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Characterization of gold mineralization in the northern Cariboo Gold District, British Columbia, Canada, through integration of compositional studies of lode and detrital gold with historical placer production: a template for evaluation of orogenic gold districts

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Running title: Placer and lode gold in the northern Cariboo Gold District, BC

Abstract

There is a strong association between regions containing orogenic gold mineralization and exploitation of placer gold, although in many cases the nature of the source mineralization for these placer deposits remains unclear. This study describes a novel approach to evaluating the economic potential of in situ orogenic gold mineralization through characterization of both lode and placer gold mineralogy followed by synthesis of this information with records of both mineral occurrences and historical placer mining. The northern Cariboo Gold District (CGD) in east-central British Columbia, Canada, was chosen as a location for the study because of the gold endowment of the area (1.2 million oz. of lode gold and between 0.5 and 3 million oz. of placer gold) and the information available from both placer and lode gold mining.

Compositional analysis of 533 gold grains from 21 lode localities and 1,914 gold grains from 30 placer localities from throughout the CGD has identified four main compositional types in terms of their alloy compositions and associated suite of mineral inclusions revealed in polished section. A distinctive low (4-7%) Ag gold that exhibits a strong Bi association in the mineral inclusion suite is geographically limited to the Wells area, where it is recorded in both lode mineralization and its placer expression. Regionally pervasive mineralization yields gold of binary Au-Ag alloy and a simple inclusion suite of sulfides and sulfarsenides. Gold in most large placers in trunk drainages was derived from multiple (mostly small) occurrences of this type. The nature of compositional variation between gold grains liberated from hypogene ore has informed the history of episodic mineralization and suggests multiple stages of gold emplacement at some localities whilst others are dominated by gold deposited in a single stage.

The new information from gold grain analysis has been considered in the context of other strands of information. Classification of a placer as either allocthonous or autocthonous informs both interpretation of compositional characteristics of the detrital gold grains and provides information on distance to the hypogene source. Mineral inclusion assemblages observed in sample populations of placer gold grains have been correlated with reports of hypogene vein mineralogy described in mineral occurrence records to clarify the geographical extent of specific mineralization types. The compositional range of alloys of different gold types has been compared to historical records of gold production and gold fineness (Au-Ag ratio) to reconstruct the size and distribution of hypogene sources prior to erosion.

Synthesis of gold compositional studies with other publically accessible data sets provides a new generic approach capable of evaluating the most attractive targets for future exploration and highlighting compositional signatures of placer gold which relate to undiscovered in situ sources.

Introduction

The significance of the relationship between placer gold to its hypogene source is commonly held in low regard by some exploration geologists. The process of ‘prospecting back to the source’ can be complicated by several factors, including multiple lode occurrences of gold, drainage evolution, and in some cases glacial transport of eroded auriferous material. Perhaps most significantly, the common mismatch between the gold inventory in placers and that in the known local potential lode sources has undermined consideration of detrital gold as a useful exploration tool. In the cases in which a geographically constrained source is present, (as may be the case with porphyry and associated epithermal mineralization), establishing a dispersion train of detrital gold may be relatively straightforward (e.g., Chapman et al., 2014), but in orogenic gold districts lode mineralization is commonly widespread, and of variable grade; thus identifying the most economically important mineralization on the basis of the abundance of placer gold is problematic.

Correlation of placer Au with lode source has traditionally been investigated using various aspects of gold mineralogy, such as alloy compositions and associated inclusion suites (e.g., McTaggart and Knight, 1993; Chapman et al., 2000a). The value of these studies is dependent upon the availability of gold samples from the full range of hypogene sources, but the approach is commonly constrained because of poor exposure. In this contribution we explain how compositional studies of gold grains from both lode and placer deposits and occurrences can be advantageously integrated with other information available in the public domain to illuminate the nature of regional orogenic mineralization. In order to establish this approach, a study was carried out on an important placer gold district in Canada where at least some of the likely hypogene gold sources can be effectively characterized.

The discovery of placer gold in east-central British Columbia, Canada, in 1859 triggered a major gold rush in an area extending roughly from the Wells-Barkerville area in the northwest to the Frasergold deposit in the southeast, referred to herein as the Cariboo Gold District (CGD, Fig. 1; Sutherland-Brown and Ash, 2009; Rhys et al., 2009). Early gold production records from the CGD, presented by Holland (1950), show the recovery of roughly 500,000 ounces (16 tonnes) of placer gold, although these figures doubtless under-represent the true amount, which Levson and Giles (1993) suggested is between 2.5 and 3 million ounces (80-96 tonnes). Nevertheless, the data presented by Holland (1950) are valuable as they provide a guide to the relative economic importance of different drainages within the CGD. Approximately half of this placer gold inventory originated from the historic centre of placer mining activity near the towns of Wells and Barkerville (the Wells-Barkerville camp; Fig. 1), and it is probable that an additional substantial and largely undocumented amount was recovered from this area in the early stages of the gold rush. Subsequent exploitation of Au-bearing orogenic quartz- pyrite veins in the Wells-Barkerville camp between 1933 and 1983 yielded an additional 1.2 million ounces (38.4 tonnes) of lode gold from the Cariboo Gold Quartz, Island Mountain and Mosquito Creek mines (Sutherland-Brown and Ash, 2009; Fig. 1).

Results of recent (bedrock) exploration within the Wells-Barkerville area and immediately to the west have suggested an indicated plus inferred gold resource of approximately 5 million ounces in the Cow Mountain area (including the historic Cariboo Gold Quartz mine), plus the potential for a similar or greater resource in each of the Island Mountain area (including the historic Island Mountain mine) and Barkerville Mountain area to the immediate north and east of Cow Mountain, respectively (Dzick, 2015; see later discussion). If these estimates are confirmed, the Wells-Barkerville camp would represent at least a world-class if not a giant lode gold deposit using the classification of Groves et al. (2003). Consequently, this study focuses mainly on the Wells-Barkerville camp and surrounding placer areas because it is the most important auriferous area within the CGD known thus far. We also discuss results of studies of placer and lode gold samples from farther south in the Cunningham Creek and Yanks Peak areas, north of Cariboo Lake (Fig. 1), which also produced a significant amount of placer gold.

In many placer districts worldwide there are apparent discrepancies between the size and spatial distribution of the placer resource and the known lode deposits. In the CGD different hypotheses have been developed to explain the presence of abundant, coarse placer gold. These range from those which have advocated a secondary origin for the gold (Johnson and Uglow, 1926, and Eyles et al., 1995) and the purely detrital model proposed by Warren (1936) and McTaggart and Knight (1993) and supported by the present study. Proponents of the detrital model cite the inheritance of mineralogical features of hypogene mineralization into the placer grains, as powerful supporting evidence, and on this basis, McTaggart and Knight (1993), concluded that undiscovered lode sources must have contributed gold to several important placer deposits in the CGD.

This study applies gold grain characterization to inform a regional assessment of the mineralization which is only partly possible through the study of the known lode occurrences. Correlation of mineralogical signatures of gold from hypogene occurrences with the local placer expression has been used by Chapman et al. (2010a) to illuminate systematic spatial variation within the small rich, orogenic Au vein system centred on the Lone Star area of the Klondike District, Yukon. Similar challenges in characterizing the geographical extent of hypogene ores and their relative economic potential are encountered within the northern part of the CGD and consequently the same methodology has been applied here.

The study aims to synthesize historical data concerning gold abundance with new data describing the variation in composition in placer and lode gold to characterize the hydrothermal system or systems responsible for gold mineralization. In addition we aim to demonstrate how the approach of synthesizing data from different sources can enhance understanding of the economic potential of orogenic gold districts.

Geology and Mineralization

Regional Bedrock Geology

The CGD is underlain by parts of four main tectonostratigraphic terranes (Fig. 1). Bedrock underlying the northern part of the CGD, which is the focus of this study, comprises polydeformed, low to medium grade metamorphic rocks of the Barkerville terrane, including a variety of phyllitic and schistose metaclastic rocks with local interlayers of limestone, marble and amphibolite. Metamorphic rocks of the Cariboo terrane structurally overlie the Barkerville terrane units along the northeast-dipping Pleasant Valley thrust fault, and both the Barkerville and Cariboo terranes in the northern CGD are in turn overlain by mafic volcanic rocks and associated sedimentary units of the oceanic Slide Mountain terrane (Struik, 1987, 1988; Fig. 1). The southwestern margin of the Barkerville terrane is overthrust by much less deformed and less metamorphosed, Middle and Late Triassic siliciclastic and volcanic rock units of the Quesnel terrane. The Crooked Amphibolite (Fig. 1), which occurs as a discontinuous lens of mafic metavolcanic rocks and minor serpentinite along the boundary between the Quesnel terrane and the underlying Barkerville terrane, is thought to represent a thrust fault bounded body of Slide Mountain terrane.

Metamorphic rocks in the CGD have been affected by two dominant syn- to post-accretionary phases of deformation (D1 and D2; Rhys et al., 2009). D1 structures include east- to northeast verging, tight to isoclinal, northwest trending F1 folds with a strong penetrative cleavage. The D1 event is interpreted to be associated with emplacement of the Quesnel terrane onto the Barkerville terrane (Rees, 1987; Bloodgood, 1987, 1992; Panteleyev et al., 1996; Ferri and Schiarizza, 2006). D1 was accompanied and locally outlasted by peak regional metamorphism, which ranged from lower to medium greenschist facies in the northern CGD and grades progressively into upper greenschist and then amphibolite facies farther to the northwest, and southeast of Cariboo Lake (Fig. 1). D2 structures refold both the earlier S1 foliation and associated folds, and include a secondary, locally dominant crenulation cleavage (S2), which is axial planar to D2 folds. An intense, shallowly northwest plunging composite intersection and elongation lineation (L2) occurs at the intersection of S2 and older S1 foliation in the Wells-Barkerville area, and is parallel to F2 fold axes. The long axes of many gold-bearing zones in the area are parallel to L2, and extensional veins related to many gold deposits in the area are approximately orthogonal to L2 (Rhys et al., 2009).

Structurally late, north- to north-northeasterly trending, dextral faults with limited amounts of displacement occur throughout the CGD, extending across and offsetting lithologic contacts, including major thrust surfaces associated with terrane boundaries. These faults have a protracted structural history, locally displaying early semi-brittle fabrics, with widespread later brittle displacements along clay gouge seams (Rhys et al., 2009). These structures are commonly spatially associated with late gold-bearing quartz veins that are widespread throughout the district.

Lode Mineralization

Most historic gold exploration and placer and lode gold production in the CGD has been from areas underlain by low to medium metamorphic grade metaclastic rocks and minor amphibolite and limestone of the Barkerville terrane. As discussed above, nearly all historical lode gold production and much of the placer production from the CGD were from the Wells-Barkerville camp in the northern portion of the CGD (Fig. 1). The locations of many of the known lode gold occurrences in the northern CGD are provided by Schiarizza (2004). Detailed mineralogical descriptions of many of these veins are provided by various authors (e.g., Galloway, 1932; Lay, 1932; Warren, 1936; Rhys and Ross, 2001). Warren (1936) noted a strong association between coarse grained Au and the Pb-Bi sulfides galenobismutite ($PbBi_2S_4$) and cosalite ($Pb_2Bi_2S_5$), commonly together with galena . Gold mineralization in this area includes both pyritic replacement bodies and gold-bearing quartz veins. The nature and structural controls on gold mineralization in the CGD are discussed in detail by Rhys et al. (2009). Approximately one-third of the lode gold production from the CGD was from pyritic replacement style mineralization (Ray et al., 2001), which occurs as multiple small (500-40,000 tonnes), manto-like, folded, northwest plunging, rod-shaped bodies of massive, fine-grained pyrite > Fe-carbonate + quartz that locally replace limestone units within dominantly metaclastic Barkerville terrane stratigraphy. Replacement style ore shoots in the Island Mountain and Mosquito Creek mines (Figs. 1, 2) are spatially associated with hinge zones of mesoscopic D2 folds. Gold in the replacement style ore occurs as fine grains along crystal boundaries and fractures, and as isolated inclusions within pyrite. Somewhat similar replacement mineralization also occurs in the Bonanza Ledge Zone southeast of Wells (Figs. 1, 2), where it replaces thinly bedded metaclastic rocks rather than limestone.

At least two stages of quartz vein emplacement occurred in the Wells-Barkerville camp (Rhys and Ross, 2001; Rhys et al., 2009). Early, deformed veins typically contain only background or low (<2 g/t) gold concentrations. These early veins are cut by several orientations of younger, steeply dipping, quartz-carbonate-pyrite veins that form complex vein arrays and host most of the vein-associated gold in the CGD. The younger veins are structurally late and are localized along small-displacement faults and locally along extensional fractures that post-date all D1 and much or all D2 strain in the region (Rhys and

Ross, 2001; Rhys et al., 2009). "Strike" or "A-veins", including the BC vein, are northwesterly striking and lie along faults that parallel the regional structural grain in the region. The other main vein sets present include widespread northeast-trending "transverse" veins and east-trending "diagonal" quartz veins. These later veins have been the source of approximately two-thirds of the lode gold production in the Wells-Barkerville camp (Hall, 1999). The relative age of the A-, transverse and diagonal veins is uncertain; however, all of the veins are mineralogically similar, comprising white quartz + pyrite with Fe-carbonate +/- muscovite selvages and pyritic cores. Scheelite and fuchsite are local accessory minerals, and native gold occurs in association with pyrite, and locally with cosalite and bismuthinite (Skerl, 1948; Rhys and Ross, 2001; Rhys and Ross, 2009; Brown and Yin, 2009).

The relationship between the replacement style and vein style mineralization in the CGD is uncertain. Where the two styles of mineralization occur together the quartz veins typically cut across and therefore postdate the replacement bodies. Rhys et al. (2009) concluded that the two styles of mineralization formed over a relatively short time interval, and likely represent different manifestations of an evolving hydrothermal event, rather than separate and unrelated events. Similarities in the mineralogy of the replacement style mineralization and that in the quartz veins (e.g., the presence of galena + cosalite in both) supports a close genetic relationship. An $^{40}Ar/^{39}Ar$ dating study of gold mineralization within the CGD by Mortensen et al. (2011) gave ages of 156–153 Ma for early (pre-mineral), deformed quartz-pyrite veins in the Wells-Barkerville camp, whereas muscovite within replacement-type ore and in late, gold-bearing extensional veins in the Wells-Barkerville camp range in age from 148–135 Ma. The dating results appear to indicate that replacement style mineralization at Mosquito Creek formed at about 148 Ma, whereas that at Bonanza Ledge formed somewhat later, at 138-136 Ma. Gold-bearing quartz veins from various localities in the Wells-Barkerville camp give ages ranging from 147-136 Ma. Collectively the dating results appear to indicate that gold introduction in the area occurred over a protracted period of at least 12 million years.

On-going exploration work by Barkerville Gold Ltd. on gold-bearing quartz vein systems and pyritic replacement deposits in the Cow Mountain area (including the old Cariboo Gold Quartz mine) in the heart of the Wells-Barkerville camp (Figs. 1, 2) has delimited an indicated resource of 35.8 MT at 2.4 g/T Au (total of 2.8 M oz. or 90.0 tonnes Au) with an additional inferred resource of 27.5 MT at 2.3 g/t (total of 2.0 M oz. or 64.3 tonnes Au; Dzick, 2015). The Cariboo Gold Quartz mine had previously produced 0.63 M oz. of gold from 1.68 MT of ore grading 11.9 g/T (Sutherland-Brown and Ash, 2009; Dzick, 2015). The Bonanza Ledge Zone on nearby Barkerville Mountain (Fig. 1, 2), which is currently being mined on a small scale by Barkerville Gold Ltd., has a total measured and indicated resource of 0.42 MT at 7.6 g/T Au (total of 0.10 M oz. or 3.2 T Au) and an additional inferred resources of 0.28 MT at 7.8 g/T (total of 0.07 M oz. or 2.3 T Au; Dzick, 2015).

The most recent work has also suggested the potential for substantial additional gold resources, possibly equivalent to or exceeding that in the Cow Mountain area, in each of the Island Mountain and Barkerville Mountain areas (Figs. 1, 2; Dzick, 2015). Previous lode production from the Island Mountain and adjacent Mosquito Creek mines totalled 1.25 MT yielding 1.36 M oz. Au (Sutherland-Brown and Ash, 2009; Dzick, 2015).

Orogenic gold mineralization is also present along the southwestern margin of the CGD (Fig. 1), particularly at the Spanish Mountain deposit (resource of 3.18 M oz. gold at 0.46 g/T; Koffyberg et al., 2012) and Frasergold deposit (non-NI 43-101 compliant resource of 0.38 M oz. at 0.78 g/T; Campbell and Giroux, 2009). These deposits are geographically well removed from the orogenic deposits and occurrences within the Barkerville terrane in the northern CGD, and are hosted by rock units of the Quesnellia terrane, which structurally overlies the Barkerville terrane (Fig. 1). Mineralization at Spanish Mountain and Frasergold formed somewhat earlier than that in the Barkerville terrane (Mortensen et al., 2011), and the relationship, if any, between these structurally higher orogenic gold systems and those within the Barkerville terrane in the northern CGD is uncertain. The gold systems and associated placer deposits in the Quesnellia terrane are described by Rhys et al. (2009),Mortensen and Chapman (2010), and Chapman and Mortensen (2011) respectively.

Lode gold occurrences and derived placer deposits within the northern CGD show a belt-like distribution (Fig. 1). Most deposits and occurrences lie within a narrow north-northwest-trending belt approximately 23 km in length, that extends from the Mosquito Creek Mine in the northwestern part of the Wells-Barkerville camp southeastwards through prospects on Antler and then Cunningham creeks (Figs. 1, 2). A second, sub-parallel trend is located approximately 10 km to the west-southwest of the above trend, and comprises two clusters of lode gold deposits and derived placers, one in the Lightning Creek (Stanley) area in the north and the other in the vicinity of Yanks Peak approximately 35 km to the southeast (Figs. 1, 3). Numerous quartz veins and vein systems are present in the area between these two belts; however, none appear to have contained significant amounts of gold. These trends may correspond to structural corridors formed by poorly defined high strain zones or faults in the region. In the Wells-Barkerville camp in the northeastern trend both gold-bearing veins and replacement style mineralization are roughly stratabound within a 150-250 m thick part of the Barkerville Terrane stratigraphy, emphasizing the probable importance of both lithological and structural controls on localization of mineralization (Rhys et al., 2009). It is uncertain why the two mineralized trends terminate; however, Rhys et al. (2009) note that, as is common in many orogenic gold districts, mineralization is preferentially hosted in lower to middle greenschist facies rocks, and higher grade (amphibolite facies) rocks to the northwest and southeast may represent less favourable hosts.

Surficial Geology

The surficial geology and stratigraphic setting of placer gold deposits in the CGD has been described by Levson and Giles (1993) and the following section is very briefly summarized from that work. The study area experienced multiple continental-scale glaciations during the Pleistocene (mainly in Late Wisconsinian time). Surficial units in the CGD range in age from Tertiary to Recent, and include pre-glacial fluvial deposits of Miocene age, early interglacial fluvial deposits of pre-Late Wisconsinian age, deposits (mainly glaciofluvial units as well as minor till) of Late Wisconsinian age, and post-glacial terrace deposits, alluvial fans and colluvium of mainly Holocene age. Levson and Giles (1993) characterize the placer deposits in the study area according to their sedimentary characteristics:

i. Paleogulches (high gradient, narrow valley settings)
ii. Large, pre-late Wisconsin palaeochannels
iii. Late Wisconsin glacial and fluvioglacial placers
iv. Post glacial and colluvial and alluvial fans.

These classifications do not necessarily infer a proximal or distal source for the gold, although gold from paleogulches is likely to be locally derived. However, coarse gold with a rough grain morphology indicative of limited fluvial transport has also been reported in other placer environments in the study area (e.g., the post-glacial and colluvial deposits and alluvial fans in Nelson and Slough creeks approximately 10 km west of Wells; Fig. 2). Table 1 indicates the depositional setting in which placer populations studied here were formed (according to the classification system of Levson and Giles, 1993). Many of our sample locations as described in Table 1 were chosen specifically because they are likely to contain proximal gold (i.e., from paleogulch settings). Most samples examined previously by McTaggart and Knight (1993) were obtained from placer deposits within main drainages, which potentially contain gold from settings ii-iv above. The approach to characterizing such samples is discussed below.

Methodology

Studies of gold grain compositions which combine data sets from alloy and inclusion analyses are dependent upon the availability of multiple gold grains from a single locality. The term 'sample population' is used to refer to gold grains from a specific locality, (see table 1) where the number of grains within each population is indicated.

The suite of sample populations used in this study was a combination of those previously considered by McTaggart and Knight (1993; Tables 1a and 1b), together with new suites of lode and placer samples that were collected by the authors in 2008 and 2009 (Table 1c). Sample localities for the northern part of the study area (Wells-Barkerville and Lightning Creek areas) and the southern and eastern parts (Antler and Cunningham creeks and Yanks Peak areas) are shown in Figure 2.

The sample populations of gold grains from lode gold examined in this study are indicated in Table 1a. Grains from lode gold localities were liberated from vein material by crushing grab samples of up to 5kg, followed by panning. New placer gold samples were collected from the present drainage by panning or sluicing (as described by Chapman et al. 2010a). Specialized field techniques for the recovery of populations of placer gold grains in areas of low abundance were described by Leake et al. (1998), and these were adopted here. Gold grains were identified in the field and sufficient material was processed in order to collect a suitable number of grains. Ideally over 50 grains were collected (Figure 1c) but in some cases, time constraints in the field coupled with low abundance of grains resulted in a smaller population size (e.g., Perkin's Gulch and Little Snowshoe Creek; Table 1c).

Analysis

Gold grains in samples collected during the present study were analysed according to the methodology of Chapman et al. (2010a), which involved identifying opaque mineral inclusions in each grain section using the back-scattered electron analysis (BSE) facility of the scanning electron microscope (SEM) and determination of the alloy composition using an electron microprobe (EMP). In the present study the overwhelming majority of grains were homogenous with respect to silver (as deduced from the uniform grey scale viewed in BSE), and only one analysis was undertaken per grain. Gold rich rims were ignored as they are not a result of hypogene processes (Groen et al., 1990). In some cases, gold grains from a single locality were subdivided empirically according to morphology and texture (e.g., rough, implying relatively short transport distances, vs. smooth/flaky, implying longer transport distances) prior to mounting the grains for analysis. In this way compositional data could be correlated with a bimodal measure of transport distance from hypogene source. Polished sections of the gold grains studied McTaggart and Knight (1993) (Tables 1a, b) had previously been analysed by EMP and these grains were re-examined for contained inclusions during the present study.

Presentation of data

Characterization of the signatures of gold grain populations is based on the correlation of alloy composition and associated inclusion assemblages of the gold particles. The alloy compositions are represented by ‘cumulative percentile vs. increasing Ag’ plots, in which each data point refers to the analysis of a different gold grain. These plots facilitate direct comparison of populations comprising different numbers of gold grains. Suites of mineral inclusions are established by recording the numbers of grains in a population which contain a specific inclusion. For the purposes of discrimination between sample populations, the raw inclusion data may be manipulated to highlight differences. This process usually involves combining results for individual mineral inclusion species to generate data relating to a mineral class (i.e., sulfides, sulfarsenides or tellurides). In other cases consideration of individual minerals may be informative, where they are diagnostic for particular populations. Suites of mineral inclusions are represented using triangular diagrams with axes selected to emphasise mineralogical variation.

Results

Reproducibility of alloy and inclusion signatures

Previous studies of placer gold compositions have established that alloy signatures generated by re-sampling and re-analysing grains from individual localities are generally reproducible (e.g., Chapman et al., 2000b; Chapman et al., 2010a). Figure 3A compares the Ag contents obtained from placer gold grains in multiple samples taken from two specific drainages (Beggs Gulch and Burns Creek) during this study with those reported by McTaggart and Knight (1993) from the same drainages (although not from exactly the same sample sites). The same compositional ranges are evident, although in slightly different proportions in the duplicate samples. Figure 3B shows the Ag contents of gold grains recovered from two placer samples collected 0.5 km apart from Chisholm Creek during the present study, and in this case the curves are very nearly coincident. We consider the approach to sampling and analysis to be robust as evidenced both by the data presented here and by comparisons previously reported (e.g., Chapman et al., 2010a). Confidence in the reproducibility of the alloy signatures permits interpretation of relatively minor differences in alloy compositions of populations. Analysis of gold grains yielded data describing the concentrations of Ag, Au, Cu and Hg. The Cu content of gold was below detection limit in all cases and is not considered further.

The characterization of a population of gold grains is achieved through consideration of the alloy composition coupled with the inclusion assemblage. Leake et al. (1998) suggested that around 30 grains were required to characterize a single population, on the basis that around 20% of grains revealed inclusions. Chapman et al. (2000b) demonstrated that re-sampling a placer locality to obtain 30 grains yielded populations with comparable inclusion suites, but fewer grains were required to establish the range and proportions of alloy compositions.. However, since that time other studies (e.g., Chapman et al. 2010a,b) have sought to collect larger populations such that, i. sample populations containing gold from multiple sources may be characterized in terms of each contributing source and ii. sample populations which exhibit a lower incidence of inclusions generate useful data sets. In the present study, several populations contained a very small number of inclusions and in such cases data from individual populations may be combined if there is sufficient justification, either on the basis of geographical proximity and similar alloy compositions.

Lode Gold Mineralization

The ranges in Ag contents of populations of lode gold examined during the study are shown graphically in Figure 4, and conform to three types. Figures 4A and 4B depict sample populations which exhibit a single predominant narrow range of Ag contents. Figure 4B shows the variation in Ag content of various sample populations from auriferous veins exposed on Cow Mountain, most of which exhibit a very limited range of alloy compositions. Gold grains from some other localities also show a continuum of compositions, but over a wider range of Ag contents (Fig. 4C) . There is a clear similarity between the alloy signatures of gold grain populations from the Wells Adit and Proserpine (8-14% Ag) and Burns Mountains and the BC Vein (5-9% Ag). However the sample from the Warspite lode occurrence, which is <4 km from Prospeprine, is considerably more Ag-rich. The sample populations depicted in Figure 4D comprise two or more sub-populations, each characterized by a different but relatively narrow Ag range (e.g., Myrtle, which contains sub populations of 9.2-9.5, 11.0-12.8 and 15.0-18.0% Ag). In some cases the same sub population range appears to be present in different samples. For example, the 11.5-12.8 % Ag population appears in samples from both the Bonanza Ledge and Myrtle occurrences. The sample from the Bonanza Ledge occurrence comprises two sub populations, one displaying a narrow Ag range, and the other with lower but highly variable Ag contents.

The relationship between gold, pyrite and cosalite in some parts of the study area was recorded in studies of polished blocks of ore (Fig. 5). Gold grains with low Ag content appear to have formed coeval with cosalite at Cow Mountain (Fig 5A), whereas pyrite predated cosalite deposition in an ore sample from the Mosquito Creek mine (Fig 5B) .

Placer Gold Signatures

Before comparing signatures of placer gold populations from throughout the study area it is necessary to investigate the compositional variations present within populations of gold grains from individual drainages.

Gold grains in the sample from upper Chisholm Creek exhibited two distinct morphological sub populations, which were analysed separately according to whether they were 'flaky' or 'rough' grains (Fig. 6A). When combined, these sub populations yield a Ag plot identical to that of the sample population collected in lower Chisholm Creek (Fig. 3B). Around 25% of the grains in the 'rough' population comprise a narrow compositional range of 17-23% Ag that is largely absent in the flaky (and presumed to be more far-travelled) gold population. This observation is interpreted to indicate modification to a placer population by an influx of gold along an individual watercourse. We propose that a similar scenario provides a likely explanation for the minor compositional differences between placer populations collected at different locations within both Beggs Gulch and Burns Creek (Fig. 3A).

Similar variations in grain morphology are evident in the various sub populations of placer gold from Lowhee Creek (Fig. 6B). The population of larger, equant grains (Fig. 6C) has a smaller compositional range than does the population of 'rough' grains which exhibited an additional, slightly higher (10-12%) Ag content.

Consideration of Placer Signatures by Locality

When dealing with large data sets in which the composition of lode Au varies between sampling localities, it is generally advantageous to make an initial classification using the alloy compositions, and to subsequently refine this using inclusion assemblages as an additional discriminant. This approach has been adopted in the present study and Ag plots of populations of parts of the study area are presented in Figure 7, with a commentary and further context provided by Table 2.

Three types of placer signature may be identified in terms of the Ag plots in Figure 7. Samples from paleogulch environments such as Dragon Creek (Fig.7B) or Beggs Gulch (Fig. 7D) commonly show a dominant curve portion which exhibits a shallow gradient. The approach to interpreting this feature is the same as that applied to the lode signatures described above; i.e., the gold grains were derived from a single mineralizing event, which in the context of a placer sample is consistent with the small catchment area. Sample populations collected from larger drainages may show evidence of two distinct contribution sources, sometimes with mutually exclusive Ag ranges (e.g., Williams Creek; Fig. 7A), and upper Antler Ck (Fig 7D). Finally, sample populations from trunk drainages may exhibit a continuum of Ag values, reflecting multiple sources each with a different Ag range, e.g., Ballarat - St Georges Mine (Fig. 7A) and Cunningham Creek (Fig. 7E) . In some cases this form of Ag plot may be observed in samples from smaller drainages, and this may either be a consequence of: i. a source which itself exhibits alloy variation (e.g., Myrtle; Fig. 4B), ii. the reworking of local palaeogravel derived from a wider area, or iii. reworking of glacially transported sediments.

The co-variance of Ag and Hg in gold alloy for selected sample populations is provided in Figure 8. The gold from Dragon Creek shows a relatively small compositional field clerly identifiable by measurable Hg. Gold grains of this type are absent in sample populations from al other localities with the exception of a few grains from Montgomery Creek (which is adjacent to Dragon Creek; Fig. 2). Some grains from California Creek contained a few Ag and Hg- rich grains but they were not common.

Inclusions were scarce in the gold grains from many localities in the study area (Tables 1B,C). Nevertheless the correlation of alloy chemistry with inclusion suites throughout the study area has greatly aided the characterization of one particularly important gold signature and allowed discrimination between this and other populations of similar alloy composition. In addition, the study of inclusions has permitted correlation of microchemical signatures with the previous descriptions of vein mineralogy provided by Schiarriza (2004).

The abundance of inclusions and their mineralogy is shown in Table 1 and varies markedly between different samples. Many sample populations contained insufficient inclusions to be able to plot the data in a meaningful way on Figure 9; however, in some cases, amalgamation of inclusion data from two or more related samples was possible, validated by geographical proximity, very similar alloy signatures and similarity between the individual small inclusion suites. In addition, the groupings formed an inclusion mineralogy consistent with the vein mineralogy of the localities reported by Schiarizza (2004). The groups constructed were: (Little Snowshoe, Keithley, Cunningham and Peter creeks), all Antler Creek samples, and (Maude Creek plus Ballarat-St. Georges Mine). Figure 9 depicts the relative abundance of grains containing pyrite, Co-Ni-sulpharsenides, Bi-bearing minerals and sulfides of Pb, Zn or Cu. The low-Ag gold from the Wells area shows a clear association with Bi-Pb sulfides (and their secondary mineral derivatives) and Co-Ni-bearing sulfarsenides. Inclusion assemblages of placer gold populations from Chisholm and Burns creeks and Lowhee Creek form a small compositional field in the left-hand triangle of Figure 9. In the adjoining truncated triangular diagram, gold from Chisholm Creek plots between the clusters of gold samples from Burns and Lowhee creeks and the more regionally widespread pyrite+simple sulfide signature. This is a consequence of the flaky gold corresponding to the Bi-bearing type, whereas the rough gold (see Fig. 6A) mainly contains only pyrite inclusions. Samples from the northern and central portions of the study area (Ballarat Mine, Maude Creek and Antler Creek; Fig. 2) do not contains the Pb-Bi and Co-Ni-bearing inclusions that were observed in gold from Lowhee, Chisholm and Burns creeks. Several placer populations contained inclusions of arsenopyrite, noteably those from Mosquito Creek and upper Lowhee Creek. Various carbonates (Ca±Fe±Mg) were recorded as inclusions in most sample populations, but otherwise pyrite was the most common mineral inclusion observed.

For the purposes of the present study, classifications of gold types based on compositions were based on specific ranges of Ag contents linked either to another feature, such as inclusion signature or atypical Hg content in the alloy. Populations of gold grains from placers which exhibited a wide compositional range were interpreted in terms of the characteristics of the potential contributing signatures .

Characterization of Gold Types

The binary alloy compositions and inclusion suites described above can be used to identify specific gold signatures which are present in several of the sample populations, and these are defined in Table 3.

Many studies which use gold compositions to inform placer-lode relationships have relied on the Ag content of the alloy as a primary discriminant (e.g., Knight et al., 1999; Chapman et al., 2000a). The Ag content of gold grains liberated from a lode sample commonly exhibits a lower Ag range compared with that from local placers. This pattern is explained by variation in alloy composition within the mineralization as a whole, (both laterally and vertically), which is reflected in the placer sample derived by bulk erosion of the occurrence. The detailed study of compositional variation of gold within discrete orogenic hydrothermal systems in the Klondike (Chapman et al., 2010a,b) highlighted a potential problem with characterizing a mineralizing system solely on the basis of the Ag content of gold grains collected from a specific site within that system. In the characterization of gold from the northern CGD study area presented in Table 3, Ag_{alloy} is used to describe different gold types but only in those cases for which one or more other discriminants supports that classification.

Gold types in the northern CGD have been identified according to distinctive inclusion signatures observed both in lode and placer gold. The suite of Pb-Bi and Co-Ni bearing inclusions is mostly contained within a low Ag alloy, and this signature has been designated type 1. Most placer and lode gold from the rest of the study area is a binary Au-Ag alloy which contains very few inclusions, but where present these comprise carbonates and base metal sulfides (Table 3). The characterization of type 2a gold has been designed to represent a regional type, and consequently it accommodates a broad range of alloy compositions. In addition there is a common low (5-10%) Ag signature in placer gold from a well-defined geographical area around Burns Mountains which extends into Coulter Creek and Slough Creek (Figs. 2 and 7B), but which is also evident in some populations around Barkerville (e.g., BC vein, Fig. 4C). None of the diagnostic inclusion species associated with type 1 gold are present, and this signature has been classified as type 2b on the basis that in this case inclusion suites provide a better discriminant for gold type than variation in Ag.

The range in Ag contents for types 1, 2a and 2b is not mutually exclusive, as evidenced by the presence of a few grains of gold containing 5% Ag in the sample from Bonanza Ledge (Fig. 4A) and the placer sample from Antler Creek (Fig. 7C). At present the lack of inclusions in gold grains designated type 2a precludes categorical classification either as a variety of type 1, a low Ag version of type 2, or a separate type. Whilst the majority of grains designated type 1 are low-Ag alloy, two placer grains from Lowhee Creek exhibited Bi mineral inclusions within alloy comprising 10 and 23% Ag respectively. Rhys and Ross (2001) report minor cosalite in the BC vein and the high Ag- Pb/Bi signature may be related to this source rather than the typical 'Cow Mountain alloy signature' (Fig. 4B). The classification of gold types proposed above is consistent with that suggested by McTaggart and Knight (1993) who also identified three ranges of Ag within binary Au-Ag alloys. The current study represents a refinement to this work through identification of the inclusion assemblage specific to type 1 gold and the commonality between inclusion assemblages across a wide range of Ag contents in gold types 2a and 2b. In this classification process higher weighting has been given to the data describing inclusions species than to Ag range, because $Au\text{-}Ag_{alloy}$ can vary within a single mineralizing event (e.g., Warspite Au546; Fig. 4C)

Elsewhere, two other types of gold have been identified both of which have limited geographical extents. Gold from Dragon Creek is designated type 3 because of the distinctly elevated and characteristic Hg content of the alloy (Fig. 8). Lode gold in the Mosquito Creek Mine includes both vein and replacement style mineralization. McTaggart and Knight (1993) analyzed very fine grains of gold that occur as thin films and as inclusions and fracture fillings within pyrite from pyritic replacement ore from the Mosquito Creek mine, and found that this gold was significantly more Ag-rich than most of the vein-hosted gold in the Wells-Barkerville area; however, the Hg content was below detection limit. This gold type has been designated type 4, but it has not been clearly identified in placer samples, probably because few, if any, of the fine gold particles that appear to typify this type of mineralization would have been recovered by either standard field techniques or placer mining.

Discussion

General considerations

Establishing placer-lode relationships is dependent on the applicability of the detrital model of placer formation, the relative importance of different transport mechanisms (e.g., glacial/fluvial) which have been in effect during the geomorphological evolution of the area, and the original particle size of the native gold.

The methodology employed in the present study involves the systematic screening of internal textures and mineralogy of every gold particle, and the possibility that some particles or parts of these particles could be authigenic is recognised. This subject is discussed in detail in Chapman et al. (2011) and the reader is referred to that text. In summary, in all the many thousands of placer gold grains studied during the present project (or indeed in any other project which has involved the internal study of large numbers of detrital gold grains such as Knight et al., 1999, Chapman et al., 2000a,b,c, 2009, 2010a,b, 2011), there has been no conclusive evidence for either the ab initio growth of gold or economically significant augmentation of pre-existing gold grains. There is, however, considerable evidence for the detrital placer model, based on: i. evolution of gold morphology with fluvial dispersion (Crawford, 2007), ii. the presence of mineral inclusions which are unstable in surficial environments, and iii. the exact correlation of detrital gold mineralogy with that of known sources at various localities worldwide: e.g., Malaysia (Henney et al., 1994); Zimbabwe (Naden et al., 1995); the British Caledonides (Chapman et al., 2000a, 2009); Ecuador (Potter and Styles, 2003); and the Dawson Range Canada (Chapman et al., 2010a,b, 2014, 2015). In the present study, the mineralogy of different lode occurrences has been reflected in the inclusion assemblages of their local placer expressions, and consequently the validity of the detrital placer model is assured.

Levson and Giles (1993) infer a variety of glacial and fluvio-glacial environments in their summary of regional Quaternary geology which provide mechanisms for distribution of detrital gold independent of current drainage patterns. Consideration of ranges of compositions within populations of both placer and lode samples can inform the extent to which such mechanisms have occurred. In many cases the signatures of placer gold from gulch environments is locally specific (e.g., Lowhee Creek, Beggs Gulch, Dragon Creek) and around Wells, the distribution of type 1 gold is sympathetic to local vein mineralogy. Such samples have formed the foundation of the interpretation provided here, whereas potentially more complex sample polulations from trunk drainages are interpreted in terms of these previously defined sub populations.

Placer mining in the northern CGD has recovered gold from a variety of sedimentary environments (Levson and Giles, 1993) corresponding to both autochthonous and allochthonous placers. Gold grains of less than around 50µm may not accumulate in placers due to their hydrodynamic behaviour, and they are difficult to collect in the field (by panning) for the same reason. If some or all the hypogene gold inventory is below 50µm then establishing placer lode relationships is problematic. In the current study, gold grains were recovered from the majority of crushed ore samples by panning, and consequently the hypogene ore is of sufficient size to accumulate in fluvial placers. An exception is gold associated with the replacement style of mineralization at the Mosquito Mine (McTaggart and Knight, 1993), and this constraint has been acknowledged in the following discussion.

Consideration of both alloy and inclusion signatures has allowed us to establish whether a placer population has been derived from single or multiple lode sources. This information can now be used in conjunction with overview of lode occurrences (Schiarriza, 2004) and placer operations (Holland, 1950) to establish the nature of the eroded mineralization and to speculate on its original extent.

Establishing placer-lode relationships through compositional studies

The range of Ag signatures identified in the lode sources in the study area has been characterised in the four Ag cumulative plots that comprise Figure 4A-D. Signatures of placer gold commonly exhibit a wider alloy range than samples from the corresponding lode source (e.g., Chapman et al., 2010a). However signatures from single lode gold occurrences may themselves be complex, showing multiple sub populations each of narrow compositional range (e.g., Fig. 4D). Consequently it is not possible to conclude that placer populations which exhibit a wide range of Ag contents are necessarily derived from multiple sources. It is commonly helpful to consider the nature of the placer environment when interpreting these data.

Allochthonous placer deposits commonly exhibit a wide range of Ag contents which reflect multiple lode sources (e.g., Cunningham Creek - sample AU 496 - Fig. 7E, and Ballarat-St Georges - sample AU 500 – Fig. 7A), whereas autochonous placers typically show a more tightly defined sigature which may correlate to areas of high placer gold abundance (e.g., the Lowhee Creek populations, depicted in Fig. 6B). This general classification correlates with the descriptions of placer environments provided by Levson and Giles (1993), in which the paleogulches (high gradient narrow valley settings) provide the only example of an environment in which the presence of purely autochthonous placers is likely. In the present study, emphasis has been placed on using the signatures of gold from autochthonous placers for comparison with local lode sources to establish placer-lode gold relationships (Fig. 10 and Table 4).

Figure 10 shows examples of the Ag contents of placer samples in relation to those of local potential sources. It is recognised that there are other relevant mineralized localities for which there is no gold compositional data available; however, useful information may be gained from descriptions of these occurrences available in the literature.

In the Lowhee Creek catchment (Fig. 10A), placer gold in the headwaters (upper Lowhee Creek) exhibits a range of Ag contents mostly consistent with a mixture of the local lode sources of the BC Vein, Wells Adit and Myrtle. However, this sample population also contains some low-Ag grains (lower than those recorded in these lode sources), and hence it appears likely that there is some contribution from veins similar to those sampled 2 km to the north (Au 546-551). Rhys and Ross (2001) describe the 'Lowhee showing' as an auriferous quartz-pyrite vein in the middle reaches of the Lowhee drainage. It is probable that the small rough gold grains recorded at the lower Lowhee placer locality were derived from this source. The placer inventory in lower Lowhee Gulch shows evidence of contributions both from a local source (on the basis of gold grain morphology), together with higher-Ag gold grains (from one or more of the Myrtle and Wells adit localities), but these are subordinate to the type 1 signature of gold from the Cariboo Gold Quartz mine and their surface expressions (samples Au 546-551).

Figure 10B shows the relationship between the signatures of placer gold from Williams Creek and Ballerat-St Georges with that of gold from the three lode localities of Warspite (AU 586), Proserpine (AU 587) and the BC Vein (Fig. 2). Several observations can be made from these data sets. Firstly, both placer populations contain some gold grains of higher Ag content than are recorded at the lode localities represented here. Secondly, the population of gold grains from the historically important placers in Williams Creek shows a clear bimodal character, with the lower Ag range corresponding exactly to the compositional range of gold from the BC Vein. Consequently the origins of roughly half the placer gold in Williams Creek could be ascribed to the erosion of this single major source. Schiarizza (2004) records a large number of gold localities on the west side of the Williams Creek valley, including the Proserpine and Warspite localities. Figure 10B shows that the signatures of gold from these two adjacent lode sources differs substantially. Consequently it might be expected that the placer sample from Williams Creek would also exhibit a wide range of Ag contents reflecting a large number of sources, rather than the apparent bimodal population seen in Figure 10B . Holland (1950) reports the fineness range of gold from Grouse Creek (which rises across the watershed from Williams Creek) as between 813 and 833, a narrow range similar to the high Ag population in Williams Creek (19-23% Ag), suggesting related sources in the headwaters. A wider Ag compositional range is observed in the sample from the Ballarat-St Georges Mine, which, although only 0.5 km downstream from the Williams Creek sample locality, contains sediments from a wide variety of sources (Levson and Giles, 1993).

Figure 10C compares the Ag contents of the lode source AU 502 on Burns Mountain with that of placer gold from the adjacent Perkins Gulch. The population of placer gold exhibits a range of Ag contents which encompass the lode gold source, but which also contains some more Ag-rich material. The same pattern is observed in the placer gold from Chisholm Creek which is interpreted to represent a mixture of gold types from different sources (see discussion above). Type 1b gold, present in the Slough Creek catchment and within the large placers of Lightening Creek (Fig. 7D), is most probably derived from sources similar to Burns Mountain and the Forsters Ledge locality described by Schiarizza (2004).

In the southern part of the study area, the Midas adit is the largest known in situ gold occurrence, but only roughly 15% of the placer grains in Little Snowshoe Creek, whose catchment includes the Midas adit occurrence (Fig. 2), show a compositional overlap (Fig.10D). Hibernia is the only lode gold sample available for this study from the Cunningham Creek drainage (Fig. 2); however, the signature from this occurrence is either trivial or absent within the two placer populations from Cunningham Creek (Fig. 10D), indicating the presence of other significant undiscovered lode sources within this drainage. Schiarizza (2004) reported several in situ gold localities in the Cunningham Creek catchment and it is likely that the economically important placers of Cunningham Creek were derived from multiple lode occurrences.

Antler Creek also formed an important placer area in the northern CGD, but the potential sources of the placer gold from this drainage remain unclear as no known lode mineralization has yet been identified (Schiarizza, 2004). The tributaries of Beggs Gulch and California Creek are both relatively small but both placer samples exhibit atypically high Ag ranges. This result suggests that a distinct local source remains to be discovered. This high-Ag signature is present in placer samples from Antler Creek but it is augmented by another alloy whose Ag range is typical of type 2 gold.

In general, the correlation between lode and placer signatures in terms of gold type is very strong. In the Wells area, type 1 gold is present in both lode and placers, whereas the economically important placers in the drainages of Williams, Antler, Cunningham and Keithley creeks are entirely type 2 gold. Some lode localities of type 2 gold exhibit an arsenopyrite signature and this is refelected in the local placers; e.g., upper Lowhee Creek. Whilst there are several occurrences of arsenopyrite-bearing type 1 gold in the Cunningham Creek catchment, there are also several occurrences of simple Au-pyrite-galena mineralization (Schiarizza, 2004), and overall there is insuficient sampling density of either lode or placer to establish individual source-placer connections. The low-Ag type 2b gold has been identified at the Burns Mountain lode locality and forms strong sub populations in several nearby placers.

Implications of placer signatures for the size(s) of the source(s)

Holland (1950) provided production estimates for most placer streams in the CGD until 1945, and reported a total gold production to that point of roughly 0.5 million ounces (16 T). Information for specific creeks relevant to this study is presented in Table 5. This data set is incomplete both because of subsequent production and the absence of records for the early stages of the gold rush. Nevertheless there is much useful information to be gained particularly when the information is considered in conjunction with the approach of the current study.

Data presented in Table 5 has been used to construct Figure 11 which relates the Au content of gold from the same locality as measured by mean Ag values of placer populations (derived from the present study) to the mid point of the fineness range (derived from mining records). It is recognised that both data sets are subject to bias resulting from weighting in the particle size-composition relationships; nevertheless the correlation between the two data sets is mostly very good (Au from fineness data = 0.997 x Au from the present study), although there are two outlying points. Lowhee Gulch has been discussed in a previous section, where two contributing populations were described, and large differences in grain size according to composition were noted (Figs. 6 B,C) . It seems probable that the deviation from the ideal compositional relationship in Figure 11 is a consequence of bias introduced by a combination of greater degrees of mining in the lower portions of the valley coupled with a change in overall placer alloy composition along the drainage (Fig. 6B). Secondly, whilst production from Dragon Creek was modest, the recorded fineness of gold from this drainage is higher than suggested by the data generated in the present study. This may indicate that the recent sampling site was upstream of the major focus of mining. This interpretation also suggests that the high-Ag and -Hg type 3 gold is economically insignificant in the context of the Dragon Creek placer overall, and consequently this type is not considered in the analysis of the placer gold inventory in Table 5.

The definition of gold type adopted in Table 5 has been informed both from data generated in the present study, but also from the bulk fineness data derived from mining records. This approach is justified on the basis of the strong correlation of compositional data from different sources illustrated in Figure 11. Consequently placer gold from Grouse Creek can be confidently ascribed to type 2a as a consequence of the reported fineness range (813-833), and gold from Dragon Creek has been reclassified as type 2 with a contribution from type 3, as a consequence of the disparity in Ag content discussed above.

To some extent the relative overall importance of types 1, 2a and 2b gold may be gleaned through study of the placer populations. Table 5 provides estimates of the mass of gold relating to different types on the basis of the plots presented in Figure 7. For example the population from lower Lowhee Creek has been classified as 80% type 1 and 20% type 2a, on the basis of a break in slope of the curve at the 80th cumulative percentile. It is recognised that the data available can only generate approximate values; nevertheless a clear pattern emerges. The majority of type 1 placer gold has been won from a 'gulch' environment in which it has formed autochthonous placers. The placers of Lowhee Creek and Mosquito Creek derived most gold from the proximal mineralization at Cow Mountain and the Mosquito Creek mine, respectively.

The type 2b signature is common to both the placer localities around Wells and Burns Mountain and is also present in the BC Vein, Burns Mountain, and Forster's Ledge localities (Schiarizza, 2004). Type 2a gold is widespread, comprising most placer gold in the Antler, Cunningham and Keithley creek drainages. In the middle reaches of these valleys placer populations exhibit a wide range of Ag compositions (Fig 7D,E), but the sample from upper Antler Creek (Fig. 7D) shows a pronounced sub population which is interpreted as evidence for a local source.

Whilst a continuum of Ag contents over a wide range is consistent with a large number of small contributing sources, it is possible to recognise individual strong signatures. For example, the number of lode occurrences in the Williams Creek catchment around Barkerville shown in Figure 12 might suggest that the historically rich placers were derived from a large number of small sources and that the placer signature would reflect this diversity. However, the Ag plot for placer gold from Williams Creek shown in Figure 10B is clearly bimodal, with one population corresponding almost exactly to the compositional range of gold from the BC Vein lode source (Fig. 10B).

Gold Mineralizing Events

Classification of the placer and lode gold into discrete types provides a basis for examining the nature of the mineralizing systems in the CGD. This can be achieved in two ways, firstly by linking gold type to mineralization ages, and secondly through consideration of the compositional variation of lode gold and its possible relation to the mineralizing environment.

Inter-relationship of gold types and relationship to episode of mineralization

Table 3 provides evidence for a correlation between the mineralogical signature of the gold particles and the age of the source mineralization. The various stages of vein mineralization is characterized by age, based on the limited amount of available $^{40}Ar/^{39}Ar$ age data (from Mortensen et al., 2011). The earliest stage of gold-bearing vein mineralization is that at Cow Mountain (Cariboo Gold Quartz mine), which has been characterized during the present study as type 1 gold. The diagnostic feature of this gold type comprises a low Ag content (Fig. 4A) and an association with cosalite and galena (Fig. 5). In contrast, the mineralogy of the later auriferous veins (including those at Warspite) is consistently reported as pyrite ± galena±sphalerite ± arsenopyrite (Schiarizza, 2004) which corresponds to type 2a gold (Table 3). Interpreting the affiliation of type 2b gold is currently problematic, due to the absence of any useful inclusion signature.

The temporal distinction between types 1 and type 2a vein mineralization around Wells is consistent with the delineation in their distribution, as indicated in Figure 12. Whilst there is some spatial overlap in the occurrence of both gold types (e.g., along Lowhee Gulch) gold-bearing mineralization consistent with type 2 gold has not yet been reported within the zone of type 1a gold. However, this may simply reflect the relative abundance of the two types, as several authors refer to cosalite as an indicator for high grade gold (e.g., Brown and Yin, 2009). In the Stanley area it is more difficult to establish the relationship between the various gold types both due to the absence of age information for lode mineralization and the uncertainty regarding the relationship of type 2b gold to the other gold types. Consequently the significance of the apparent spatial overlap of gold types around Burns Mountain shown in Figure 12 is currently unclear.

Speculation on the conditions of mineralization

Data sets which describe the Ag content of gold grains derived from vein material can be used to speculate on the nature of the environment of gold precipitation. Gammons and Williams-Jones (1995) described the controls on Au/Ag_{alloy} in terms of Au and Ag speciation and the various equilibrium relationships. Chapman et al. (2010a) applied these controls to interpret the shapes of Ag plots in terms of the chemical stability of the mineralizing system. These authors proposed that stable mineralizing environments equated to stable chemical conditions resulting in a small range of alloy compositions (e.g., the sample from Cow Mountain; Fig. 4A). Horizontal data arrays on cumulative percentile vs. Ag content plots could also indicate rapid precipitation of Au alloy associated with sudden changes in the chemical environment, such as might be related to changes in aS_2 or pressure release. Signatures which comprise multiple plateaus (e.g., Myrtle; Fig. 4D) indicate a corresponding number of mineralizing environments, probably reflecting episodic gold deposition. However, a continuous wide range of Ag contents within the same vein (e.g., Warspite, sample AU 586, Fig. 4C) could indicate an evolving system and/or the influence of multiple parameters on alloy composition.

In general, the data describing type 1 gold is suggestive of a consistent mineralizing environment, which may be interpreted as indicative of a strong hydrothermal system buffered against local changes through interaction with wall rock, or changes in metal deposition/aS_2 variation which can accompany Au precipitation. Analysis of gold grains liberated from type 2a mineralization shows a wider range of signatures. The near duplication of Ag ranges from different vein systems (e.g., gold of 10-12% Ag at both Myrtle and Bonanza Ledge (Fig. 4D) are interpreted as indicative of similar environments of mineralization, which is consistent with the hypothesis of periodic fluid mobility along pre-existing fault systems. Most populations of type 2 gold from lodes exhibit sub populations of different Ag contents (Fig. 4D), which is consistent with the observation of Rhys and Ross (2001), who noted that the Wells area had been subjected to several episodes of gold mineralization. This model may also account for the different character of in situ mineralization at nearby localities, e.g., the Proserpine and Warspite lode samples (Fig. 4C). Vein heterogeneity is not confined to only the small veins, as Rhys and Ross (2001) report highly variable Au grades in the BC vein, although it is not known whether this variation also manifests as compositional variation in the gold alloy.

The common pyrite-galena-chalcopyrite ± arsenopyrite mineralization associated with type 2a gold is entirely typical of orogenic gold from many localities worldwide (summarised in Chapman et al. 2009). Although Bi signatures have been recorded in gold mineralization in orogenic belts this appears to most commonly be a feature of intrusion-related mineralization (e.g., Bierlein and Crowe, 2000). The distinctive association of gold with cosalite (which in part defines type 1 gold) is unique, and the underlying reasons for the inferred high Bi content of the mineralizing fluid remain unclear.

Implications For Exploration

This study has clarified the relationships between placer and lode gold in the northern CGD. Consequently it is appropriate to evaluate the implications for future exploration in two ways: firstly in the context of the generic exploration practice, and secondly with respect to the study area.

Integration of gold compositional signatures with other data sets

The placer goldfields in the CGD exhibit features common to other well known placer areas in orogenic belts worldwide. Placer-lode relationships may not be transparent, and it is commonly difficult to account for the location of the richest placers in the context of known lode sources. The present study has permitted evaluation of the different approaches to the evaluation of placer genesis in the CGD, and the benefits afforded by combining information from different data sets. Generic implications of these elements and their syntheses are discussed below.

Historical placer production records alone provide information on the geographical abundance of gold. In many cases, however, historical data may be incomplete either because the early (and commonly richest) phases of gold rushes are not well documented, or because placer mining has avoided specific localities owing to the costs associated with removing excessive overburden. Nevertheless, useful comparative data on placer grade may easily be obtained, together with some information on the composition through records of gold fineness. These data may prove useful in comparative studies for investigating whether detrital Au has been derived from single or multiple lode sources, and can generate vectors to the location of the lode source(s), even in areas which exhibit complex surficial geology.

Fluvial sedimentology can inform interpretation of the modern or paleo-placer environment, and can establish whether a particular placer locality represents an allochthonous or autochthonous concentration. This information is important when considering the implications of production records, because in some cases rich placer deposits may in fact be distal to their source. Records of historical placer production may include also information on the morphology and physical character of the detrital gold grains, features which have been shown to be related to fluvial transport distance (e.g., Townley et al., 2003; Crawford, 2007).

Gold composition studies permit more focussed interogation of lode-placer relationships, but benefit from consideration in the context of information from production records and fluvial sedimentology. There are several characteristics of Au composition which can be usefully applied in evaluating regional mineralization. Firstly, the present study identified a correlation between the economic importance of Au mineralization and the range of Ag contents. Narrow ranges of alloy compositions indicate strong, stable mineralizing systems that were buffered against the influences of changes in conditions associated with gold precipitation. Similar patterns of high gold abundance correlating to a specific placer signature have been observed in orogenic gold districts elsewhere; e.g., the Klondike District in Yukon, Canada (Chapman et al., 2010b), and various minor localities in the Caledonides of Britain and Ireland (e.g., Leake et al., 1998; Chapman et al., 2000c). In general, a narrow range of Ag contents within an autochthonous placer is indicative of a proximal source, whereas a similar signature in an allocthonous placer indicates the regional dominance of a signature associated with stable mineralizing conditions, consistent with either a large single system or several smaller but similar regionally widespread systems. Secondly, the presence of localised populations of high-Ag gold alloys is similar to those identified in other areas. In the Klondike District, this signature is evident at the Violet and Virgin occurrences (Chapman et al., 2010a,b), and in the White Gold District at Golden Saddle (Chapman, R.J., unpublished data). Detailed surveys of auriferous districts of lower gold abundance reveal a similar pattern; e.g., the Leadhills District, Scotland (Leake et al., 1998), and County Mayo, Ireland (Chapman et al., 2000a). Commonly, heterogeneous gold grains exhibit late Ag-rich alloy, either mantling the core or as pervasive films. Consequently there is evidence that these relatively Ag-rich alloys are associated with the late stages of mineralization in a waning hydrothermal system and may represent mineralization which is a less attractive exploration target. These Ag-rich alloys are commonly associated with relatively high Hg contents, although the underlying reasons for this association remain unclear. Thirdly, the consideration of inclusion assemblages in conjunction with alloy compositions is a vital aid to characterizing populations of detrital Au, even in areas such as the CGD and the Klondike District (Chapman et al., 2000a,b) where the overall incidence of inclusions within polished sections is low. Finally, correlation of Au composition with grain morphology in a population of detrital grains can establish the relative proximity and mineralogy of sources that contributed to the placer inventory.

Data from mineral occurrence records, such as that found in outputs from regional or national geological surveys, may provide another source of information which can be correlated with gold compositional data. Gold occurrences are commonly described in terms of the associated mineralogy in outcrop, and these data sets may be compared to inclusion species recorded both in gold particles liberated from in situ material and in detrital gold samples. This approach facilitated far more robust predictions of the geographical limits of gold types in the CGD than would have been otherwise possible.

The integration of these various data sets can help to evaluate the relative importance of sources contributing to a single placer population. In cases where multiple sources are present, this approach permits identification of the most economically promising signature, which can subsequently inform the exporation process.

Implications for exploration in the northern CGD

Table 4 provides a summary of the placer-lode relationships in the study area, and this information may be considered in the context of the production figures linked to gold type presented in Table 5. The key results from this analysis are as follows: i. the economically important mineralization at Cow Mountain yields gold particles with a distinctive mineralogy, which have also been found at Burns and Chisholm creeks, for which there is no known hypogene source; ii. the historically rich placers of Williams Creek appear to be in part related to a major occurrence of type 2a gold at the BC Vein; however, the source of the high-Ag population which is also present in Grouse Creek (Table 5) remains unclear and may represent an attractive exporation target for the following reasons. The amount of type 2a placer gold recorded from Williams and Grouse creeks is approximately 56,000 oz (although the actual figure is certainly far higher). Both creeks are several kilometers long and the catchments host multiple lode occurrences (Schiarizza, 2004). Analyses of lode gold populations from different localities in the present study demonstrate the probable heterogeneity in sources of gold feeding the Williams and Grouse creek placers (Figs. 4C and D), but the variable signatures of these minor sources are only a minor component of the placer signatures. Consequently the dominance of a narrow compositional range of gold particles within these allochthonous placers is strongly suggestive of a potentially important undiscovered source;. iii. in contrast, other distinctive signatures recorded in placer populations have a very local distribution (e.g., Dragon Creek and Beggs Gulch) and may not be indicative of significant local mineralization; iv. the abundance of type 2b gold around Burns Mountain and within the large placers of Lightening Creek indicates a strong pervasive mineralizing episode. However, the two known lode occurrences (Foster's Ledge and Burns Mountain) of this gold type are small, suggesting that the placer is derived from numerous, but small hypogene occurrences; v. placer gold from Cunningham, Antler, Little Snowshoe and Keithley creeks shows no apparent influence from the known local lode sources at Hibernia and Midas. In this case the placers in the trunk drainages appear to represent gold derived from a large number of sources, which implies that these sources are probably relatively minor.

Regional considerations

The interpretation provided above has established a framework within which to consider placer-lode relationships within the CGD. Careful examination of the placer gold in the CGD and integration with information from known lode occurrences shows that lode mineralization occurs in discrete centres or belts that are of limited aerial extent, rather than being spread over relatively large areas, as is commonly inferred from the more widespread distribution of placer gold. The character of the D2 deformation that appears to have at least in part controlled the localization of gold-bearing veins and replacement style ore (Rhys et al., 2011) remains largely unchanged to the northwest and southeast along and beyond the ends of the mineralized trends, as do the general lithological units present. There is also no obvious abundance of north or northeast-trending cross-structures in either the Well-Barkerville or Yanks Peak area that might have provided additional controls for focusing hydrothermal fluid flow. Therefore, although it is likely that there are regional scale structural and lithological controls on the general location of the main northwest-trending auriferous belts, the reason why there are apparent centers of mineralization along these trends is still uncertain. Lead isotopic compositions of lode gold occurrences in the northern CGD show considerable scatter, which led Mortensen et al. (2011) to conclude that metals in the gold-bearing veins and replacement bodies are largely locally derived, either from the immediate host rocks or from similar rock units in the subsurface. If correct, this hypothesis suggests that there may be subtle compositional variations within the local rock units that make them particularly fertile. Lode gold occurrences in the CGD are hosted within a portion of the belt that experienced relatively low grade metamorphism (lower to middle greenschist facies), and are largely or entirely absent within the same rock units at higher metamorphic grade (upper greenschist to lower amphibolite facies) along strike to the northwest and southeast (Fig. 1). This observation is consistent with a model such as that proposed for orogenic gold mineralization in the Otago Schist Belt in New Zealand, in which gold and other associated elements have been remobilized from large volumes of schist at depth, across the prograde greenschist-amphibolite facies transition, and redeposited at shallower structural levels in the crust (e.g., Pitcairn et al., 2006; Mortensen et al., 2010). However, there are two arguments against such a model for the CGD. First, one would expect that gold-bearing vein systems would have originally been present at higher structural levels to the northwest and southeast of the CGD, and that gold derived from these now-eroded rock masses would be present in widespread placer deposits. Scattered orogenic style quartz veins are present in the higher grade metamorphic rocks; however, they do not contain gold, and no significant placer gold has been discovered thus far outside of the CGD. Secondly, the lower greenschist to lower amphibolite facies metamorphism that affected the Barkerville terrane in this area was associated with the D1 deformation event, whereas the introduction of gold as pyritic replacement bodies or mineralized quartz veins was late or post-tectonic with respect to the D2 event, and therefore probably significantly younger than the metamorphism. We therefore conclude that some as yet unidentified combination of lithological and/or structural controls was responsible for the preferential formation of gold-bearing veins in the immediate Wells area and in certain localities surrounding it.

Orogenic gold mineralization in the Quesnellia terrane (Spanish Mountain and Frasergold deposits; Fig. 1) in the southwestern part of the CGD occurs at higher structural levels and is somewhat older than that in the Barkerville terrane in the northern CGD (Rhys et al., 2009; Mortensen et al., 2011), and it is unclear whether there is any relationship between these styles of mineralization and that in the Well-Barkerville camp. Gold in the Spanish Mountain and Frasergold deposits, and in placers derived from these deposits, is also compositionally very different from that in the Barkerville terrane (Mortensen and Chapman, 2010; Chapman and Mortensen, 2011). The nature and origin of the Quesnellia terrane lode and placer deposits will be described in more detail elsewhere.

Conclusions

Study of placer-lode gold relationships in the northern CGD has permitted both an evaluation of the economic potential of regional orogenic gold mineralization and development of a methodology which could find wider application in other mineralized regions.

Hypogene gold distribution in the Wells-Barkerville gold district is irregular with a major centre of mineralization evident near the town of Wells. Two major types of gold mineralization have been identified based on the mineralogy of the native gold. Type 1 exhibits a strong Au-Bi signature and the gold alloys themselves are low-Ag (4-7%). Type 2 gold has been subdivided according to alloy composition. Type 2a gold is regionally widespread and comprises a Au-pyrite/galena/chalcopyrite ± arsenopyrite association, with gold alloys typically containing between 10 and 25% Ag. Type 2b gold exhibits a narrower range of Ag contents (5-10%). Type 1 gold represents an earlier phase of mineralization than type 2a gold, although the timing of type 2b gold remains uncertain. Compositional characterization of gold grains from lode samples and comparison with gold in local placers has shown that these features persist and can be used to identify which type has contributed to specific placers.

Application of gold type analysis to historical production data has indicated that type 2a gold is the most important source type for placer gold in the CGD and that there are numerous geographically widespread lode occurrences which have contributed to allochthonous placers in trunk drainages. Placer gold from Williams Creek exhibits two distinct compositional ranges, in roughly equal proportions, one of which corresponds to the type 2a gold recorded at the nearby BC vein. The other, more Ag-rich alloy signature is also predominant in gold from the adjacent Grouse Creek. There is currently no known plausible source which can account for this specific signature. Economically important placers containing type 1 gold around Wells are autochthonous and provide a clear indication of the nature and locality of the source lode mineralization. Type 2b gold is an important component of many relatively rich placers in the Lightening and Slough creek drainages; however, no corresponding large lode sources have yet been discovered.

The range of Ag contents within gold grains liberated from lode sources in the CGD has been used to infer conditions of mineralization. Narrow ranges of Ag are interpreted as representing stable conditions of precipitation (e.g., BC Vein, Bonanza ledge, Cow Mountain veins). Some lode samples yielded single populations, whereas others exhibited multiple narow ranges of Ag, believed to represent multiple phases of mineralization (e.g., Myrtle).

The study has clarified the placer lode relationships in the northern CGD, and illuminated the spatial distribution of gold formed during different mineralizing events. These new insights will inform subsequent studies of the controls on emplacement of regional orogenic gold, which presently remain unclear.

Integration of data sets describing in situ mineral occurrences, placer production records and considerations of fluvial sedimentolgy with detailed gold mineralogical data describing populations of in situ and detrital particles (in terms of alloy compositions and mineral inclusion suites) can greatly illuminate the nature of orogenic gold mineralization in a region. Characterization of potential sources in terms of their native gold mineralogy can be related to both mineral occurrence records and placer gold composition studies to generate a more detailed understanding of the nature and extent of gold mineralization than is possible by consideration of each element in isolation. Interpretation of the data sets must be undertaken in the context of whether the placer deposits under study are allochthonous or autochthonous. Finally, application of historical records of placer mining in terms of gold production records and gold fineness can permit evluation of the magnetude of the various potential sources and their potential as subsequent exploration tagets.

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