Re-Os dating of gold in gold-bearing orogenic vein systems in the Klondike district – progress report

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ABSTRACT

This is a preliminary study to determine the feasibility of using Re-Os to determine the age of gold in orogenic vein gold of the Klondike district, Yukon. Our objectives were to measure gold from several different vein systems to determine if enough Re and Os exists in native gold samples from the Klondike district to properly date the system. Six samples from different veins contain measurable concentrations of Re and Os and plot with significant variation on a Re-Os isochron diagram. The results indicate the need for detailed sampling of one vein system to better constrain age and source information from Re-Os systematics. Analysis of both native gold and synchronous pyrite from veins may provide enough data to determine age contraints, if native gold is not available.

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INTRODUCTION

A major impediment to identifying the key controls on formation of orogenic gold deposits is the difficulty in determining the absolute age of the mineralization. Without such information, it is impossible to understand how the timing of vein formation and introduction of gold fits into the structural and thermal evolution of a particular orogenic belt. Many analytical approaches that have proven effective for dating other styles of mineralization are difficult or impossible to apply when investigating orogenic gold systems. For example, there is typically no temporally or genetically related magmatism associated with orogenic gold; hence, it is difficult to closely bracket the age of mineralization by dating pre and post-mineral intrusive rocks. Most orogenic gold veins are hosted in low to medium grade, commonly highly micaceous, country rocks. It is typically difficult, if not impossible, to obtain a pure sample of hydrothermal mica from a vein alteration envelope $^{40}Ar/^{39}Ar$ dating that is unequivocally related to the veining and does not include older mica grains from the wall rock (*e.g.*, Mortensen *et al.*, 2010). Many orogenic veins form by repeated extensional events, producing "crack-seal" textures that include thin septa of micaceous wall rock between ribbons of vein quartz. Much of the mica that occurs locally with orogenic veins is therefore more likely to simply represent a fragment of the wall rock and not hydrothermal in origin. An additional complication in attempting to use $^{40}Ar/^{39}Ar$ methods on micas to date orogenic gold systems is that such veins typically form at a relatively late stage within cooling orogenic belts, and vein fluids show a temperature range that is not very different from the ambient temperature of the host rocks themselves at the time of vein formation. The effective closure temperature of the $^{40}Ar/^{39}Ar$ system in white mica is ~300°C. In at least some cases, both the country rock and any contained orogenic vein systems may not cool through this temperature until sometime after vein formation. In such instances, the resulting ages will reflect regional cooling of the orogen rather than the age of vein formation.

Dating gangue minerals within orogenic veins can potentially avoid some of the pitfalls listed above; however, there are relatively few minerals in such veins that are amenable to precise and accurate dating. As mentioned previously, dating white mica that occurs within some orogenic veins has many obstacles. Rutile is a relatively rare gangue phase in some orogenic veins, and the U-Pb system in rutile has a relatively high effective closure temperature (400-500°C; Blackburn *et al.*, 2011); thus U-Pb rutile dating offers some potential. U-Pb dating of hydrothermal monazite and/or xenotime (either as a gangue phase in the veins themselves or in hydrothermal alteration envelopes surrounding veins) has been used to determine the ages of several Archean and younger orogenic gold deposits (*e.g.*, Veilreicher *et al.*, 2003; Yudovskaya *et al.*, 2011); however, these phosphate minerals occur very rarely in orogenic vein systems. Similarly, although Re-Os dating of molybdenite is one of the most robust methods available for dating many styles of epigenetic mineralization, molybdenite has rarely been reported in orogenic veins, and this method is therefore of limited use.

The ideal solution to the problem would be to devise a method to date the gold in the veins directly. Previous studies (Kirk *et al.*, 2002; Mathur, 2005; Mathur *et al.*, 2003; Schaefer *et al.*, 2010) have shown that gold in a variety of intrusion and non-intrusion related vein systems can contain significant and variable amounts of Re, and that analytically measurable variations in $^{187}Os/^{186}Os$ ratios are generated that can constrain isochrons, from which the depositional age of the gold can be calculated. In this paper, we describe and report preliminary results for a scoping study, initiated in 2012, investigating the possibility of determining the age(s) of gold-bearing veins that were the main source of the rich placer gold deposits in the Klondike district in western Yukon (Chapman *et al.*, 2010a,b).

GEOLOGICAL SETTING AND NATURE OF GOLD-BEARING VEINS

Gold-bearing orogenic quartz veins have been identified in a number of localities in the Klondike (Fig. 1 and veins similar to those described in Chapman *et al.*, 2010a,b), and gold compositional studies by Chapman *et al.* (2010a,b) have demonstrated that these were the main source of the rich placer gold deposits in this area. A concentration of gold-bearing veins has been recognized at the head of rich placer ground on Eldorado and Bonanza creeks (including the Boulder Lode occurrence at the old Lone Star mine and the Nugget zone northeast of Eldorado Creek; Fig. 1). A second concentration of gold-bearing veins in the King Solomon Dome area (including the Sheba occurrence; Fig. 1) was interpreted as the main source for the pay streaks in streams that radiate out from this area, providing most of the gold that has been recovered from Hunker and Dominion creeks and part of the gold mined on Sulphur and Quartz creeks (Chapman *et al.*, 2010). The Virgin

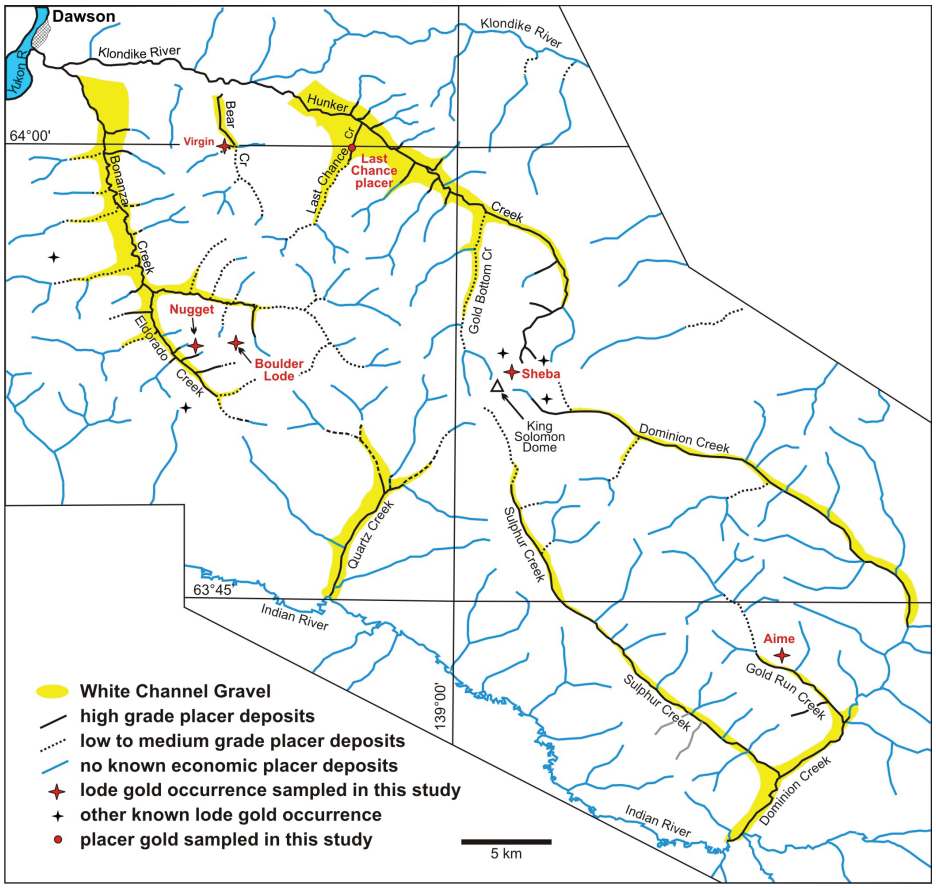

Figure 1. *Map showing the location of the main placer gold deposits in the Klondike District, together with the distribution of the locally gold-bearing White Channel Gravel deposits, and known lode gold deposits. Modified from Chapman et al. 2010a.*

vein occurrence, located on a left limit tributary of Bear Creek (Fig. 1), fed at least part of the Bear Creek placer pay streak. Finally veins on the left limit of lower Gold Run Creek (including the Aime occurrence; Fig. 1) likely contributed at least some of the gold that has been mined from Gold Run and lower Dominion creeks (Chapman *et al.*, 2010).

Gold-bearing veins in the Klondike are typical orogenic veins (Mortensen *et al.*, 1992; Rushton *et al.*, 1993), consisting almost entirely of quartz with only minor carbonate and rare barite and scheelite. They are simple extensional veins, and most represent single stage infillings of open fractures. Ribbon textures reflecting repeated "crack-seal" events during vein formation have been observed at a few localities in the Klondike, but appear to be rare. Sulphide content in the veins is typically low; pyrite concentrations occur in <1 to 2 cm thick selvages along the vein margins, and scattered grains of galena, sphalerite, chalcopyrite, and other sulphides and sulfosalts occur sporadically in the interiors of some veins. Gold is almost entirely confined to the pyritic selvages along the vein margins, and occurs locally as free grains within quartz. Locally sericitic alteration occurs in wall rocks immediately adjacent to the veins. Alteration envelopes, up to several metres wide, containing variable amounts of introduced ferroan carbonate and pyrite occur locally, especially where the veins crosscut mafic schist. Structural controls on the emplacement of gold-bearing veins in the Klondike have been described by MacKenzie *et al.* (2008a). This work showed that most veins formed during the latter stages of, or immediately following, the D_4 deformation event, which is a relatively late stage deformation in the area, characterized by locally developed zones of buckle folds and high-angle reverse faults.

Lead isotopic studies of sulphides from orogenic veins in the Klondike (Mortensen, work in progress) show a high degree of scatter in isotopic compositions and a correlation between the Pb isotopic compositions and compositional ranges from individual vein systems and the lithological composition of the immediate host rocks. This is interpreted to indicate that the lead, and presumably other vein components including gold, were deposited from small-scale hydrothermal systems and were derived from local host rocks, rather than being introduced from external sources, as has been postulated for many other orogenic vein systems (*e.g.*, Goldfarb *et al.*, 2005; Pitcairn *et al.*, 2007; Mortensen *et al.*, 2010).

The characteristics of gold-bearing veins are generally similar throughout the Klondike, and at this point available evidence is most consistent with a single episode of veining in the area. However, the possibility that two or more discrete mineralizing events have occurred cannot be precluded based on available evidence.

PREVIOUS DATING STUDIES OF KLONDIKE VEINS

Metamorphic cooling ages in the Klondike, determined by K-Ar and $^{40}Ar/^{39}Ar$ dating of metamorphic muscovite and biotite, range from *ca.* 185 to 162 Ma (Mortensen, 1990; unpublished data). Two K-Ar ages of 140±2 Ma and 134±1.5 Ma were reported by Mortensen (Hunt and Roddick, 1992) for muscovite that was interpreted to be part of the hydrothermal vein assemblage at the Sheba occurrence in the King Solomon Dome area (Fig. 1). These ages have subsequently been confirmed by $^{40}Ar/^{39}Ar$ methods that yielded ages of 144-145 Ma from muscovite samples both within the vein and from sericitic alteration envelopes (Mortensen, unpublished data). However, rutile from a gold-bearing quartz vein at the Mackay occurrence approximately 2 km east of the Sheba vein, has given a preliminary U-Pb isochron age of *ca.* 160 Ma (Mortensen, work in progress). Veins in the Mackay occurrence are currently interpreted as the same generation as those at the Sheba, raising the possibility that the $^{40}Ar/^{39}Ar$ ages from Sheba may reflect regional uplift and cooling rather than the age of the veining itself. There are presently no other independent constraints on the age(s) of the veins.

PREVIOUS Re-Os DATING OF GOLD

Kirk *et al.* (2002) provide a well developed isochron for gold separates from the Witwatersrand gold deposits in South Africa. The isochron age was interpreted as detrital and is the best evidence that gold in the basin originated from outside of the basin. Schafer *et al.* (2010) carried out a more detailed study of two mines in the Vaal reef in the Witwatersrand which Kirk *et al.* (2002) presented, but demonstrated mixing as a possible interpretation of the data.

Mathur *et al.* (2003; 2005) reported Re-Os data from gold-rich ores and native gold from high temperature, intrusion-related hydrothermal systems, including a Cu-Au porphyry deposit (Grasberg, Indonesia) and high and low sulphidation epithermal veins (Bucaramanga, Columbia). The resulting isochrons were interpreted to correspond to times of sulphide and gold deposition in these deposits, and indicated consistent, but relatively radiogenic, initial Os isotopic compositions for the mineralizing fluids.

GOLD SAMPLES FOR Re-Os DATING

It was anticipated at the outset of this study that Re and Os contents of gold from orogenic veins in the Klondike might be low, which would require relatively large amounts of gold for each analysis. Although gold is present in trace amounts in many of the Klondike veins, it is difficult to obtain sufficient gold from surface exposures for Re-Os analysis. This necessitated targeting veins or parts of veins known from previous work to contain significant amounts of gold, and to specifically sample the pyritic selvages, which typically contain the majority of the gold in any particular vein. A total of eight samples of pyritic selvage material were collected for the study in June, 2012; this included samples from the Boulder Lode and Nugget zones at the Lone Star occurrence (three samples; Fig. 1), the Sheba occurrence in the King Solomon Dome area (three samples; Fig. 1), and the Aime occurrence on lower Gold Run Creek (two samples; Fig. 1). Individual sample sizes ranged from 5-30 kg. These samples were crushed, ground, put over a wet shaking (Wilfley) table, and then flushed through heavy liquids at the University of British Columbia. Although much of the pyrite in these samples was thoroughly oxidized, the concentrates recovered from all of the samples comprised mainly pyrite with a lesser amount of galena. All gold grains present were hand-picked under a binocular microscope. Enough gold for analysis was recovered from the Boulder Lode and Nugget zone samples and two samples from the Aime occurrence. Unfortunately, none of the Sheba occurrence vein samples yielded sufficient gold for analysis. A sixth lode gold sample was obtained by hand panning approximately 200 kg of fine material extracted from a collapsed ore bin at the Virgin vein occurrence on Bear Creek (Fig. 1). An additional sample of panned placer gold was obtained from the right limit of lower Last Chance Creek (Fig. 1). This sample was known to be compositionally homogeneous (based on analytical work reported in Chapman *et al.*, 2010b), and showed a similar compositional range and micro-inclusion suite as the gold from the Virgin lode sample. Gold recovered from the seven vein and placer samples ranged in weight from 0.1 to 0.18 g.

ANALYTICAL METHODS AND RESULTS

Approximately 0.08 to 0.1 g of gold from each sample was loaded into carius tubes for Re-Os isotope analysis. Samples were dissolved in 12 ml of re-aquaregia with the addition of 2 ml of hydrogen peroxide and enriched spikes

of ^{185}Re and ^{190}Os, which were used to determine Re-Os concentrations by the isotope dilution method. Re and Os were purified from the matrix solutions with distillation and further chemistry, as described by Mathur *et al.* (2000). Purified samples of Re and Os were loaded onto filaments and analysed on the negative thermal ionization mass spectrometer at the University of Arizona. Concentrations of Re-Os were low in these samples. The analytical blank can greatly impact the measurement; thus a blank was monitored during the chemical processing of the samples. The Os blank was 0.17 picograms (with $^{187}Os/^{188}Os = 0.19$) and the Re blank was 8 picograms.

A total of seven analyses yielded analytically viable data. The concentration of Os in the gold samples varied between 12 and 257 ppt and Re varied between 0.7 and 4 ppb. The measured $^{187}Os/^{188}Os$ varied between 0.18 and 1.7 and the $^{187}Re/^{188}Os$ varied between 21 and 586. Errors for the samples were determined by varying the blank Os concentration as this is the largest source of error in the analysis. The concentrations of Re and Os in the native samples are similar to Re-Os concentrations observed in gold analyses from porphyry and epithermal sulphide systems. The exception is the placer gold sample from Last Chance Creek which yielded a slightly higher concentration of Os of 267 ppt.

Analytical data from the seven gold analyses are shown on an isochron plot in Figure 2. The implications of the data are discussed below.

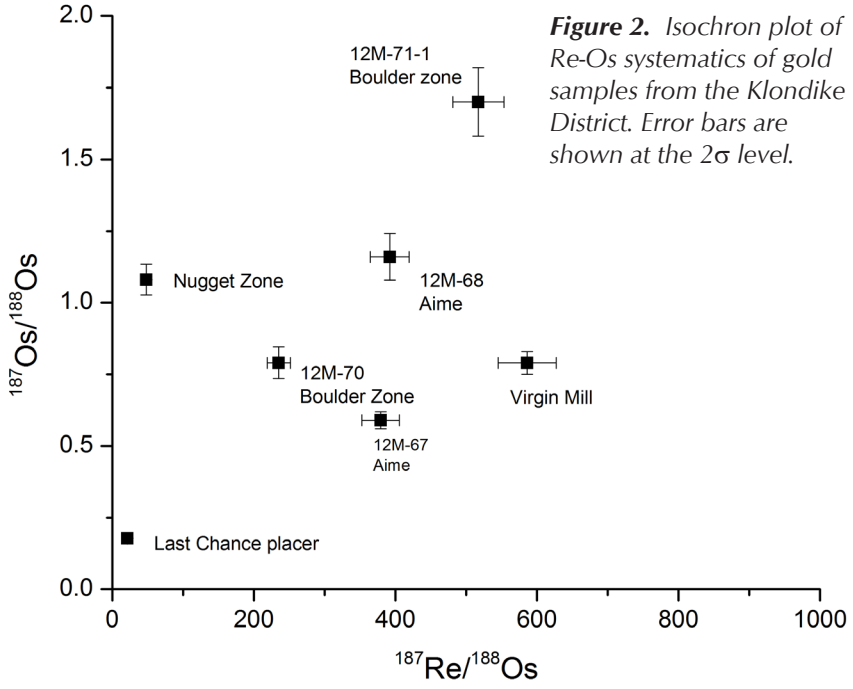

Figure 2. *Isochron plot of Re-Os systematics of gold samples from the Klondike District. Error bars are shown at the 2σ level.*

DISCUSSION

The main goal of this study was to evaluate the possibility of using Re and Os in samples of native gold from the Klondike to determine the age(s) of vein formation and the source(s) of Os (and by inference Au). This method requires that there be measurable amounts of Re and Os in the gold samples, as well as a sufficient range of Re/Os ratios to produce a well-constrained isochron. Three conditions must also be met in order to generate an isochron that is geologically meaningful: a) all samples must have incorporated initial Os of the same isotopic composition; b) the individual samples have to be of the same age and be related to one another (*i.e.*, formed from the same hydrothermal system); and c) the Re-Os isotopic system must have remained undisturbed since the gold was deposited. Initial results of the study have shown that lode gold samples from the Klondike district do contain sufficient concentrations of both Re and Os to permit relatively precise determination of Re and Os isotopic compositions, and our initial sample suite produced a considerable range of $^{187}Re/^{188}Os$ values (21-588). Therefore, in theory, the Re-Os system in gold from the Klondike should be amenable to isochron dating. However, there are several important considerations that potentially bear on the application of this method in the Klondike. First, we cannot be certain that all of the gold-bearing veins in the Klondike formed at the same time as evidenced by petrologic and geologic mapping relationships. Second, gold compositional studies by Chapman *et al.* (2010a,b) suggest that the gold-bearing veins are the products of relatively small hydrothermal systems (scale of <10 km in diameter). The seven samples that were analysed came from localities as much as 45 km apart, and it is therefore unlikely that they represent products of the same hydrothermal system. Third, Pb isotopic studies discussed above suggest that the gold and possibly other contained metals in the veins are derived locally; hence there is no basis to suggest that the Re-Os geochemistry of the vein fluids responsible for the formation of individual veins from different parts of the Klondike would necessarily be related.

There is a high degree of scatter in our data (Fig. 2). Three samples from the Lone Star Ridge area between upper Bonanza

Creek and Eldorado Creek (two samples from the Boulder Lode occurrence and one from the Nugget zone) are all from veins hosted within the same felsic metavolcanic package. The two samples from the Boulder Lode were taken from veins within ~200 m of one another, so might be expected to be closely related and to have formed from the same ore fluid. The Nugget zone sample is from a locality ~2 km farther to the west (Fig. 1). The measured isotopic composition of the Nugget zone gold sample (Fig. 2) indicates that it formed from a mineralizing fluid with a considerably more radiogenic initial Os isotopic composition, and appears to be incompatible with having formed from the same hydrothermal system that produced the Boulder Lode veins. Although some minor differences in the Os isotopic composition of the mineralizing fluids might be expected in view of the variability in Pb isotopic composition within and between individual veins in the Klondike, this amount of heterogeneity was quite unexpected. Two samples from veins ~250 m apart at the Aime occurrence in the southern Klondike (Fig. 1) that are very similar in composition and overall character and are hosted within the same mafic schist package also yield isotopic compositions that indicate that they did not form from the same, isotopically homogeneous ore fluid.

Interpretation of the Re-Os data along with the other trace metal studies is complicated. Osmium has been shown to be immobile in melts and hydrothermal fluids (McCandless *et al.*, 1993; Suzuki *et al.*, 1996, 2000; Woodhead and Brauns, 2004); however, in contrast, Re is very mobile in melts and lower temperature hydrothermal fluids. The variation of the initial Os ratio that we infer from the measured compositions of the Klondike gold samples suggests two possibilities: 1) fluids scavenged osmium from diverse local metal sources; or 2) a single fluid which never reached isotopic equilibrium/closure temperature could be responsible for mineralization. At this point, the first scenario is most likely given the evidence from Pb isotopic studies discussed above. This is significant, because to date, the mobility of Os has not been demonstrated and may be indicated for the first time here in the Klondike gold. The exact mechanism by which variable amounts of initial Os, derived from isotopically distinct, relatively local reservoirs could be mobilized into orogenic veins is unclear. Gold in veins in the Eldorado Creek area (Dysle zone and Violet occurrence) has been shown to include two distinct coexisting gold phases, based on alloy composition (Chapman *et al.*, 2010a), suggesting that the veins formed from distinct pulses of hydrothermal fluid, each of which had different Ag/Au proportions, and may have also had different Os isotopic compositions, implying derivation from distinct sources.

SUGGESTIONS FOR FUTURE WORK

The results of this scoping study suggest that there is a surprisingly large amount of variability in the initial Os isotopic composition of mineralizing fluids responsible for the formation of gold-bearing veins in the Klondike. Although it is unclear whether this is likely to be typical of all orogenic gold systems, it certainly represents a significant challenge for utilizing the Re-Os method to date veins in this area. The main problem appears to be variability between different hydrothermal systems, and perhaps even within closely spaced veins in the same system, related to either very local sources for the Os and/or mixing between ore fluids with somewhat different Os isotopic composition. Our work has shown that there is both adequate amounts of Re and Os in gold from the Klondike veins, and a sufficient range of Re/Os ratios to apply isochron dating methods, if sample suites that meet the criteria for valid isochron dating can be identified. The intimate association between gold and pyrite in most of the veins in the Klondike, and the demonstrated resistance to resetting of the Re-Os system in pyrite (Brenan *et al.*, 2000), suggests that a fruitful approach might be to construct isochrons based on multiple aliquots of gold from a specific part of a single vein, together with multiple fractions of the associated pyrite. The gold to be analysed would have to be examined petrographically and alloy compositions determined using electron microprobe methods in order to preclude any possibility of there being mixed populations of gold alloy phases present. Another very interesting line of research would be to test the source(s) of gold in the orogenic veins in the Boulder Lode area using Re-Os isotopic systematics of the gold and potential sources (especially pyrite in the host schist), which has been suggested by MacKenzie *et al.* (2008b) and Mortensen (unpublished data) to be the ultimate source of the vein gold.

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