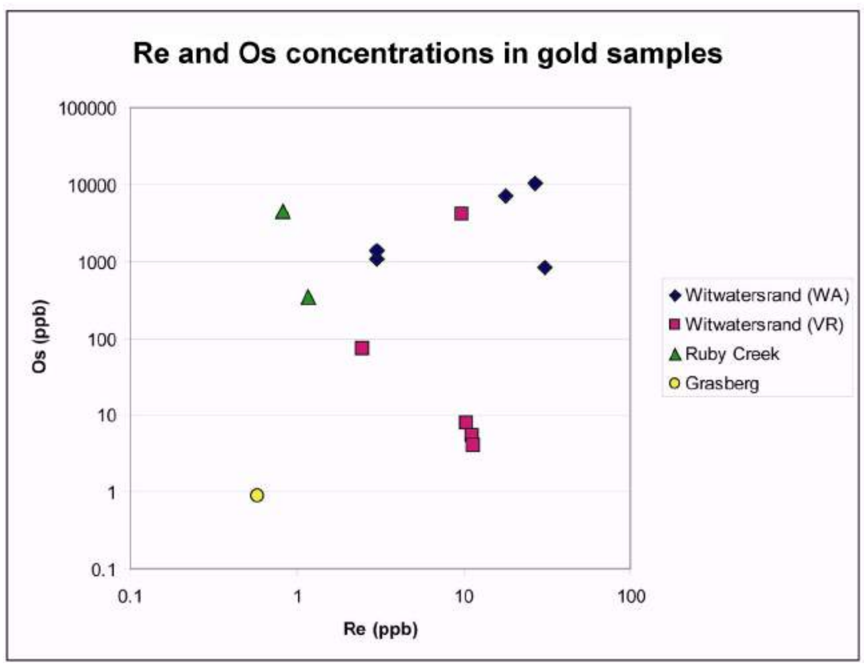

Figure 9. Osmium and rhenium concentrations of Au deposits compared with Au from Ruby Creek. The Witwatersrand deposit is historically the largest Au deposit in the world, accounting for about 40% of total world production (Frimmel and Minter, 2002) and is mantle-derived (Kirk et al., 2002). The two Witwatersrand samples are from different formations: WA (Western Area) and VR (Vaal Reef). The Grasberg is a porphyry Cu-Au deposit in Indonesia. Modified from Kirk et al. (2002).

valid. It is probably true that most, if not all, of the rock types that were dated at Adanac were still undergoing some crystallization just before (1 Ma) or during mineralization.

The Au from Ruby Creek analyzed in comparison with magnetite from Adanac is derived from rocks more like peridotite than porphyry-deposit hostrocks. The question of whether some of the Au in the Atlin mining camp is igneous derived remains unanswered. The next step in answering this question would be to try to get multiple samples of magnetite from the Mount Leonard stock or the Surprise Lake batholith to compare with multiple Au samples from the Boulder Creek placer deposits or Au from sheeted quartz veins to the southwest of Adanac.

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